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Oceans on Mars: An assessment of the observational evidence and possible fate

Michael H. Carr
U.S. Geological Survey, Menlo Park, California, USA

James W. Head III
Department of Geological Sciences, Brown University, Providence, Rhode Island, USA

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[1] If the large Late Hesperian outflow channels were eroded by extensive floods, as appears likely, then large bodies of water must have once occupied the northern plains during that period. Previous estimates of the sizes of bodies of water in the northern lowlands range up to 3×10^8 km^3. Several contacts have been previously mapped around the edges of the northern plains and interpreted to be shorelines remaining from these former standing bodies of water. We examine the elevations and geologic relations along these contacts in detail and find little support for their interpretation as shorelines. Some contacts are clearly of volcanic origin, and all have significant variations in elevation. Better support for the former presence of water over large parts of the northern plains is provided by the Vastitas Borealis Formation (VBF). Most of the post-Noachian fill within the northern basin is ridged plains of Lower Hesperian age, interpreted to be volcanic in origin. Overlying the ridged plains is the VBF, a thin veneer of material of Upper Hesperian age. The VBF may have been deposited from large floods. Support for this interpretation is the similarity in age between the outflow channels and the VBF, the presence of the VBF at the lower ends of the outflow channels, and identification of numerous features in the outcrop areas of the VBF that are suggestive of basal melting of an ice sheet. To cover all the area over which the VBF is exposed would require $\sim 2.3 \times 10^7$ km^3 of water. Spread over the entire surface of Mars, this volume is equal to a global layer (global equivalent layer, or GEL) ~156 m deep. We find no support for the larger estimates of ocean volumes that range up to 3×10^8 km^3 and which imply comparable amounts of water per unit area as are currently present on the surface of the Earth. Under present climatic conditions on Mars an ocean would freeze in a geologically short time period ($\sim 10^4$ years), then would sublimate away at rates strongly dependent on the presence or absence of debris on the ice surface. The present VBF is interpreted as a sublimation residue from the ponded outflow channel effluents. The fate of a volume of water thought to have been emplaced by the outflow channels ($\sim 2.3 \times 10^7$ km^3) is largely accounted for by the presence of other existing reservoirs on the planet. An approximately 20–30 m GEL of water is estimated to be in the present polar caps, and a 50 m GEL may have escaped to space since the Hesperian, leaving ~80 m GEL unaccounted for. This amount may be partly trapped in other volatile-rich deposits on the surface, and a significant amount could have reentered the groundwater system by south polar basal melting and been progressively cold-trapped at the base of a growing cryosphere. On the basis of our assessment of the Hesperian-aged deposits, we predict that testing of the *Clifford and Parker* [2001] hypothesis that a Noachian-aged ocean covered up to one third of the surface of Mars will be made very difficult by the enhanced degradation rates in the Noachian and subsequent geological events in the northern lowlands. *INDEX TERMS:* 6225 Planetology: Solar System Objects: Mars; 4267 Oceanography: General: Paleoceanography; 5407 Planetary Sciences: Atmospheres—evolution; 5470 Planetary Sciences: Surface materials and properties; 1635 Global Change: Oceans (4203); *KEYWORDS:* Mars, oceans, channels, shorelines, Hesperian

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1. Introduction

[2] The purpose of this paper is to assess the observational evidence for post-Noachian oceans in the northern plains of Mars in light of new data provided by the Mars Global Surveyor nominal mission. We focus on the post-Noachian time period because of the likely connection between formation of any oceans and the formation of the large outflow channels, which are mainly Hesperian in age [*Tanaka*, 1986], and because low cumulative amounts of erosion since the end of the Noachian [*Arvidson et al.*, 1979; *Carr*, 1992; *Golombek and Bridges*, 2000] cause most post-Noachian landforms to be well preserved. The conclusion by most researchers that the large outflow channels discovered by Mariner 9 were formed by large floods [*McCauley et al.*, 1972; *Masursky*, 1973; *Milton*, 1973; *Baker and Milton*, 1974; *Baker*, 1979, 1982; *Baker and Kochel*, 1979] implies that substantial bodies of water were left behind after their formation. Yet until the late 1980s little was done to determine where such bodies of water might have been present, how big they might have been, and whether they had left any evidence of their former presence. It was recognized that the northern plains constitute an ancient depression, possibly formed by one or more giant impacts [*Wilhelms and Squyres*, 1984; *McGill and Squyres*, 1991] and that the depression is partly filled with deposits, that, at the surface, are mostly Hesperian in age [*Scott and Tanaka*, 1986; *Tanaka and Scott*, 1987; *Greeley and Guest*, 1987]. Many of the unique features of the northern plains were variously interpreted as due to repeated deposition and removal of debris blankets [*Soderblom et al.*, 1973], presence of pervasive ground ice [*Carr and Schaber*, 1977; *Rossbacher and Judson*, 1981], volcano-ice interactions [*Hodges and Moore*, 1994; *Chapman*, 1994], widespread volcanism [*Tanaka and Scott*, 1987], and large-scale mass-wasting [*Jons*, 1985, 1986, *Tanaka et al.*, 2001]. Among the first to discuss the possibility of former oceans in the northern plains were *Lucchitta et al.* [1986], who suggested that the polygonally fractured ground found in the plains downstream of outflow channels could be the result of compaction and warping of sediments deposited in standing bodies of water.

[3] The idea that oceans were formerly present in the northern plains was elaborated upon in some detail by *Parker et al.* [1989, 1993]. They noted a variety of features around and within the plains that they interpreted as indicative of former shorelines. These included (1) cliffs and onlap relations in the fretted terrain, (2) plains with subdued parallel ridges or "thumbprint" textures, (3) terraces on fretted valley walls, (4) evidence of backflow in the lower reaches of some outflow channels, (5) abrupt termination of outflow channels as they debouch onto the plains, and (6) massifs with stepped slopes. From these observations they identified two discontinuous contacts that were tentatively interpreted as shorelines. An outer contact 1 roughly coincided with the plains-upland boundary, and an inner contact 2 lay almost wholly within the plains. *Scott et al.* [1991, 1995], also identified a number of possible shorelines, using similar criteria, but interpreted the discontinuous possible shorelines in terms of a number of separate bodies of water rather than a single large ocean in the northern plains. Parker and coworkers subsequently identified several additional shorelines both within the former contact 1 and outside it [*Parker*, 1998; *Parker et al.*, 2001; *Grant and Parker*, 2001]. Some of these "shorelines" imply large volumes of water at the surface (Figure 1). The "Meridiani shoreline" [*Edgett and Parker*, 1997; *Parker et al.*, 2001; *Clifford and Parker*, 2002], for example, is at an elevation of roughly 0 km and would enclose a volume of water equivalent to over 1.5 km spread evenly over the whole planet's surface (GEL).

[4] The low-lying northern plains are not the only locations where standing bodies of water may have been. *McCauley* [1978] suggested that layered sediments within the canyons indicated that lakes had been formerly present, a suggestion that has been adopted by many others [e.g., *Nedell et al.*, 1987]. *Cabrol and Grin* [1999] and *Haberle et al.* [2001] have proposed that layered sediments in numerous craters within the southern highlands are the result of deposition from lakes within the craters. On a larger scale, *Malin and Edgett* [2000, 2001] suggest that subaqueous processes were likely involved in the deposition of layered sediments observed in many locations throughout the southern highlands. *Moore and Wilhelms* [2001] interpret many of the features in Hellas as the result of lacustrine processes. *Parker et al.* [2000] and *Clifford and Parker* [2001] present a case for overland flow of water from the south polar region to the northern lowlands, with water draining into and filling the Argyre basin, overtopping it to the north, and flowing down the Chryse trough into the northern lowlands. The system terminates at the Meridiani "shoreline" [*Edgett and Parker*, 1997; *Parker et al.*, 2000] (Table 1), associated with a "primordial" ocean [*Clifford and Parker*, 2001, p. 62], indicating an age of the system greater than contact 1, which is "at least 4 Ga" [*Clifford and Parker*, 2001, p. 44]. If this scenario is true, this system would be over 8000 km in length and would be the longest know fluvial system in the solar system [*Parker*, 1989]. The continuity of features in the system proposed by *Parker et al.* [2000], their contemporaneity, and their ancient age have recently been questioned by *Hiesinger and Head* [2002], who find that several of the elements of the proposed system are independent features of differing ages.

[5] Meanwhile, *Baker et al.* [1991] adopted the ocean hypothesis to explain otherwise anomalous landform assemblages, such as possible Amazonian age glacial features in the southern hemisphere [*Kargel and Strom*, 1992] and Hesperian and Amazonian age valley networks [*Gulick and Baker*, 1989, 1990]. They suggested that since the end of the Noachian, climatic conditions on Mars have been mostly similar to those that prevail today, but that these long cold periods were episodically interrupted by brief warm events. The warm events were caused by immense floods that formed temporary oceans and released large amounts of water and carbon dioxide into the atmosphere, thereby changing the global climate. They suggested that, after the ocean forming events, the carbon dioxide was scavenged out of the atmosphere, the water infiltrated into the porous subsurface and the planet

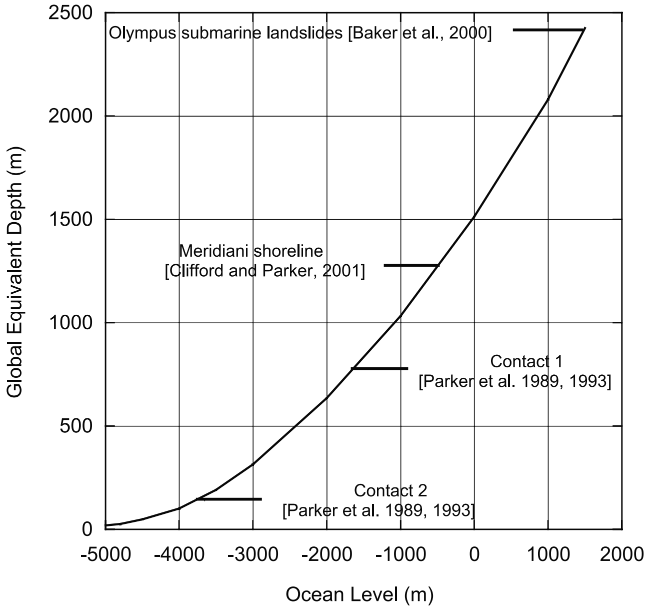

Figure 1. Volumes of water that would be contained by oceans in the northern plains as a function of the elevation of the ocean surface. Volumes are derived from MOLA data averaged over one-degree boxes.

reverted to its former frozen state. Further elaborations of this model are given by *Baker et al.* [2000] and *Baker* [2001]. The volumes of water implied by the *Baker et al.* model are higher than the upper estimates of Parker and coworkers. *Baker et al.* [2000] suggested, for example, that the Olympus Mons aureole deposits are submarine landslides. Parts of the aureole are at elevations in excess of 1.5 km above the datum, which implies a volume of water in excess of 2.5 km GEL (spread evenly over the whole planet), or roughly equivalent to the Earth's surface inventory of ~3 km GEL.

[6] Finally, *Clifford and Parker* [2001] considered the hydraulic and thermal conditions that produced the elevated source regions of the Late Hesperian outflow channels, and used these conclusions to assess the implications for the nature and evolution of the hydrosphere of Mars. The presence of outflow channel sources at such high elevations, and evidence that the channel heads emerged from groundwater sources beneath a cryosphere, led *Clifford and Parker* [2001] to the conclusion that early Mars history must have been characterized by at least one third of the surface being covered by standing bodies of water and ice, most specifically, an ice-covered ocean in the northern lowlands. In their scenario, the long-term decline in planetary heat flow led to cold-trapping of water into the growing cryosphere, progressively decreasing the total inventory of groundwater. According to their model, the Late Hesperian outflow channels and formation of a northern ocean represent the last major influx of groundwater into the northern lowlands.

[7] Acquisition of data by Mars Global Surveyor has provided abundant new evidence for assessing the ocean hypothesis. Since the spacecraft achieved its nominal mapping orbit in March 1999, it has returned over 250 gigabytes of data [*Albee et al.*, 2001]. The data of most interest here are those from the high-resolution camera (MOC) and from the altimeter (MOLA), although data from the other instruments have important implications for the long-term evolution of the solid planet and its climate, which in turn have implications for the possible former presence of ocean. Early in the mission, *Head et al.* [1998, 1999] demonstrated that the outer contact 1 of *Parker et al.* [1989, 1993] had a wide range in elevations (>6 km) and so was unlikely to be a shoreline unless Mars had been much more tectonically active than previously thought. They suggested that the inner contact 2 of Parker et al. was a more probable shoreline candidate. It has a much smaller range of elevations, particularly if parts adjacent to the volcanically active provinces of Tharsis and Elysium are excluded. *Head et al.* [1999] also pointed out what appeared to be terraces at constant elevation within the large impact basin Utopia. *Head et*

Table 1. Volumes of Potential Reservoirs or Sinks

	Elevation, m	Volume, km^3	Equivalent Global Depth, m
Deuteronilus shoreline	−3792	1.9×10^7	130
Outer boundary Vastitas Borealis Formation	−3658	2.3×10^7	156
Arabia shoreline	−2090	8.7×10^7	599
Meridiani shoreline	0	2.2×10^8	1510
Submerged Olympus Mons aureole	1500	3.5×10^8	2430
Total northern plains	<−3500	2.6×10^7	196
Utopia basin	<−4350	1.5×10^6	10
North Polar basin	<−4350	7.4×10^6	51
North polar cap[a]		$1.2–1.7 \times 10^6$	8–12
South polar cap[a]		$1.2–1.7 \times 10^6$	13–21
Megaregolith capacity (20% surface porosity)[b]		7.8×10^7	540
Megaregolith capacity (50% surface porosity)[b]		2.0×10^8	1400
Lost to space[c]		7.2×10^6	50

[a] From *Smith et al.* [1999].
[b] From *Clifford* [1993].
[c] From *Kass* [2001].

al. [2001] and *Kreslavsky and Head* [1999, 2000, 2002a] subsequently demonstrated that the area of the northern plains within contact 1 has a number of characteristics that suggest that it is a volcanic plain covered with a thin veneer of sediments, and their favored interpretation is that the sediments were deposited from standing bodies of water created by the large outflow channels. The volume of water that would have been contained within contact 2 is roughly 150 meters GEL (spread over the whole planet), over an order of magnitude lower than the higher estimates of Parker and Baker and coworkers.

[8] Little support for oceans and shorelines has been found in the MOC images. The contacts mapped by *Parker et al.* [1989, 1993] were targeted by MOC for detailed observation, but *Malin and Edgett* [1999, 2001] found no evidence for the shorelines in these images. In one case northwest of Acheron Fossae they claim that, along the Parker et al. contact there are escarpments facing upslope, rather than toward a former ocean. Because of the scale, however, this claim cannot be confirmed by the MOLA data. In the Nilosyrtis region, where many of the "shoreline" features were originally identified, numerous terraces can be identified in the MOC images and MOLA data. However, distinguishing breaks in slope caused by shoreline processes from those due to other causes, such as layering in the bedrock, mass wasting, and other processes, will be challenging [*Carr*, 2001].

[9] The possibility that large bodies of water were present in the northern plains is based largely on the premise that the outflow channels were cut by water. While this is plausible, it is not proven and numerous other suggestions have been made (summarized by *Carr* [1981, 1996]). Recent advocates of alternate hypotheses include *Hoffman* [2000] and *Tanaka et al.* [2001], who suggest that CO_2 may have played a prominent role in cutting some outflow channels, and *Leovy and Armstrong* [2003], who discuss previous suggestions that lava erosion and wind erosion may also have played significant roles. Failure to detect carbonates and clays by TES on Mars Global Surveyor [*Bandfield et al.*, 2000; *Christensen et al.*, 2001] and the nature of alteration assemblages in Martian meteorites [*Bridges et al.*, 2001] also cast doubt on any model that has liquid water stable at the Martian surface for geologically significant periods.

[10] While recognizing the other possibilities, we accept that the outflow channels were likely cut by water and that after their formation standing bodies of water were left at their termini. Our intent is to examine what geologic evidence exists for the former presence of these bodies of water, and from this evidence estimate how large the bodies of water were [e.g., *Head et al.*, 2001]. The approach is three pronged. We first examine the geomorphic evidence for shorelines, then look at the area that might have been covered by an ocean for evidence of modification of the pre-existing terrain as a consequence of the water's presence. Finally we try and reconcile the appearance and disappearance of large bodies of water with other aspects of the planet's evolution. MOLA data is used extensively both as a measure of elevations and to reconstruct topography. Because MOLA data are given in East longitude, we use this convention throughout the paper.

2. Northern Lowlands

[11] The north-south dichotomy caused by dominantly highstanding cratered terrain in the south and low standing, sparsely cratered plains in the north has long been recognized [e.g., *Kliore et al.*, 1973; *U.S. Geological Survey*, 1972]. The plains have very low slopes and are at elevations approximately 5 km lower than the cratered southern uplands [*Smith et al.*, 1998, 1999]. Gravity data indicate that the crust is thinner in the north than in the south, being typically 30–40 km thick under the northern plains and 40–80 km thick under the southern uplands [*Zuber et al.*, 2000]. Thus the dichotomy is expressed in three ways, elevation, crater density, and crustal thickness, although the three boundaries do not everywhere coincide. Recent studies, described below, have provided an improved picture of the substructure and stratigraphy of the northern lowlands [e.g., *Frey et al.*, 2002; *Head et al.*, 2002].

[12] Within the plains are two subsidiary depressions: a circular Utopia basin centered at 45°N, 110°E, and a more elongate North Polar basin centered at roughly 70°N 330°E (Figure 2). The Utopia basin reaches depths of 5000 m below the datum; the Polar basin reaches depths of 5200 m below the datum. The barrier between the two basins has a minimum elevation of −4300 m. Floods that carved the large valleys around Chryse Planitia would have flowed into the North Polar basin, those that cut the valleys northeast of Elysium would have flowed into the Utopia basin. Water from southern Elysium Planitia would have flowed through Marte Vallis into Amazonis Planitia. Similarly, water that cut the channels along the highland front south of Amazonis Planitia would have flowed into Amazonis Planitia. Amazonis Planitia merges northward with the north polar basin but it apparently was not itself an enclosed basin prior to the Late Hesperian, when proto-Olympus Mons flow units may have dammed outflow from the south [e.g., *Fuller and Head*, 2002a, 2002b]. Amazonis Planitia is extremely flat [*Aharonson et al.*, 1998]. Its surface slopes northward from −3800 m at 17°N, 205°E to −3900 m at 30°N, 200°E, a slope of only 1:10,000 over a distance of 800 km. Because of the low slopes it is not clear whether water flowing into Amazonis Planitia from the south during most of the Hesperian would ultimately reach the North Polar basin before flow was arrested by processes such as freezing and infiltration. Finally the Isidis basin, which reaches depths of −3900 m, and whose floor is tilted toward the south, is presently separated from the main northern depression by a ridge with a minimum elevation of −3500 m. This raises the question of whether any water flowing into Isidis would have flowed into the Utopia basin during the Hesperian, or whether the barrier and topographic tilt might postdate the Hesperian.

[13] The number of craters superimposed on the northern plains indicates that most of the present surface is Upper Hesperian (VBF) or younger in age [*Scott and Tanaka*, 1986; *Tanaka and Scott*, 1987; *Greeley and Guest*, 1987]. However, in many areas, low hills poking

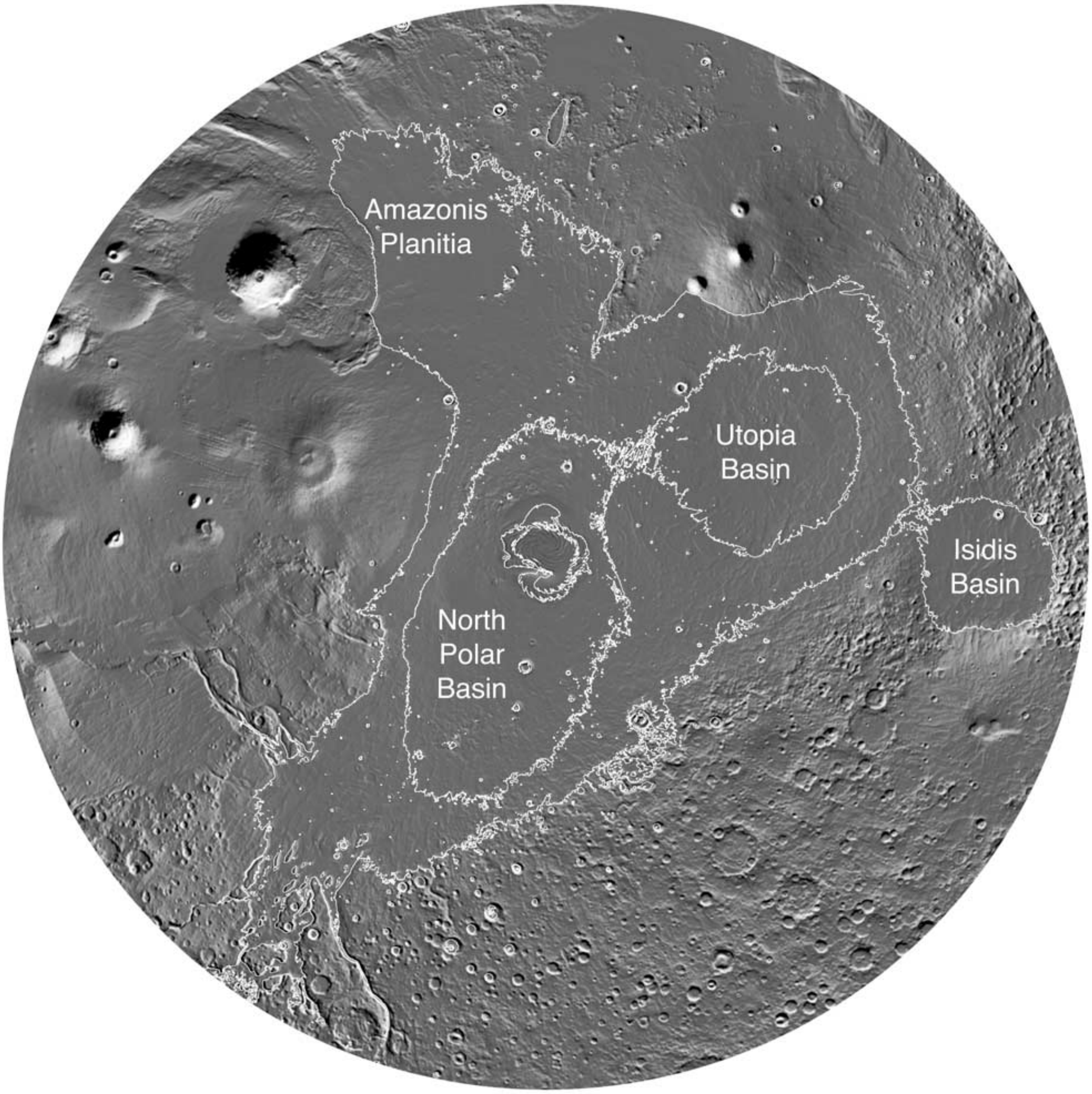

Figure 2. The northern hemisphere of Mars. Two contours are shown: an outer one at −3500 m, the height of the barrier between the Isidis basin and the northern plains, and an inner one at −4350 m, the height of the barrier between the Utopia basin and the North Polar basin. Polar stereographic projection.

through the plains outline the remnants of large craters in numbers that indicate a Noachian age [*McGill*, 1989]. In addition, many MOC images show subdued craters in numbers comparable to the southern highlands [*Malin and Edgett*, 2001] and faint circular depressions, detectable only in the MOLA data, are common throughout the northern plains [*Frey*, 2002; *Frey et al.*, 2002]. The depressions probably overlie craters in the ancient surface on which the plains materials were deposited. The areal density of the depressions indicates a Lower Noachian age for this surface [*Frey et al.*, 2002]. *Frey et al.* [2002] conclude from the dimensions of partly buried craters, that the depth of the Noachian surface below the present plains surface varies from 0–5 km. Evidence has been outlined for the presence of extensive Hesperian-aged ridged plains overlying the Noachain aged surface and underlying the Vastitas Borealis Formation [*Head et al.*, 2002]. Possible origins for the large depression occupied by the plains include a single impact or multiple large impacts early in the history of the planet, or some early endogenetic cause [*McGill and Squyres*, 1991]. *Zuber et al.* [2000] favor an endogenetic origin because of the absence, except for the Utopia basin, of gravity signatures expected of large impact basins.

[14] Viking image data for much of the northern lowlands was often partly obscured by seasonal clouds and

hazes, and few wrinkle-ridge structures were observed and mapped from these data [*Chicarro et al.*, 1985]. New Mars Global Surveyor MOLA data demonstrated that ridged plains dominate the topography of the northern plains at a regional scale [*Withers and Neumann*, 2001; *Head et al.*, 2002]. The materials that form the ridged plains likely constitute most of the post-Noachian fill within the northern basin. The extensive ridged plains farther south, as in Lunae Planum, Solis Planum and Hesperia Planum are thought to be volcanic because of their resemblance to lunar maria, their wide range in elevation, and the occasional presence of flow lobes, cinder cones and other likely volcanic features [e.g., *Mouginis-Mark et al.*, 1992]. The ridged plains in the northern basin are continuous with, and closely resemble those farther south. The most straightforward interpretation is that they are also volcanic [*Head et al.*, 2002]. The ridges in the northern plains of the western hemisphere form a coherent, parallel set that extends northward from Chryse, around the northern edge of Tharsis then south through Amazonis Planitia and the Phlegra Montes. They are part of the ridge system that extends all around Tharsis [*Banerdt et al.*, 1992]. The ridges in the eastern hemisphere form a more random or polygonal pattern related to local features such as the Isidis and Utopia basins [*Head et al.*, 2002]. While recognizing possible alternatives, for the rest of the paper we assume that the northern ridged plains are volcanic like most of those elsewhere on the planet.

[15] The low regional slopes within the northern plains have been compared with the Earth's oceanic abyssal plains [*Smith et al.*, 1998; *Aharonson et al.*, 1998], but the regional slopes are dominated by the ridged plains surface so, like the ridged plains themselves, the generally low regional slopes are probably the result of volcanic processes [*Head et al.*, 2002]. Even where ridges are absent, the regional-scale topography appears to be the result of volcanism. The flattest region of the planet is Amazonis Planitia [*Aharonson et al.*, 1998]. Although parts of its surface are almost featureless in the MOLA reconstructions of the topography and in all but the highest resolution Viking images, lava flows are visible in almost all the MOC images of the region [*Malin and Edgett*, 2001; *Keszthelyi et al.*, 2000]. Thus even the extremely low slopes of Amazonis Planitia appear to be covered mainly by volcanic deposits. However, several large fluvial channels feed into Amazonis Planitia (notably Marte Vallis and Mangala Vallis) and the volcanics there are likely to be interbedded with fluvial deposits [*Fuller and Head*, 2002a, 2002b].

[16] Much of the northern plains is highly textured at a scale of a few kilometers (pitted cones, polygons, thumbprint-like ridges, etc.). Most typically, the texture results from low hills a few kilometers across, but other textures occur as described below. These textures distinguish the northern ridged plains from those farther south and have been attributed to the presence of a thin (~100 m) deposit (the Vastitas Borealis Formation) on top of the Hesperian-aged ridged plains [*Head et al.*, 2002]. In addition, it was recognized early that high-latitude terrains commonly have a mantled appearance, which *Soderblom et al.* [1973] attributed to the presence of eolian debris mantles. MOLA and MOC data have confirmed the presence of a geologically young, latitude-dependent, probably ice- and dust-rich mantle layer that is superposed on the Vastitas Borealis Formation and other units [e.g., *Kreslavsky and Head*, 2000; *Mustard et al.*, 2001; *Malin and Edgett*, 2001; *Kreslavsky and Head*, 2002b]. On the basis of this improved understanding of the geology and stratigraphy of the northern lowlands, we now proceed to an assessment of the contacts interpreted by *Parker et al.* [1989, 1993] and *Clifford and Parker* [2001] to be shorelines.

3. Possible Shorelines

[17] *Parker et al.* [1989, 1993] originally attempted to outline former oceans in the northern plains by laterally tracing a variety of features. Some features (cliffs, benches, stepped massifs) were interpreted to be the result of wave erosion, some (spits, tombolos, curvilinear ridges) the result of wave transport. Other features were thought to be the result of the former presence of water (onlap relations, indications of upslope flow, abrupt termination of channels and valleys). Yet other features were simply linear boundaries separating different textured units. We do not examine in detail the different examples and the different criteria used by Parker and coworkers. Rather we examine the general geologic nature of the contacts, and what might be implied by their elevations. We use as a reference the shorelines portrayed by *Clifford and Parker* [2001], and which summarized previous work of Parker and his coworkers. These were transcribed onto the MOLA 1/64 degree global map, with the aid of MOLA versions of the MC charts. The MOLA versions were used rather than the photography-based MDIMs in order to map with near-uniform resolution and to avoid masking of topography by albedo features. Although there are ambiguities in places, the two most continuous contacts (the Arabia and Deuteronilus shorelines) mapped by Clifford and Parker can readily be identified in the MOLA data. Small gaps in the published contacts were filled by interpolation, using the MOLA data as a guide, but large gaps were left unfilled. Other shorelines (Ismenius, Acidalia, Aeolis, Elysium, Meridiani) that are portrayed by *Clifford and Parker* [2001] are very discontinuous and were left unexamined.

3.1. Arabia Shoreline

[18] The Arabia shoreline, the longest shoreline identified by *Clifford and Parker* [2001] closely approximates to Contact 1 of *Parker et al.* [1989, 1993]. On the basis of the reasoning that the largest ocean on Mars would have occurred during the Noachian, when the availability of liquid water was presumably the greatest, *Clifford and Parker* [2001] inferred that the age of Contact 1 must be "at least 4 Ga." The Arabia shoreline follows the plains-upland boundary and can be traced all around the planet except through Tharsis between 230°E and 270°E (Figure 3). The section between 210° and 220°E, the outer boundary of the Olympus Mons aureole, was included as part of contact 1 by *Parker et al.* [1989], but not as part of the Arabia Shoreline by *Clifford and Parker* [2001], who included it instead as part of the

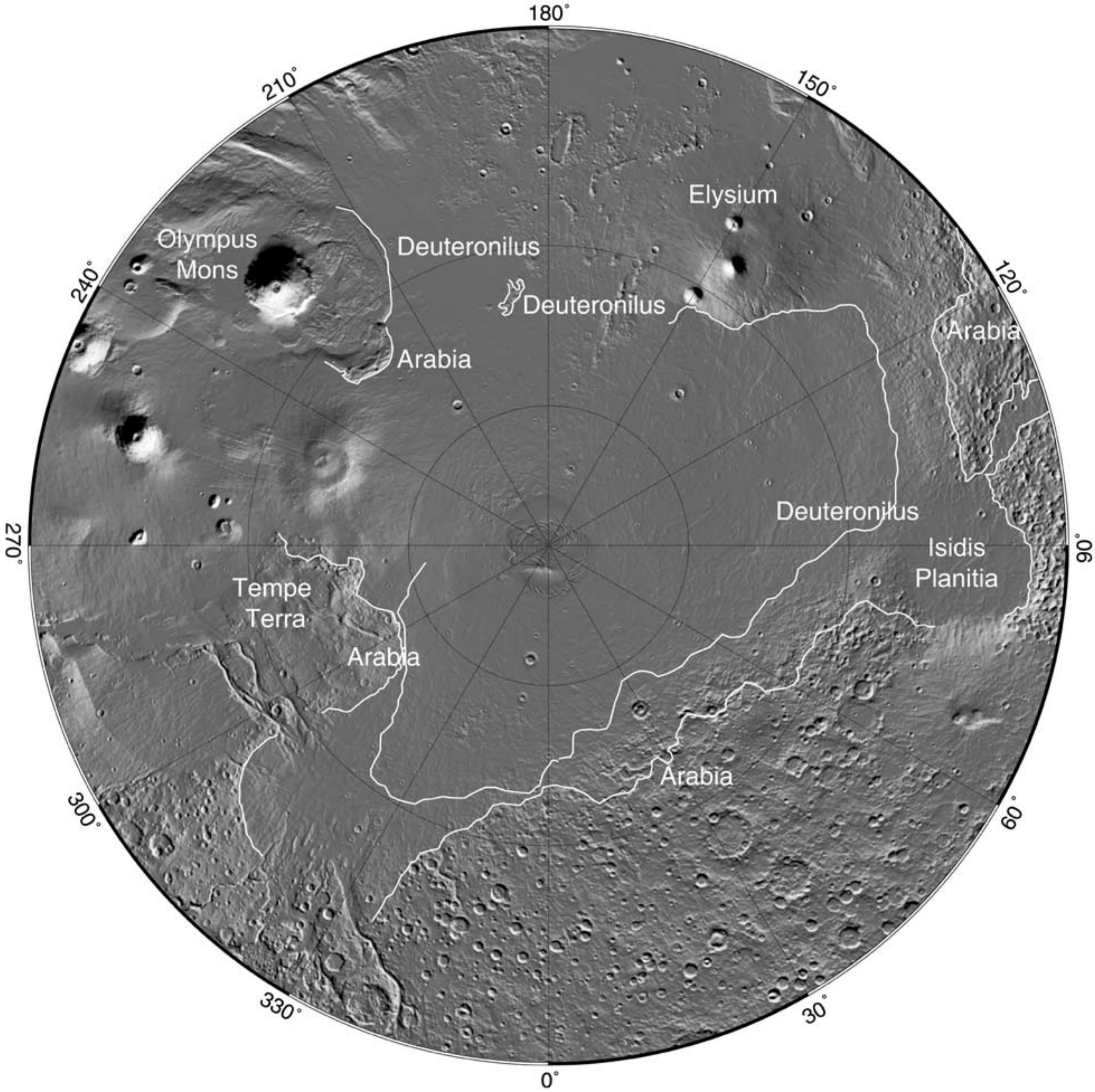

Figure 3. The Arabia and Deuteronilus "shorelines" of *Clifford and Parker* [2001]. The Arabia shoreline has been generalized (particularly in the area of the Deuteronilus Mensae (330°–0°E), where it follows an intricate path that outlines numerous islands) and interpolations have been made across small gaps. Sections of the Arabia shoreline in Arcadia Planitia and Acidalia Planitia that were mapped as dashed lines by *Clifford and Parker* [2001] are omitted here and included in Figure 12.

Deuteronilus shoreline (see below). Around Tempe Terra and along the west side of Chryse Planitia, the boundary is sharply demarcated except where crossed by Kasei Valles. In southern Chryse Planitia the boundary is also difficult to trace because of the large outflow channels entering the basin. The long section of the boundary from Eastern Chryse to Isidis between 330°E and 85°E is gradational. In this section, the continuous cratered upland to the south breaks up into isolated mesas and knobs to the north, and the elevation of the upland surface declines 3–4 km from the south edge of the transitional zone to the north edge of the zone, where the upland remnants disappear beneath the plains. Farther east the boundary is sharply defined along the southern margin of Isidis Planitia (Figure 4), but east of Isidis is another gradational section that extends to Memnonia, and along which parts are buried by the Medusae Fossae Formation. An isolated section occurs along the outer boundary of the Acheron arch, north of Olympus Mons.

[19] As pointed out by *Head et al.* [1998, 1999], the boundary deviates greatly from equal elevations (Figure 5). The elevations along the gradational parts of the boundary

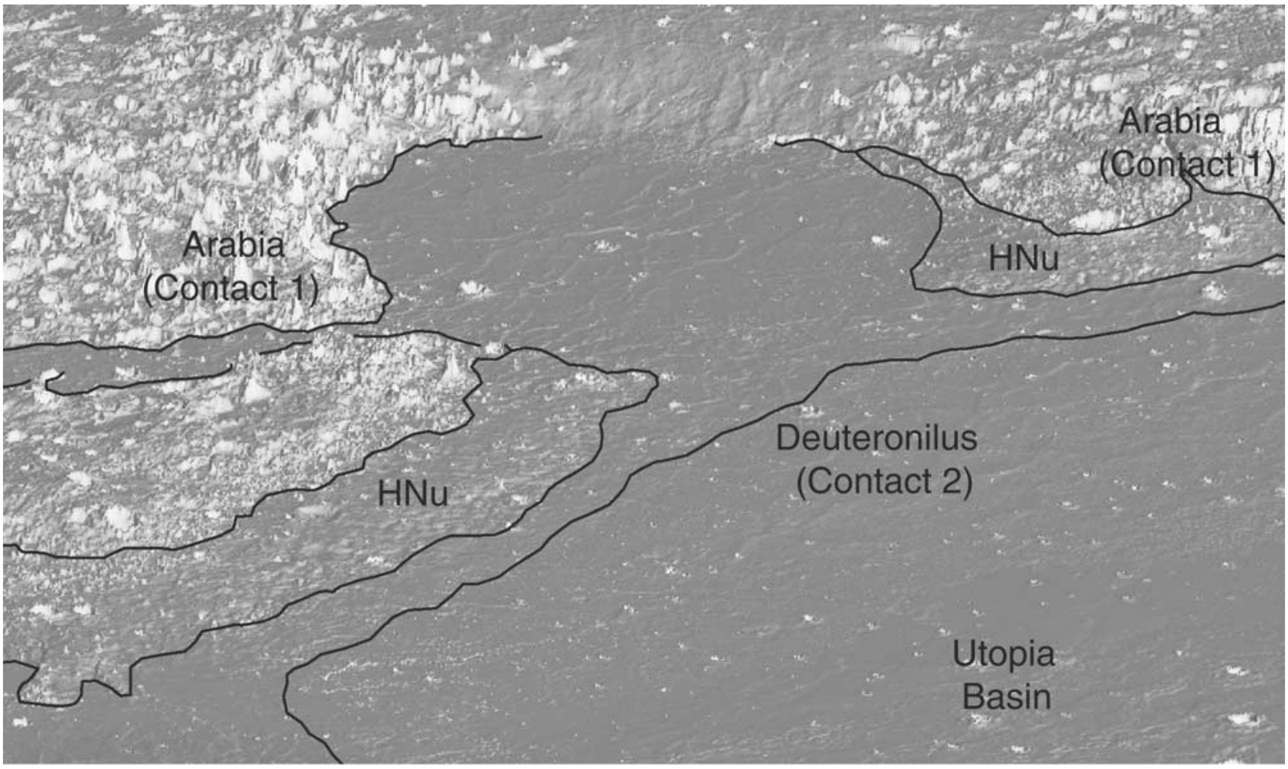

Figure 4. Perspective view looking WSW from Elysium Mons toward the Isidis basin. In the foreground, channels originating close to Elysium Mons extend down into the center of the Utopia basin. In the far-field, Hesperian volcanics from Syrtis Planitia spill into the Isidis basin, and largely underlie the Vastitas Borealis Formation fill in Isidis. Wrinkle ridges are the dominant topographic feature of the plains at this scale, and no significant terracing is discernible within the plains [see *Thomson and Head*, 2001]. HNu is an enigmatic unit between the plains and typical cratered uplands [*Greeley and Guest*, 1987]. For scale, the Isidis basin is 1000 km across. This view is similar to Figure 4b of *Head et al.* [1999].

between 330°E and 85°E and between 80°E and 160°E show a large scatter, reflecting the complex nature of the boundary, with its numerous cliffs, mesas, knobs and valleys. The boundary was generalized along this section so that much of the scatter in elevations is likely due to these local effects [*Parker et al.*, 2001], but the long wavelength deviations cannot be attributed to this cause. The mean elevation of the Deuteronilus-Nilosyrtis section, for example, rises from −4000 m at 340°E to −1000 m at 75°E. East of the Chryse basin the boundary is at roughly −3800 m, whereas to the southwest of the Chryse basin, where the boundary is very well demarcated, the short section from 11.6°N, 316.4°E to 24.9°N, 304.8°E ranges from −2720 m to −1850 m. In the Acheron section, the elevations rise steadily from −4000 m at 34°N, 217°E to 0 m at 38°N, 230°E. In all, the boundary is at an elevation of −2090 ± 1400 m.

[20] Most of the arguments by *Parker et al.* [1989] in favor of this boundary being a shoreline were based on relations in Deuteronilus. In this region, some process of disintegration has resulted in partial destruction of the old upland terrain, and this was followed by or accompanied by partial filling of the areas between the upland remnants, which are commonly surrounded by cliffs. Mass wasting on most slopes has resulted in formation of prominent debris flows, with sharply defined breaks in slope at their upper and lower margins [*Squyres*, 1978; *Lucchitta*, 1984], and in widening and partial filling of many of the upland valleys. The picture is further complicated by layered bedrock exposed in cliffs above the debris flows, deposits pasted on many north facing slopes, and remnants of layered deposits on the upland surface [*Carr*, 2001]. Thus breaks in slope resulting from mass wasting, bedrock layering, and other processes are common on all slopes, and with this backdrop we consider that identification of breaks in slope that result from marine processes [e.g., *Parker et al.*, 1989, Figure 8; *Parker et al.*, 1993, Figures 2 and 3] very challenging. Even a constant elevation of a break in slope does not necessarily imply that it was a shoreline. For example, Figure 6 shows a section of the Deuteronilus Mensae. Debris flows occur at the bases of all steep slopes. The debris flows are readily recognizable by sharply-defined, convex upward outer margins and striae oriented at right angles to the margins. In the area shown in Figure 6, the outer edges of the debris flows in the foreground closely follow the −3600 m contour, and the break in slope where the debris flow abuts against the upland escarpment closely follows the −3100 m contour. The uniform heights result because the plains are almost level and

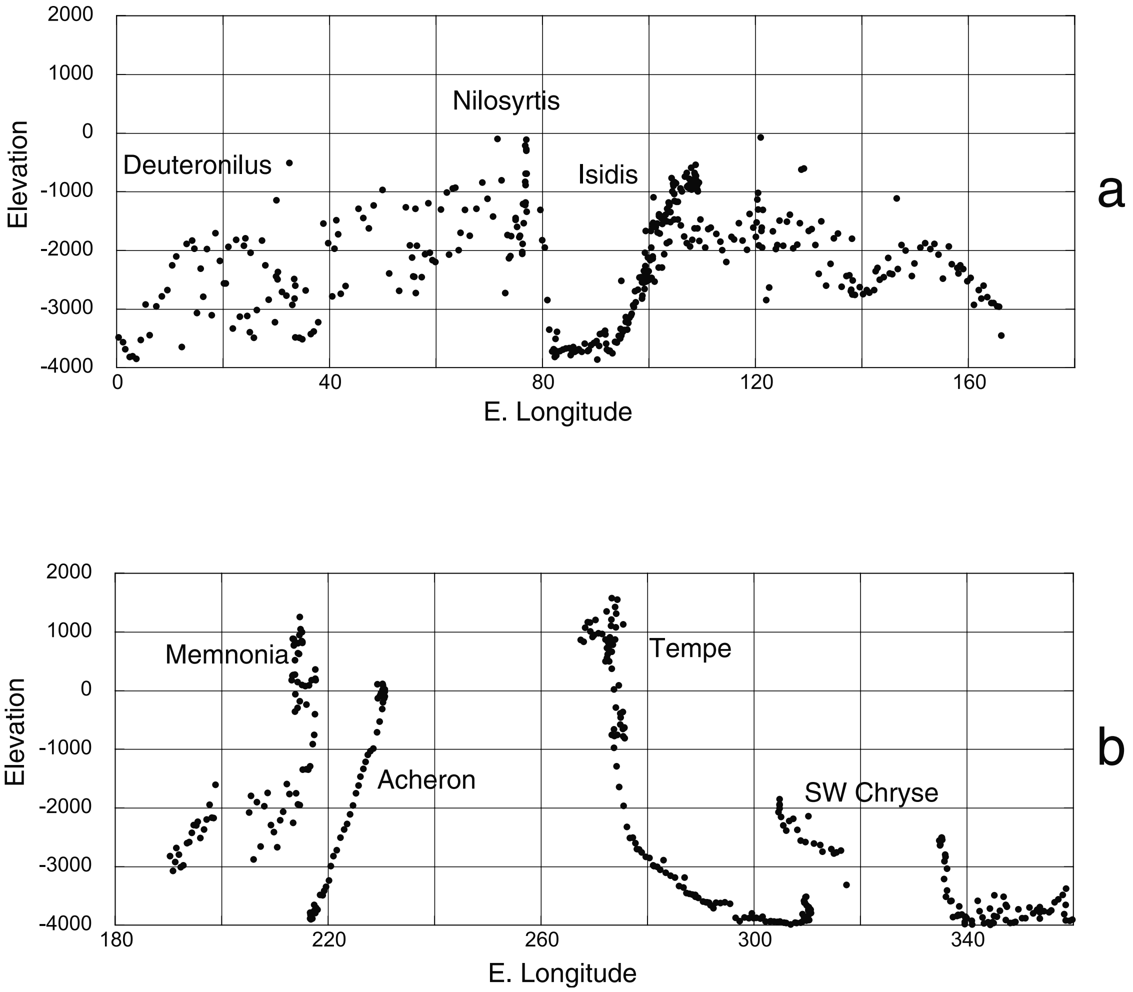

Figure 5. Elevations along the generalized Arabia "shoreline" as depicted in Figure 3. The shoreline has a range of elevation of several kilometers. Particularly large ranges in elevation occur around Tempe, along the Acheron arch, north of Olympus Mons, and around the Isidis basin.

the superposed debris flows are of nearly uniform thickness [see also *Carr*, 2001, Figure 10]. Thus mass wasting of a mesa margin on a nearly flat plain offers a plausible alternative interpretation to shorelines [*Carr*, 2001].

[21] Onlap relations were also invoked by Parker et al. to support their identification of Contact 1 as a shoreline. Clearly, there has been infilling between the upland remnants in the Deuteronilus-Protonilus region, and a younger fill abuts against the older upland where the boundary is sharp, as around Tempe Terra and southern Isidis. But there is little support for the conclusion that these relations are due to marine sedimentation. As discussed above, much of the northern plains consists of ridged plains [e.g., *Head et al.*, 2002] that resemble ridged plains elsewhere on the planet (e.g., Lunae Planum, Hesperia Planum, Solis Planum) and which are generally viewed as volcanic in origin.

[22] The simplest interpretation of what is observed along much of contact 1, and one that is consistent with relations elsewhere on the planet, is that the onlap of ridged plains onto the uplands and the filling between upland remnants along the plains-upland boundary (contact 1) is due largely to volcanism, although other processes, such as mass wasting, have certainly contributed, as discussed in the introduction. The relations along the Acheron arch are particularly compelling (Figure 7). Along almost the entire length of the Acheron boundary, mapped by *Clifford and Parker* [2001] as part of the Arabia shoreline (Figure 3), lava flows can be discerned lapping onto the older fractured upland surface (in particular, see the extensive flow adjacent to the edge of Acheron perturbing topographic contours in the upper part of Figure 7), and the boundary itself has a significant regional slope (Figure 5). Thus the primary cause of the present contact around Acheron is volcanism and neither the elevations nor the surface morphology provide any support for the view that it was formerly a shoreline.

[23] In summary, the large range in elevations along contact 1 strongly suggest that it was not a shoreline, and the geologic relations along the boundary provide little evidence to counter that view. Instead, volcanic and mass-wasting processes appear to dominate in the formation of the boundary.

3.2. Deuteronilus Shoreline

[24] The Deuteronilus shoreline of *Clifford and Parker* [2001] (Figure 3) corresponds roughly to Contact 2 of

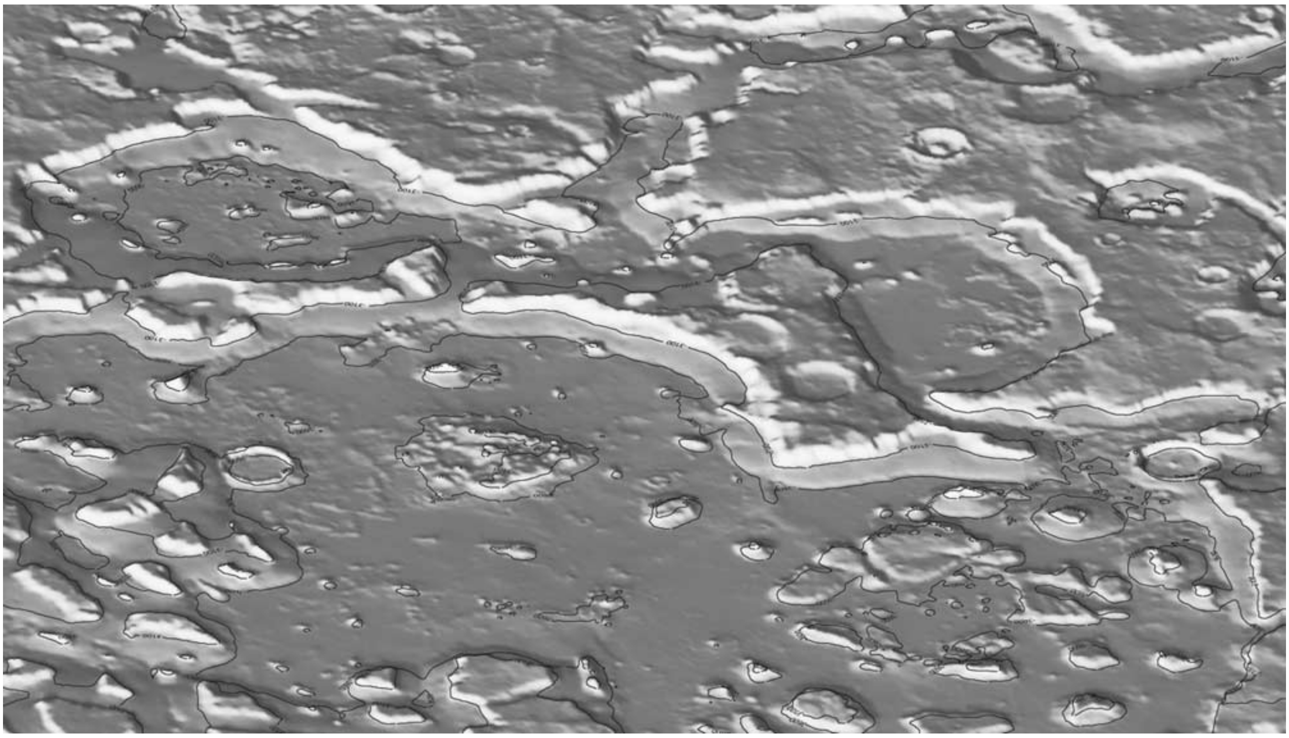

Figure 6. Perspective view looking south across the fretted terrain in Deuteronilus. The area shown extends from 37° to 45° N and 15° to 25°E (Figure 3). The −3100 m and −3600 m contours are superimposed on the terrain. Debris flows (bright regions at the base of scarps) occur at the bases of all steep slopes in the region. The contours show that the breaks in slope between the debris flows and the plains are at an almost constant elevation because of the low slopes of the plains. Similarly, the elevation of the break in slope between the upper surface of the debris flows and the escarpments against which they abut are at almost constant elevations because of the uniform thickness of the debris flows. These relations suggest that constant elevations of breaks in slope are not reliable criteria for identification of shorelines in these types of terrains.

Parker et al. [1989, 1993]. The age of contact 2 must lie between that of contact 1 ("at least ~4 Ga" [*Clifford and Parker*, 2001, p. 44]) and "the age of the youngest [shoreline which] may be as much as ~2–3Ga" [*Clifford and Parker*, 2001, p. 44]. The age of the surface unit within contact 2 (VBF: Hv) is Upper Hesperian. The Deuteronilus contact is more subtle than contact 1, and it varies considerably in appearance along its length (Figure 3). From 0°–130° E it roughly follows the outer boundary of the transition zone between the uplands to the south and the plains to the north. To the south of the contact, upland remnants are common and the plains between the remnants are generally smooth. North of the contact, upland remnants are few and the plains are commonly textured, a result of the presence of low hills, ridges and cracks.

[25] *Hiesinger et al.* [2000] investigated the elevation of contact 2 over about 800 km of lateral extent in Deuteronilus Mensae between 0° and 30° E, an area where *Parker et al.* [1989, 1993] presented contact 2 locations tied to specific Viking images. Using two different approaches to defining the elevation of the contact, they found that most of contact 2 varied within ~110 m vertical elevation over a distance of ~800 km, with a mean elevation of −3877 m and a one-sigma standard deviation of 56 m. As a test to assess whether the low average elevation and general smoothness of the terrain were contributing to the low vertical variation of the contact, *Hiesinger et al.* [2000] chose two arbitrary lines and found that their variation exceeded that of contact 2. They found further that contact 2 was associated with a break in slope, and that there were at least two parallel ridges associated with the contact in this particular region.

[26] Along other parts of the Deuteronilus contact, and paralleling it, particularly between 60°E and 90°E, are some low ridges and escarpments. This part of the contact corresponds closely to the southern boundaries of the Vastitas Borealis Formation (Hv), as mapped by *Greeley and Guest* [1987]. Between 90°E and 128°E (Figure 3) the contact is sharply defined and follows the southern boundary of the Amazonian knobby plains (Apk) [*Greeley and Guest*, 1987]. Smooth plains are to the south and textured knobby plains to the north (Figure 8). At 128°E the contact turns north, follows an outward facing escarpment, then extends north along the western edge of the main Elysium volcanic center, where there is a marked break in slope. East of this break, the surface slopes 1–2 deg. up toward central Elysium; to the west the surface slopes 0.02–0.03 deg. down into the Utopia basin. In places along the contact, smooth or knobby plains abut

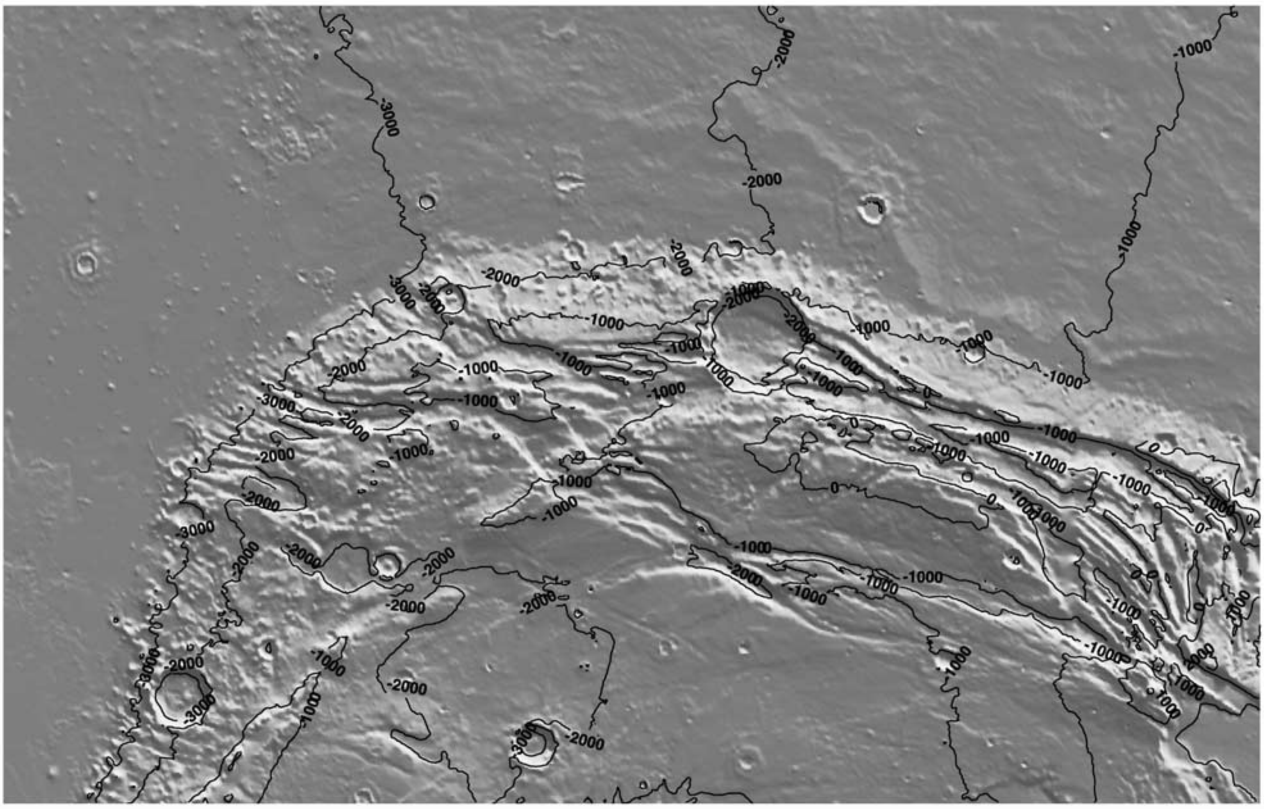

Figure 7. The outer edge of the Acheron arch mapped as part of the Arabia shoreline by *Clifford and Parker* [2001]. Flows from Alba Patera in the upper right of the image lap onto the cratered and faulted Noachian surface. In particular, note the ridged flow unit that begins at the right of the image (toward Alba Patera) and continues across the top of the image, creating downslope perturbations in the −1000 and −2000 contour lines. The boundary between the two units has an elevation range of over 2 km within the section seen here and over 4 km for the entire boundary (see Figure 5). The crater in the center of the image is 50 km across.

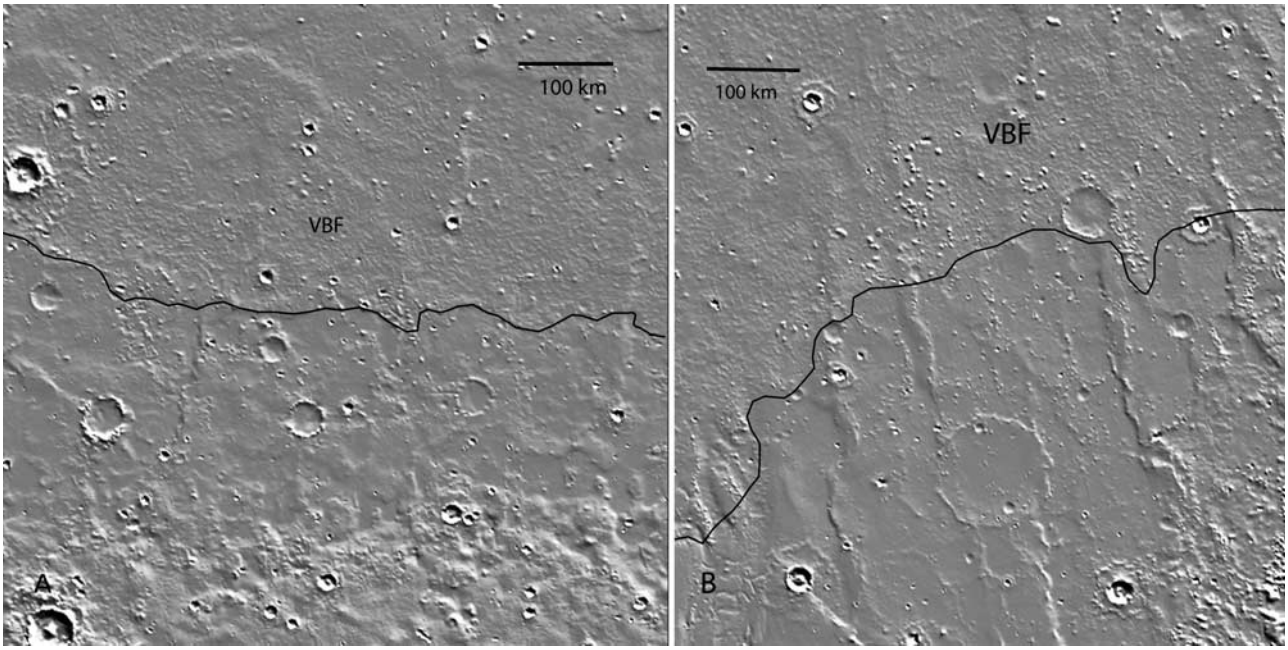

Figure 8. The Deuteronilus “shoreline” at 21°N, 104°E (A, left) and 33°N, 334°E (B, right). In both places, on opposite sides of the planet, the shoreline follows the edge of the Vastitas Borealis Formation (VBF) toward the north at top (basinward), easily recognizable by its stippled texture.

against the Elysium flows, but most of this section is crossed by lava flows and valleys, and the only indication of a contact is the break in slope. Although no continuous contact can be drawn to the east of Elysium (Figure 3) where there is an extensive area characterized by clusters of hills separated by knobby plains, *Clifford and Parker* [2001] show the shoreline around one prominent cluster at 38°N, 188°E.

[27] East of Elysium the next continuous section of the Deuteronilus shoreline is around the outer edge of the Olympus Mons aureole (Figure 3). Along almost the entire perimeter of the aureole deposits, in the MOLA reconstructions, lava flows can be seen emerging from under the aureole (Figure 9). Even where the adjacent Amazonis plains appear smooth in MOLA data, flows can commonly be seen in MOC frames [e.g., *Fuller and Head*, 2002a, 2002b]. The aureole deposits transect the flows; they appear to have either flowed over or been thrust over the flows. There is little or no indication of onlap in the opposite direction as might be expected from a shoreline. Elevations along the base of the escarpment range from −3100 m at 15°N to −3900 m at 33°N (Figure 10). The absence of marine features along the escarpment and the presence of volcanic features and reverse onlap relations does not imply that the contact was never a shoreline, it simply indicates that the primary cause of the break in slope was not wave action. Clearly if the northern plains had been filled with water, this level would have been a shoreline, but the absence of any positive indication that it was indeed a shoreline does not provide support for the interpretation of *Parker et al.* [1989, 1993] and *Clifford and Parker* [2001].

[28] The last section of the Deuteronilus shoreline, as mapped by *Clifford and Parker* [2001] (Figure 3), extends from 60°N, 285°E, to the south-south-east, wraps around the northern margin of Tempe Terra then southeast into Chryse Planitia. Around the periphery of Alba Patera are two well-defined contacts. An inner contact separates the dominantly radial Alba flows from smooth plains with circumferential ridges. The outer contact separates the smooth ridged plains from the typical knobby textured plains of Vastitas Borealis Formation. *Clifford and Parker* [2001] map the outer boundary as the Deuteronilus shoreline and the inner boundary as the Ismenius shoreline. In Chryse Planitia, the Deuteronilus shoreline follows the southern boundary of the Vastitas Borealis Formation as mapped by *Tanaka and Scott* [1987], with smooth ridged plains to the south and west, and the typical textured knobby plains of Vastitas Borealis to the northeast. Within Chryse Planitia the elevation of the contact is very consistent around much of the basin [*Ivanov and Head*, 2001]. *Tanaka et al.* [2001] note that the boundary here in western Chryse Planitia is comprised of convex outward lobes and is unlikely to be a shoreline. They suggest that the boundary is the result of debris flows shed from the adjacent upland.

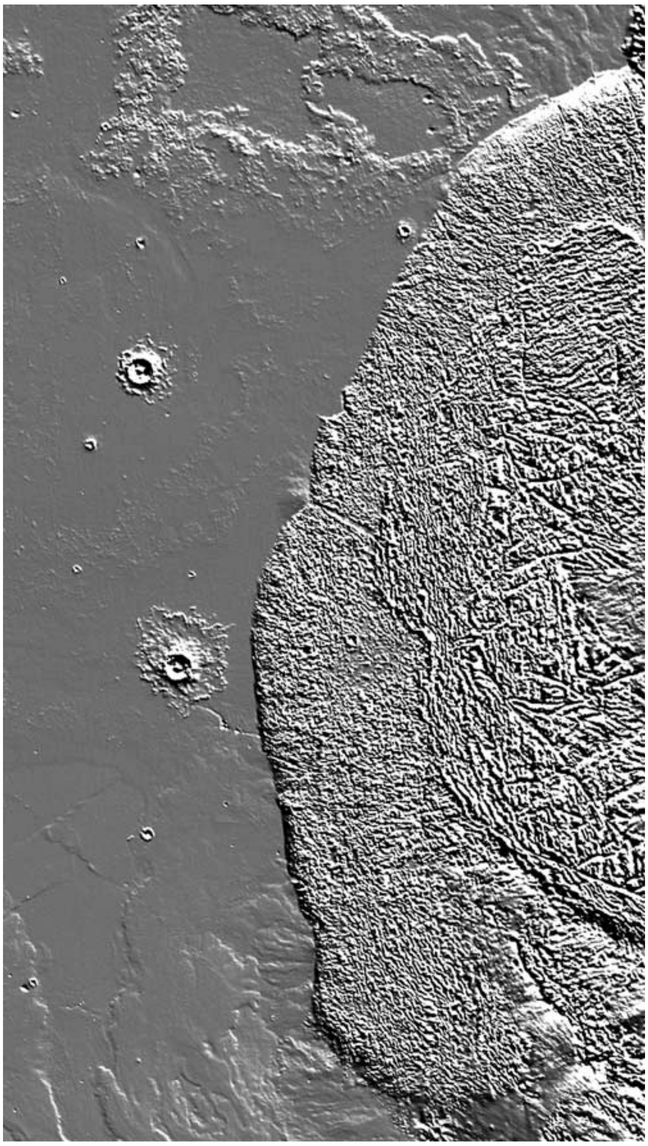

Figure 9. MOLA rendition of the contact between the Olympus Mons aureole deposits to the right and Amazonis Planitia to the left. This contact was mapped as part of the Deuteronilus shoreline by *Clifford and Parker* [2001]. However, numerous lava flows emerging from under the aureole deposits (bottom, top) suggest that the aureole deposits flowed over or were thrust over the adjacent plains [e.g., *Fuller and Head*, 2002a, 2002b] and that this is not a primary contact or shoreline between an Hesperian-aged ocean to the left and the Olympus Mons aureole deposits to the right. The fresh-appearing crater in lower center is 30 km across. The faint north-south striation is an artifact caused by the hard stretch on the MOLA elevation data.

[29] Thus, for roughly half its length (Figure 3), from 270°E eastward across Chryse Planitia, to the north of Arabia and then across southern Elysium Planitia to 130°E, Contact 2 or the Deuteronilus shoreline marks the southern extent of the Vastitas Borealis Formation. For much of the rest of its length the proposed shoreline can be traced only intermittently around clusters of hills as in western Amazonis or across lava flows as in Elysium and along the outer escarpment of the Olympus Mons aureole. Direct evidence suggesting that the contact is an actual shoreline (inward-facing cliffs, onlap relations, termination of channels, etc.) is sparse. The main arguments in

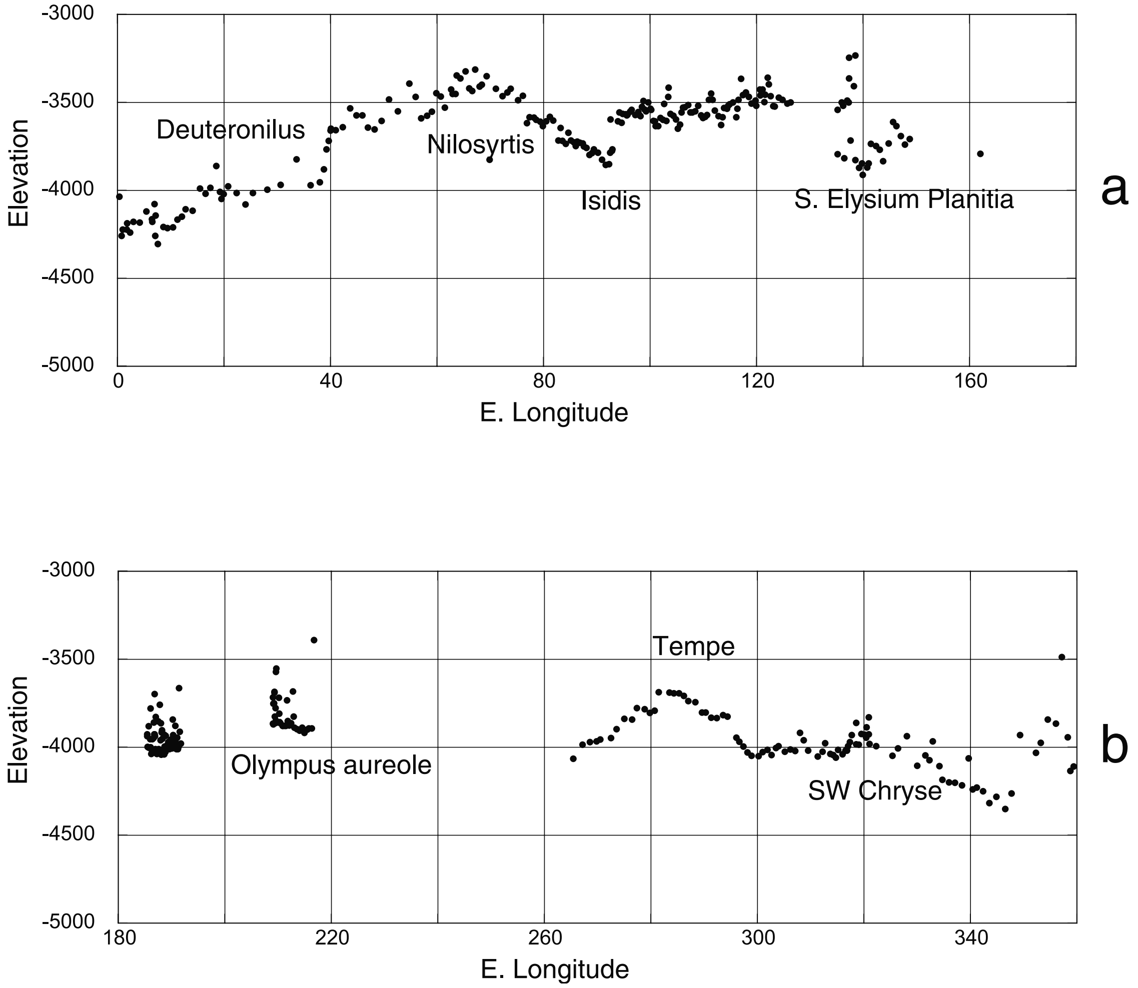

Figure 10. Elevations along the Deuteronilus shoreline as generalized in Figure 3. The boundary has a much smaller range of elevations than the Arabia shoreline (Figure 5).

support of its being a shoreline are the characteristics of the terrain enclosed by the contact (discussed in detail below) and the range in elevations along the contact. The range in elevations is much smaller than along contact 1 [*Head et al.*, 1999]. As mapped here, the mean elevation of contact 2 is −3792 ± 236 m. While the standard deviation is small, individual sections have significant ranges in elevation (Figure 10). North of Arabia, between 0° and 70°E the elevation ranges from −4100 to −3300 m, around Elysium from 20°N to 33°N elevations range from −3900 to −3100 m, and from north of Tempe into central Chryse the elevation drops from −3700 to −4300 m. The narrow range in elevations may be due in part to the low relief of the northern plains in general. For example, the average elevation of all the terrain between 60°N and 80°N (half degree increments), for example is −4492 ± 418 m.

3.3. Southern Boundary of the Vastitas Borealis Formation

[30] As noted above, the Deuteronilus shoreline (contact 2) (Figure 3) follows the southern boundary of the Vastitas Borealis Formation for much of its length (Figure 11). The main deviations are between 130°E and 270°E, through Elysium and Tharsis. Contact 2 wraps around the northwest section of the Elysium volcanic deposits and around the eastern boundary of the Olympus Mons aureole. In contrast, the southern boundary of the Vastitas Borealis Formation wraps around the channel and volcanic deposits northeast of Elysium, then continues north of Elysium and Tharsis to rejoin contact 2 north of Tempe Terra (Figure 11). This boundary, as mapped by *Tanaka and Scott* [1987], *Greeley and Guest* [1987], and *Scott and Tanaka* [1986] on the basis of surface textures seen in the Viking images is almost identical to that mapped by *Head et al.* [2002] on the basis of subdued (stealth) craters seen in the MOLA data. Elevations along the boundary are shown in Figure 12. The elevations are mostly within the −3400 to −4100 m range except where the boundary crosses the Utopia basin. Here the Vastitas Borealis Formation is overlain by the Amazonian lava flows and channel deposits of the Elysium Formation [*Greeley and Guest*, 1987; *Tanaka et al.*, 1992] and its original outer boundary would have been elsewhere before being buried by these younger deposits. The elevation of the entire boundary is −3903 ± 393 m. If the outer contact with the

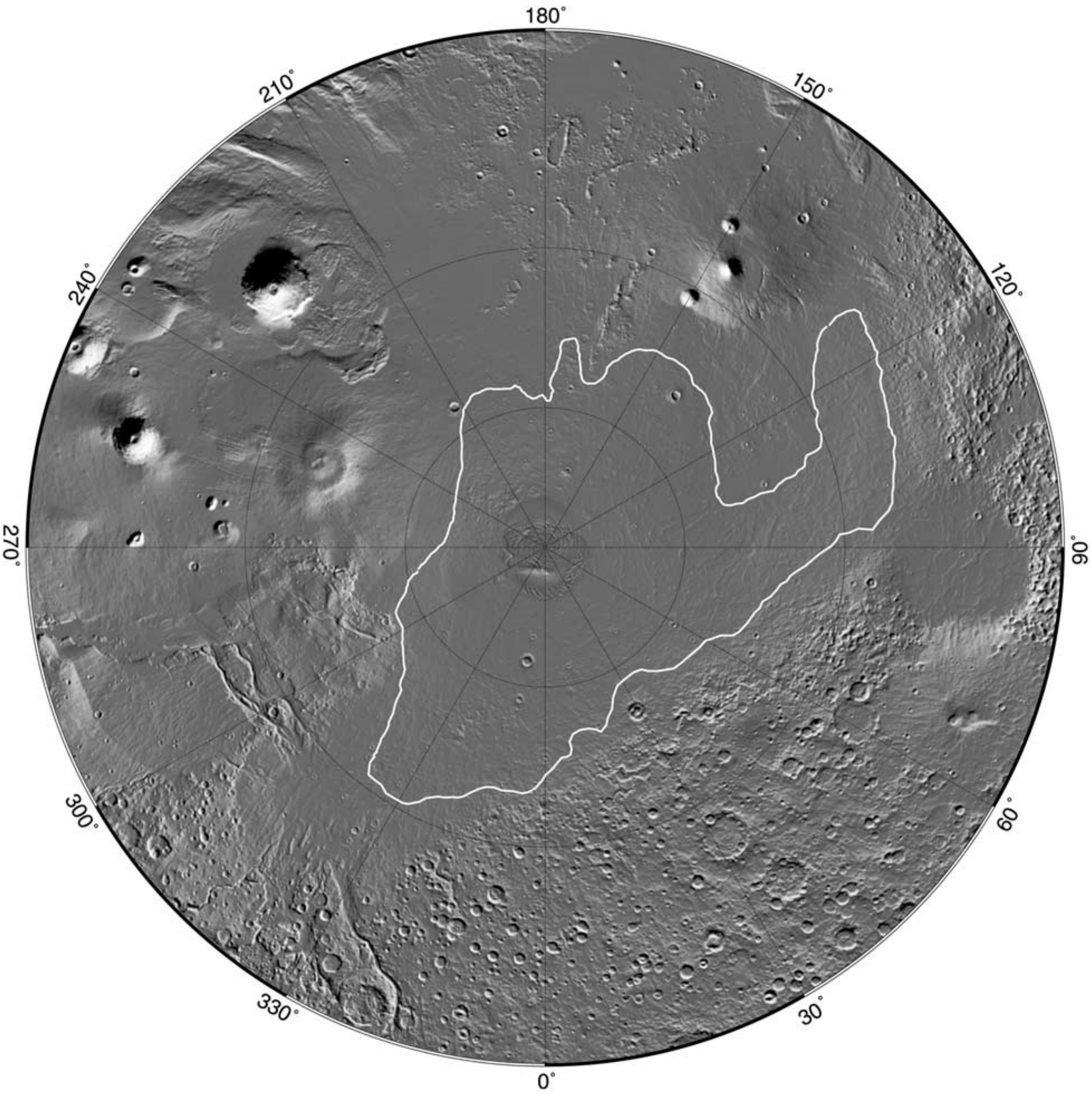

Figure 11. The outer boundary of the Vastitas Borealis Formation as recognized from its characteristic texture [*Scott and Tanaka*, 1986; *Tanaka and Scott*, 1987; *Greeley and Guest*, 1987] and the presence of stealth craters [*Kreslavsky and Head*, 2002a]. Over the long section from Tempe (270°E) eastward to southern Elysium (120°E) the Deuteronilus "shoreline" is coincident with this boundary, but for the rest of the boundary there are significant differences.

younger Elysium volcanic and channel deposits is ignored, the elevation is -3658 ± 282 m.

3.4. Other Contacts

[31] Elevations along other prominent contacts within the northern plains were determined here for completeness and to compare with the contacts just discussed (Figure 13). These contacts have not necessarily been designated as shorelines by Parker and coworkers, although parts of some have. The outer limit of the flows radial to Alba is a clearly identifiable boundary, and *Clifford and Parker* [2001] included the eastern part of this contact in the Ismenius shoreline between the Arabia and Deuteronilus shorelines. Elevations along the contact are given in Figure 14.

[32] West of Amazonis Planitia are the Cerberus and Tartarus Montes, clusters of closely spaced low hills separated by ridged plains. The hills appear to be remnants of old, possibly Noachian, terrain that has been flooded by Hesperian plains [*Tanaka and Scott*, 1987; *Greeley and Guest*, 1987; *Plescia*, 1993]. Cliffs surrounding some individual massifs of the Cerberus Montes were

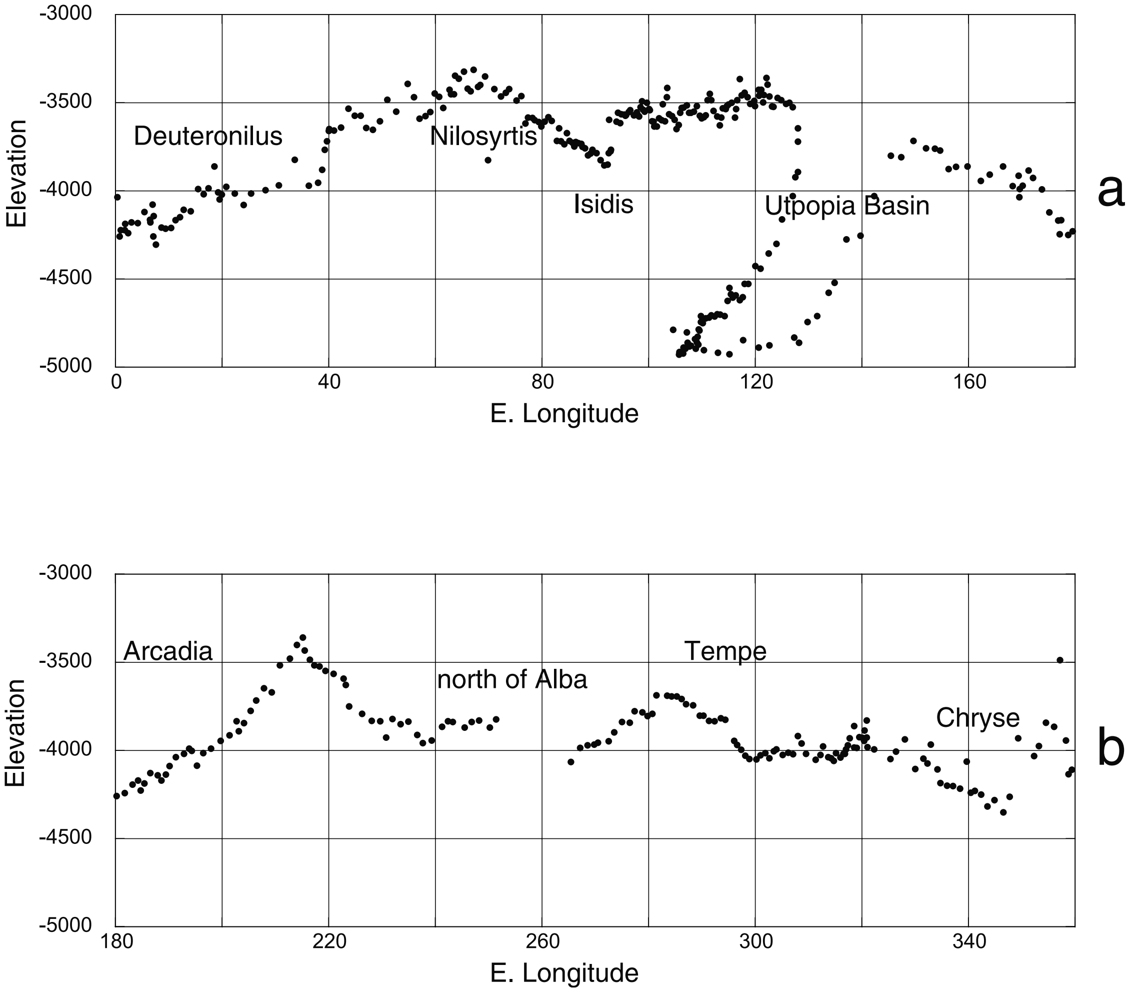

Figure 12. Elevations along the outer edge of the Vastitas Borealis Formation. The elevations range mostly between −3300 m and −4300 m except in the Utopia basin where the formation is overlain by younger units [*Greeley and Guest*, 1987; *Tanaka et al.*, 1992]. Before burial by the younger unit the boundary presumably followed the general trend between 120°E and 16°E.

cited by *Parker et al.* [1993] as examples of marine erosion, and *Clifford and Parker* [2001] tentatively included the outlines of many clusters in the region as part of the Arabia shoreline. Just west of Amazonis Planitia the plains have a very gentle slope to the north. Farther west, toward Elysium, the slopes become steeper and down to the east. Elevations of the plains-knobby terrain boundaries (−3152 ± 415 m) have a large spread in values reflecting the regional slopes of the plains, and undermining their interpretation as shorelines (Figure 14). The margin of a prominent island at 38°N, 188°E, which was included by *Parker et al.* [1989] as part of contact 1, has an elevation of −3952, well below typical elevations along contact 1 but comparable to those along contact 2. In central Amazonis the surface looks extremely smooth in the Viking and MOLA data, but MOC frames show that platey volcanic flows are common [*Keszthelyi et al.*, 2000; *Malin and Edgett*, 2001; *Fuller and Head*, 2002a, 2002b]. Thus, while the relations between the plains and the upland remnants suggest the uplands have been flooded by the plains, the elevations and the detailed surface morphology suggests that volcanism was the dominant process.

[33] In several areas of the northern plains the surface is broken into a coarse pattern of polygonal fractures, the individual polygons being of the order of 10 km across [*Lucchitta et al.*, 1986; *McGill*, 1986]. Patterned ground with polygons tens of meters across also is found extensively in polar regions [*Malin and Edgett*, 2001]. *Lucchitta et al.* [1986] pointed out that the coarse polygonal ground is found preferentially at the ends of large channels, and suggested that the polygons may have formed as a result of desiccation and compaction of sediments deposited in bodies of water that formed at the ends of the channels. If so, then the outline of the area of sedimentation might conform to an equipotential surface. Figure 14 shows elevations along the outer boundary of the large area of coarse polygonal ground centered at 35°N, 100°E. The elevation of the entire boundary is −4532 ± 307 m. The northern part of the boundary extends deep into the Utopia basin, has a large range in elevation, and is unlikely to be a shoreline. One of the

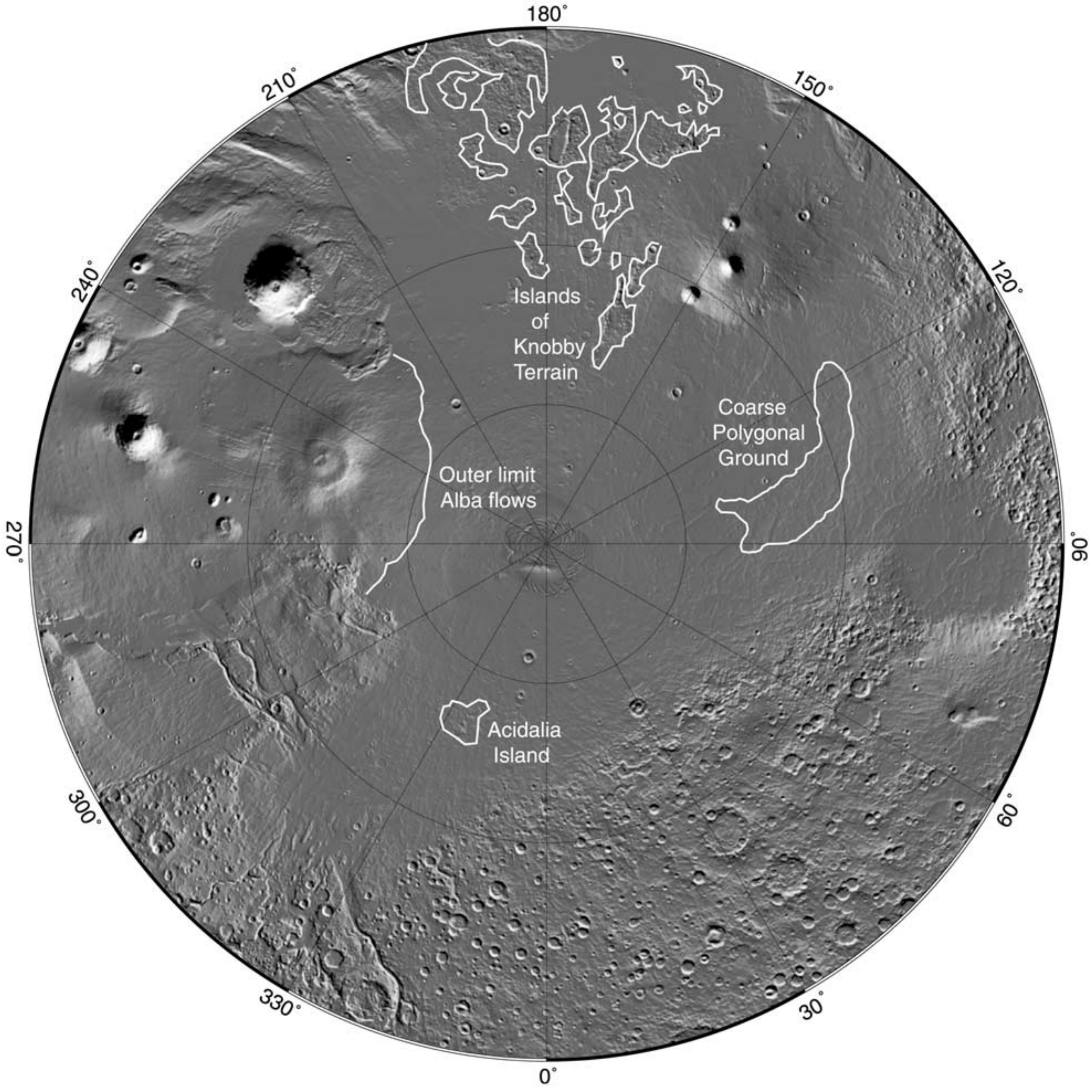

Figure 13. Miscellaneous contacts along which elevations were determined and displayed in Figure 14. The outlines of the islands of knobby terrain were tentatively identified as a part of the Arabia "shoreline" by *Clifford and Parker* [2001] but they have a wide range in elevation reflecting the south to north slope of the intervening plains. The outer boundary of the Acidalia Island at 47°N, 335°E was tentatively identified by *Clifford and Parker* [2001] as part of the Deuteronilus "shoreline," but is at a significantly lower elevation than the rest of the contact (Figure 10). The outer limit of the Alba flows were equated with shorelines lying between the Arabia and Deuteronilus shorelines. The polygonal ground has not been correlated with any shoreline but is included here because it is a clearly identifiable boundary.

main reasons for this is that, as with the boundary of the Vastitas Borealis Formation, the relations in this area are complicated by the presence of the younger flows and channel deposits [*Tanaka et al.*, 1992], and the original extent of the older units is partly masked by the younger deposits. The southern boundary between 87°E and 115°E, however, has such a narrow range of elevation (−4247 ± 39 m) that it could plausibly be interpreted as a shoreline (see further discussion by *Thomson and Head* [2001]).

[34] Centered at 47°N, 335°E in northern Acidalia is an island (Acidalia Mensa) mapped by *Scott and Tanaka* [1986]

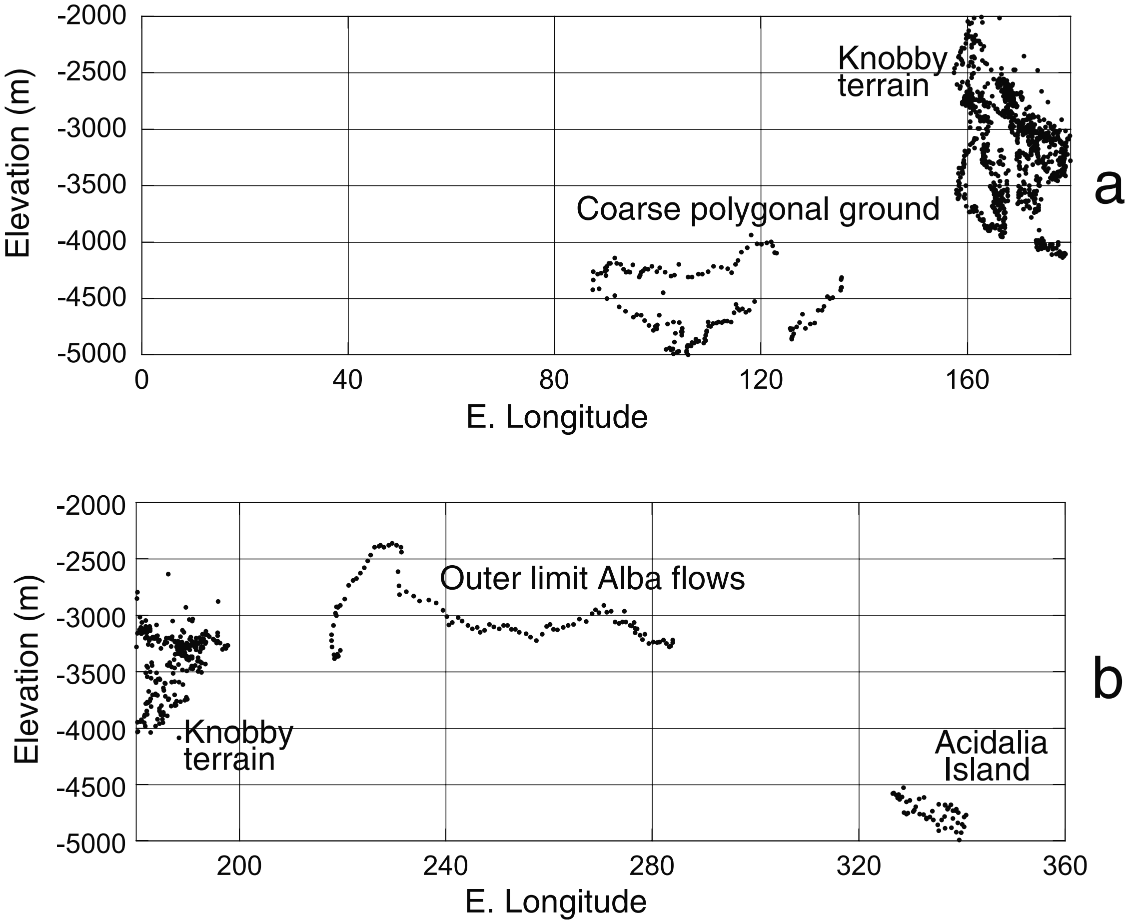

Figure 14. Elevations along the contacts shown in Figure 13.

as Noachian terrain surrounded by Hesperian plains. The boundary is at a low elevation (−4741 ± 104 m), and is clearly an area of non-deposition of the Hesperian ridged plains that fill much of the rest of the northern plains. *Parker et al.* [1989] included parts of the island's boundary in their Contact 1 and part in Contact 2. The low elevation of the boundary suggests, however, that if it is a shoreline it is one at a lower elevation than the two originally mapped.

[35] Of course these contacts, interpreted shorelines, average elevations and their variations must also be viewed in the context of potential events that have happened subsequent to the emplacement of hypothesized oceans. Clearly, responses to loading and unloading, as well as broad epeirogenic warping, could cause postemplacement topographic modifications [e.g., *Head et al.*, 1999; *McGill*, 2001; *Tanaka et al.*, 2001]. Furthermore, on a broader, more global scale, shoreline position should be compared to gravity potential (approximate an equipotential line), an analysis that is currently underway.

[36] We conclude from this section, however, that direct evidence of post-Noachian shorelines around the northern plains is equivocal. Neither the elevations nor the morphology of the surface provide strong support for most of the proposed shorelines. We have shown that events and processes (e.g., impacts, mass wasting, volcanism, tectonism, etc.) occurring subsequent to the period of formation of the outflow channels have modified the surface along much of the margin of the northern lowlands so as to obscure key relationships and to cast doubt on the interpretation of contacts mapped by *Parker et al.* [1989, 1993] and *Clifford and Parker* [2001] as shorelines.

[37] Furthermore, even if subsequent events had not covered candidate margins of standing bodies of water, as we describe above, the age of the contacts and features interpreted to be shorelines ("at least ~4 Ga" for contact 1 [*Clifford and Parker*, 2001, p. 44] and "as much as ~2–3Ga" for the "youngest shorelines" [*Clifford and Parker*, 2001, p. 44]; see also *Hartmann and Neukum* [2001]) is so great that even if they are exposed, they are likely to be very heavily degraded. For example, *Malin and Edgett* [1999, p. 3051] conclude that "even on Earth it is usually difficult to identify paleocoastlines from satellite or aerial photographs alone" and that "field study and topographic surveys were needed to corroborate the interpretations from aerial photographs of the presence of coastal landforms." They point out that vegetation patterns often provided the most compelling evidence of the position of paleoshorelines in terrestrial studies and that "without vegetation and with present access to field sites on Mars, the possibility that the planet once had oceans and coastal landforms cannot be dismissed." However, their analysis of several MOC images of the areas interpreted by *Parker et al.* [1989, 1993] to be shorelines did not find supporting evidence for the presence of shorelines, and *Malin*

and Edgett [1999] thus conclude that the interpretation failed a critical test.

[38] In summary, while we find that direct evidence of post-Noachian shorelines around the northern plains is equivocal, this does not rule out the past presence of shorelines. Clearly, if the outflow channels were cut by water, then bodies of water with margins resulted from their formation, and sedimentary deposition and perhaps erosional modification could have formed and left contacts and marginal structures representing their shorelines. But, as discussed below, modeling suggests that any such bodies of water would likely be short-lived [*Carr*, 1983; *Baker*, 2001; *Kreslavsky and Head*, 2002a]. They would likely freeze before they could produce any significant erosion, and thus wave cut cliffs and benches, and features such as spits that form by open water wave transport [e.g., see *Adams et al.*, 1999, Figure 5], should not necessarily be expected in any abundance. Evidence for the former existence of bodies of water may be more likely to be found within the areas covered by the water rather than at their outer margins. We now turn to an assessment of the characteristics of the regions of the northern lowlands that are predicted to have been flooded by outflow channel effluent.

4. Evidence for Flooding From Within the Northern Plains

[39] While the direct evidence for shorelines may not be compelling, other evidence supports the suggestion that large areas of the northern plains were formerly covered by water. As noted in section 1, several workers [e.g., *Lucchitta et al.*, 1986; *Parker et al.*, 1989, 1993] have interpreted some features of the northern plains, in addition to the shorelines, as resulting from the former presence of large bodies of water. Included are polygonal ground, curvilinear ridges, highly degraded impact craters and degraded wrinkle ridges. In this section, we examine the interior of the northern plains in light of data acquired since the early work was done, and find considerable support for the earlier interpretations.

[40] We saw above that much of the northern plains is covered by Hesperian-aged ridged plains, that are probably volcanic [*Head et al.*, 2002]. Comparison of the ridged plains within the northern basin with those farther south suggests that the northern ridged plains have been significantly modified subsequent to their formation. The plains of the northern basin are smoother than the ridged plains in areas such as Lunae Planum and Hesperia Planum [*Kreslavsky and Head*, 2000]. *Head et al.* [2002] showed, for example, that the ridges in the northern plains are, on average, only 0.7 times the height of those of Lunae Planum and Solis Planum and are spaced 1.7 times farther apart. Ridged plains within contact 2 of *Parker et al.* [1989, 1993] are also smoother than those between their contact 1 and contact 2 [*Head et al.*, 1998]. By examining different profiles in Hesperia Planum, *Head et al.* [2002] found that slopes at a baselength of 80 km best represent the intrinsic roughness of the ridged plains. They then showed that if 100 m of material were deposited on typical Hesperia Planum plains then roughnesses at 3–80 km baselines would match those of the northern ridged plains. Deposition of this layer would also increase the spacing and decrease the height of the wrinkle ridges to roughly match those measured for the northern plains. The increase in spacing is due to the complete burial of the smaller ridges.

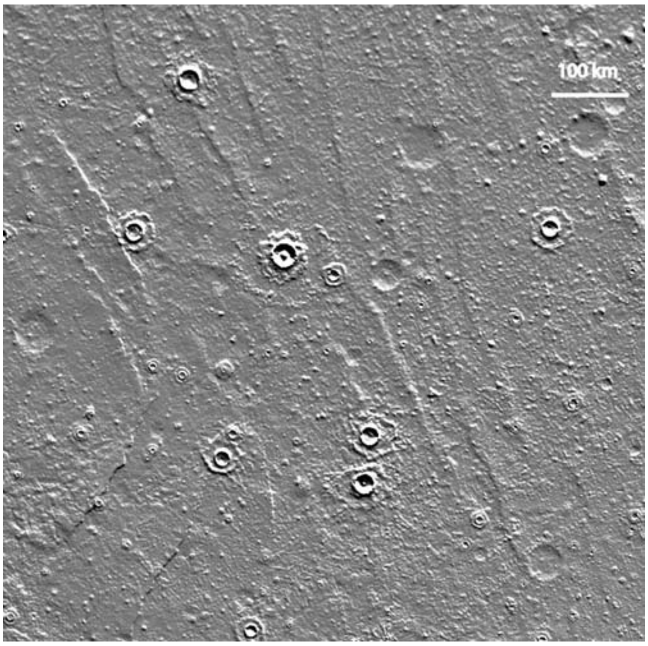

Figure 15. MOLA-based image of typical Vastitas Borealis Formation (VBF) at 60°N, 140°E. At this scale the VBF typically has a stippled appearance, caused by numerous closely spaced knobs. In places the knobs merge to form ridges, thereby imposing on the surface a faint linear pattern. Two populations of craters can be discerned. A fresh-appearing population, each with ejecta superimposed on the present surface, and a subdued (stealth) population with no discernable ejecta blankets [*Kreslavsky and Head*, 2002a]. Volcanic ridged plains are interpreted to lie at a shallow depth below the VBF, which is at the surface [*Head et al.*, 2002; *Kreslavsky and Head*, 2002a]. The stealth craters formed in the ridged plains and were subsequently buried by the VBF, which was in turn cratered by the fresh appearing population.

[41] The interpretation that the wider spacing of the ridges, their lower elevation and the relative smoothness of the surface at intermediate (3–80 km) scale as compared with ridged plains farther south is due to burial of the volcanic ridged plains by a younger unit is supported by the presence of numerous shallow, almost rimless craters termed “stealth” craters by *Head et al.* [2002] (Figure 15). They occur throughout much of the area mapped as Vastitas Borealis Formation by *Scott and Tanaka* [1986], *Tanaka and Scott* [1987], and *Greeley and Guest* [1987]. Stealth craters in the 20–80 km diameter range have depths mostly in the 0–200 m range as compared with 200 m to 1.2 km for normal craters. Stealth and normal craters are present in roughly equal numbers. While *Head et al.* [2002] give several possibilities for the formation of the subdued craters, their preferred interpretation is that the subdual of the craters, like the subdual of the ridges, is due to deposition of a later unit over the ridged plains. The total number of craters (stealth and normal) on the ridged plains indicates a lower

Hesperian age for the volcanic surface. The numbers of normal craters, those superimposed on the unit that overlies the ridged plains, gives an Upper Hesperian age for that unit. *Head et al.* [2002] called the younger unit the Vastitas Borealis Formation. The Vastitas Borealis Formation was originally proposed by *Scott and Tanaka* [1986] as a general term for fill within the northern basin. It included mottled, grooved, ridged and knobby members, and was assigned an Upper Hesperian age because most of the "stealth" craters were not detectable in the Viking data. *Head et al.* [2002] use the term in a more narrow sense to refer to Upper Hesperian materials that postdate the ridged plains, and we will continue with that usage. Because the Vastitas Borealis Formation occurs at the end of the large outflow channels and has a crater age similar to the outflow channels, *Head et al.* [2002] suggested that it may be composed primarily of materials deposited by the large floods.

[42] Over large areas of the northern plains, three stratigraphic units have, therefore, been distinguished: the Noachian basement, the Lower Hesperian ridged plains, and a thin Upper Hesperian deposit draped over the ridged plains. At scales of 1:15 M and coarser the appearance of the plains is dominated by the Noachian basement remnants (particularly around longitude 180°E) and the ridged plains. At scales of 1:5 M or finer, where the Vastitas Borealis Formation is present, its textures dominate. At even higher resolutions, such as those typical of MOC images, the surface texture of the latitude-dependent ice-dust-rich mantle unit dominates most of the northern lowlands [*Kreslavsky and Head*, 2000, 2002b; *Mustard et al.*, 2001; *Carr*, 2001; *Malin and Edgett*, 2001]. In several places younger Amazonian deposits overlie the three dominant units underlying the latitude-dependent mantle seen at MOC resolution, particularly around the polar cap, north of Alba, and in the Arcadia and Amazonis Planitiae. The smoothest and flattest areas of the northern plains at scales of 1:5M and coarser, are those of Amazonis Plantia. But at the scale of the MOC images, these plains are highly textured and appear to be formed largely of young volcanic flows [*Keszthelyi et al.*, 2000; *Malin and Edgett*, 2001; *Fuller and Head*, 2002a, 2002b].

[43] The area originally mapped as the Vastitas Borealis Formation, while bland at resolutions of several kilometers, is richly textured at resolutions of a few tens of meters to a kilometer. Textural features include polygonal fractures, parallel ridges and grooves, labyrinths of curvilinear valleys, ridges with summit pits and grooves, thumbprint patterns of regularly spaced curvilinear ridges and aligned hills, arrays of low, pitted domes, and mottled patterns (Figure 16). At MOC resolutions (a few meters) the plains are mostly bland, in part because of a thin pervasive cover with a characteristic "basketball" texture [*Mustard et al.*, 2001; *Carr*, 2001; *Kreslavsky and Head*, 2000, 2002b]. However, in places are arrays of cratered cones, irregular hollows, polygonal and parallel cracks, shadowy craters outlined by boulders and bouldery knobs (Figure 17) [*Malin and Edgett*, 2001].

[44] Thus "stealth" craters and the modification of wrinkle ridges provide good evidence for a thin Late Hesperian cover (the Vastitas Borealis Formation), of the order of 100m thick. This cover is layered (Figure 17c) and has undergone extensive, fine-scale modification to produce a wide variety of textures at the scale of MOC images. It overlies the Early Hesperian ridged plains over much of the northern basin. Since the Vastitas Borealis Formation is similar in age to many of the outflow channels, and these eroded large volumes of material that must have been deposited in the northern plains, it is reasonable to assume that the Vastitas Borealis Formation was deposited in some way by the outflow channels. This conclusion is supported by the volumes of material involved. *Kreslavsky and Head* [2002a] estimate that the volume of the Vastitas Borealis Formation is 3×10^6 km^3, which is remarkably close to the estimate of 4×10^6 km^3 for the amount of material eroded to form the circum-Chryse outflow channels [*Carr et al.*, 1987].

[45] If the outflow channels formed under climatic conditions similar to those that prevail today, water that ponded in the northern plains would rapidly freeze (see below). We should therefore expect to see evidence of ice in the areas formerly covered by water. Several types of features within the area mapped as the Vastitas Borealis Formation have been interpreted as the result of the former presence of ice (for a comprehensive summary, see *Kargel et al.* [1995]). The most striking are the "thumbprint" terrain and labyrinthine valleys (Figures 16 and 17). "Thumbprint" terrain is common around the edge of the area mapped as Vastitas Borealis Formation. It consists of whorled patterns of subparallel, curvilinear ridges 0.5–2.5 km wide. Many of the ridges have summit pits or depressions. They have been variously interpreted as glacial moraines, lines of kames, ice-pushed ridges, ice cored ridges, or other indicators of successive positions of retreating ice or ice-rich materials [e.g., *Carr and Schaber*, 1977; *Rossbacher and Judson*, 1981; *Lucchitta*, 1981; *Kargel et al.*, 1995]. In several areas, also toward the edge of the Vastitas Borealis Formation, are labyrinths of intersecting curvilinear troughs, some with central ridges. *Kargel et al.* [1995] point out their strong resemblance to terrestrial tunnel channels and eskers that form by meltwater under an ice sheet. *Kargel et al.* [1995] also point out the absence of drumlins within the northern plains, and suggest that this may be due to lack of till within the ice or lack of movement of the ice, suggestions that are consistent with a stationary ice sheet as might be expected from the freezing in place of a lake formed by floods.

[46] Is it plausible that meltwater features could form from a body of thick ice that formed from a former northern ocean? Assuming a thermal conductivity of 2 W m^{-1} K^{-1}, a surface temperature of 215 K and a 1 km thick ice sheet, then a heat flow of 0.12 W m^{-2} would be needed to raise the basal temperature to 273 K and cause melting. The best estimate for the age of the Late Hesperian is 3.2–3.7 Gyr [*Hartmann and Neukum*, 2001]. *Stevenson et al.* [1983] estimate that the heat at this time was approximately 0.1 W m^{-2} in good agreement with that needed for melting at the base of a 1 km thick ice sheet. *Zuber et al.* [2000] suggest, however, that published values for early heat flows may be too large. If the features discussed by *Kargel et al.* [1995] were formed by basal melting under a 1 km thick ice sheet when climatic conditions were similar to today's then much more water is implied than that indicated for Contact 1 in Figure 1. On the other hand, if salts were

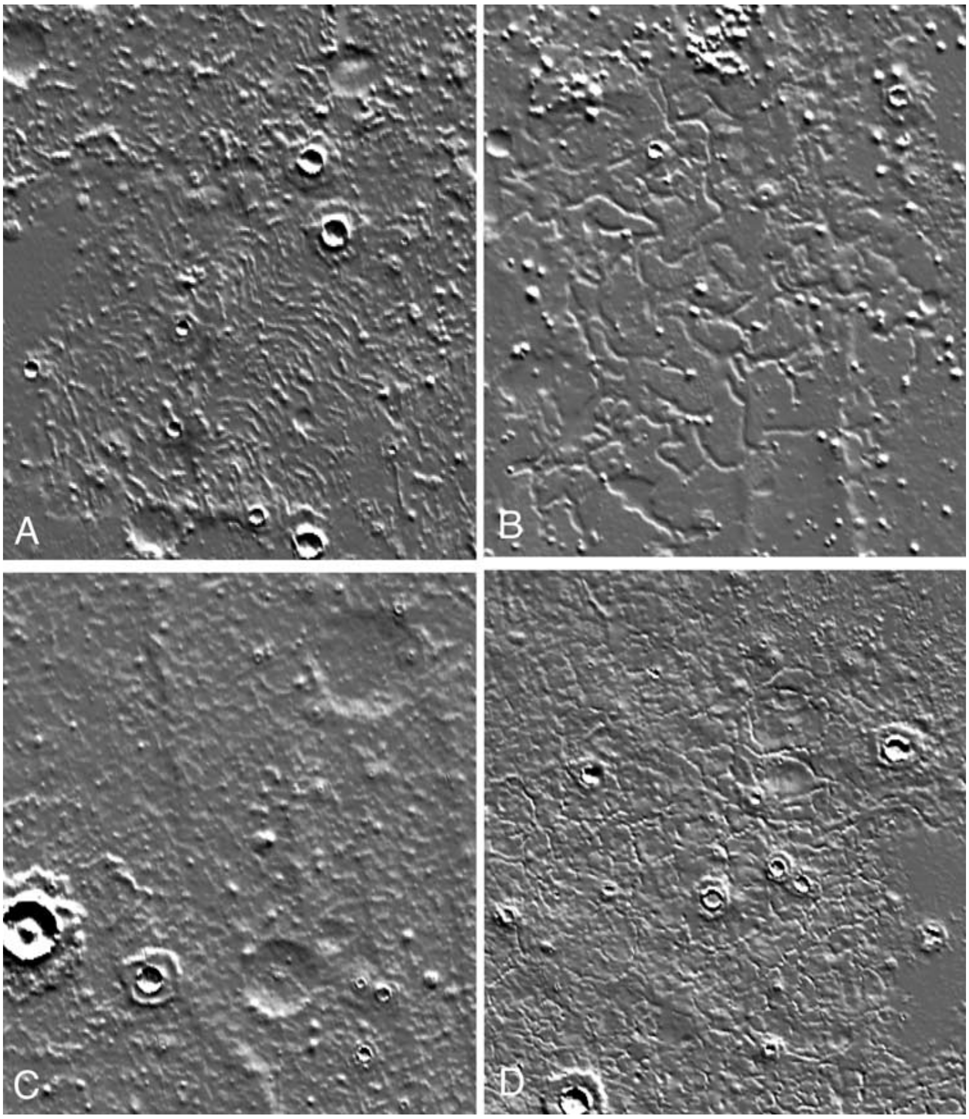

Figure 16. MOLA-scale textures on the Vastitas Borealis Formation (VBF). Each panel is 300 km across. A. Parallel curvilinear ridges or thumbprint texture at 57°N, 186°E. Such ridges commonly have lines of pits along their crests, as seen in MOC images, although these are not detectable in the MOLA-scale maps. B. Valley labyrinth at 45°N, 176°E. C. Typical VBF at 61°N, 186°E with fresh and stealth craters and numerous low hills; vertically oriented ridges are interpreted to be buried wrinkle ridges. D. Polygonally fractured ground at 40°N, 103°E. For higher-resolution Viking-based images of these and other possible glacial features, see *Kargel et al.* [1995].

concentrated in the remaining liquids as the ocean froze, then lower heat flows or thinner ice sheets would be needed to sustain liquids at the base of the ice. Observational evidence for basal melting is restricted to a few local areas. It may have occurred in this areas because of local heat anomalies, as happens on Earth [e.g., *Fahnstock et al.*, 2001].

[47] One observation that appears inconsistent with the presence of water over the area covered by the Vastitas Borealis Formation is the absence of erosion on the divide that separates the North Polar basin from the Utopia basin (Figures 18 and 19). For the ocean to have encompassed most of the Vastitas Borealis Formation its shoreline would have had to be at an elevation of around −3500 m. The minimum elevation of the divide between the two basins is −4300 m. Thus, to fill to the −3500 m level, water had to flow across the divide. The volume of water needed to fill the Utopia basin up to the level of the divide is 1.5×10^6 km^3. If the basin was filled from the Chryse side then this amount of water had to flow over the divide, yet there is no indication of any fluvial erosion across the divide. One possible explanation is that the northern plains did not repeatedly fill from a few very large events [e.g., *Baker et al.*, 1991; *Baker*, 2001] that would have required massive overflow from one basin to another. Rather, the plains may have filled gradually from numerous events, possibly on both sides of the divide, so that spillover from one side of the divide to the other was only at modest

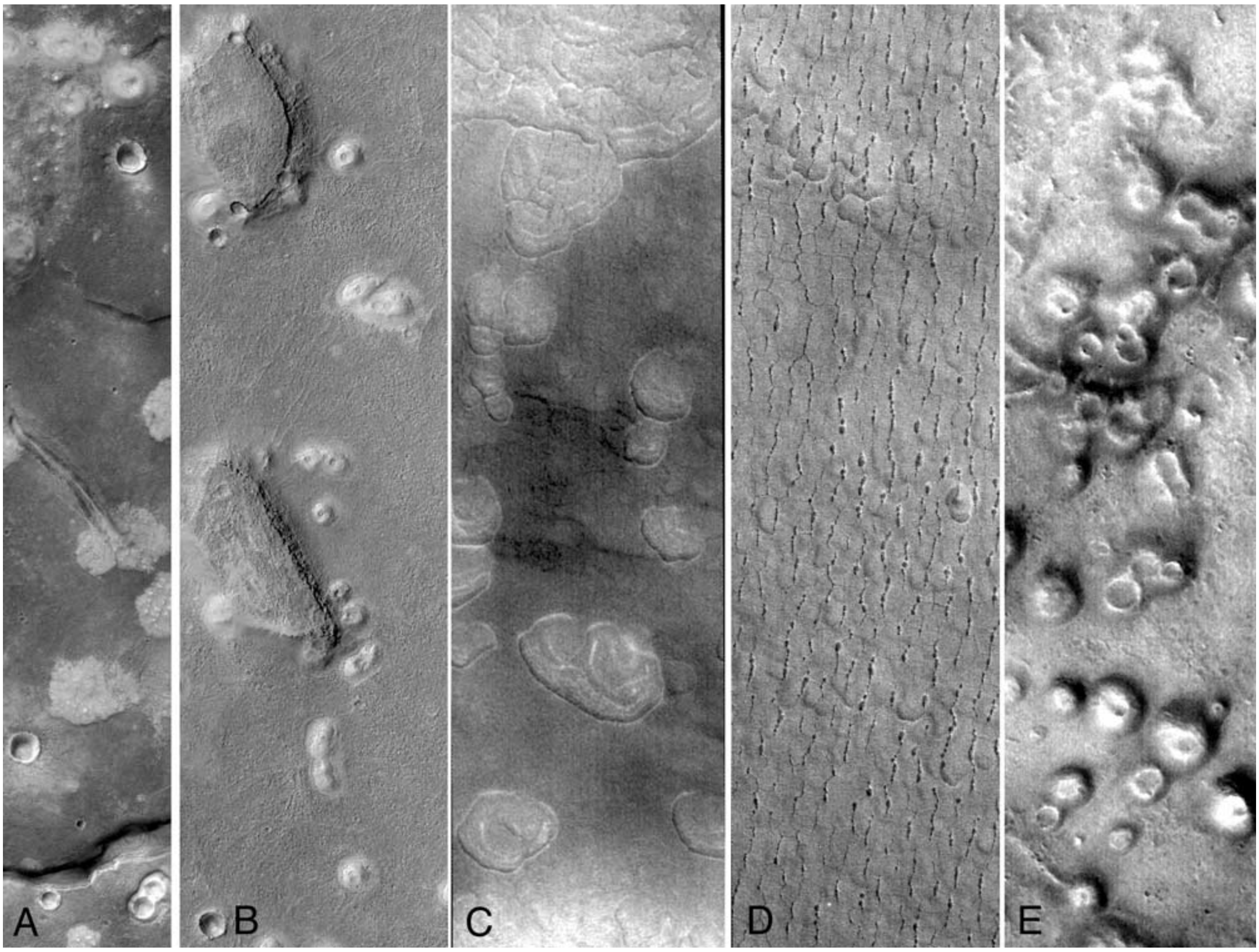

Figure 17. MOC-scale textures on the northern plains. A. Mottled terrain within an "island" surrounded by Vastitas Borealis Formation (VBF) in Acidalia Planitia at 333.2°E, 47.7°N. The mottling is caused by bright haloes around impact craters, bright low, cratered cones, and bright irregular patches with little relief. The strip is 3.2 km across (M21-01816). B. Thumbprint terrain close to the outer boundary of the VBF at 32.9°N, 87.7°E. The thumbprint texture is caused by low cratered hills and domes that have a higher albedo than their surroundings. The areas between the hills and domes has the fine-scale pitted texture typical of most surfaces at these latitudes. The strip is 3.1 km across (M23-02053). C. Possible deflation hollows within the VBF at 47.5°N, 91.2°E. The hollows may be exposing layering within the VBF. This strip and the next two are 1.6 km wide (M07-04451). D. Lines of pits within the VBF at 45.1°N, 84.2°E (M08-07602). E. Pitted cones near the outer boundary of the VBF at 39.2°N, 320.8°E. Such cones are common throughout the VBF (M11-02050).

discharges and caused little erosion. Another possibility is that the northern basin inherited a frozen ocean from the Noachian [*Clifford and Parker*, 2001] and that the northern basin was already filled with ice up to the divide before the late Hesperian floods. Curiously, the lowest elevation along the divide between the northern lowlands and the Isidis basin is −3500 m, the average level of the edge of the outer boundary of the Vastitas Borealis Formation. Below this level on both sides of the divide are typical textures of the Vastitas Borealis Formation (Figure 18).

5. Possible Fate of a Northern Ocean

[48] The fate of a newly formed ocean would depend on the climatic conditions. *Baker et al.* [1991] and *Baker* [2001] argue that the eruption of the large volumes of groundwater needed to form the oceans would be accompanied by large amounts of CO_2 that would temporarily change the global climate. The amount of CO_2 needed to change the climate is likely significant. *Haberle* [1998] and *Gulick et al.* [1997], using greenhouse models of *Pollack et al.* [1987] and *Kasting* [1991] estimate, for example, that, for the Hesperian period, a CO_2 pulse of 4 bars would result in global warming only to 250 K. Several bars of CO_2 would be needed to cause temperatures to rise over 273 K. For the planet to return to present conditions a large fraction of this CO_2 would have to be scavenged out of the atmosphere as CO_2-rich rainfall which would infiltrate into the ground and ultimately form carbonates. Yet the TES experiment on Mars Global Surveyor has detected no carbonates on the surface

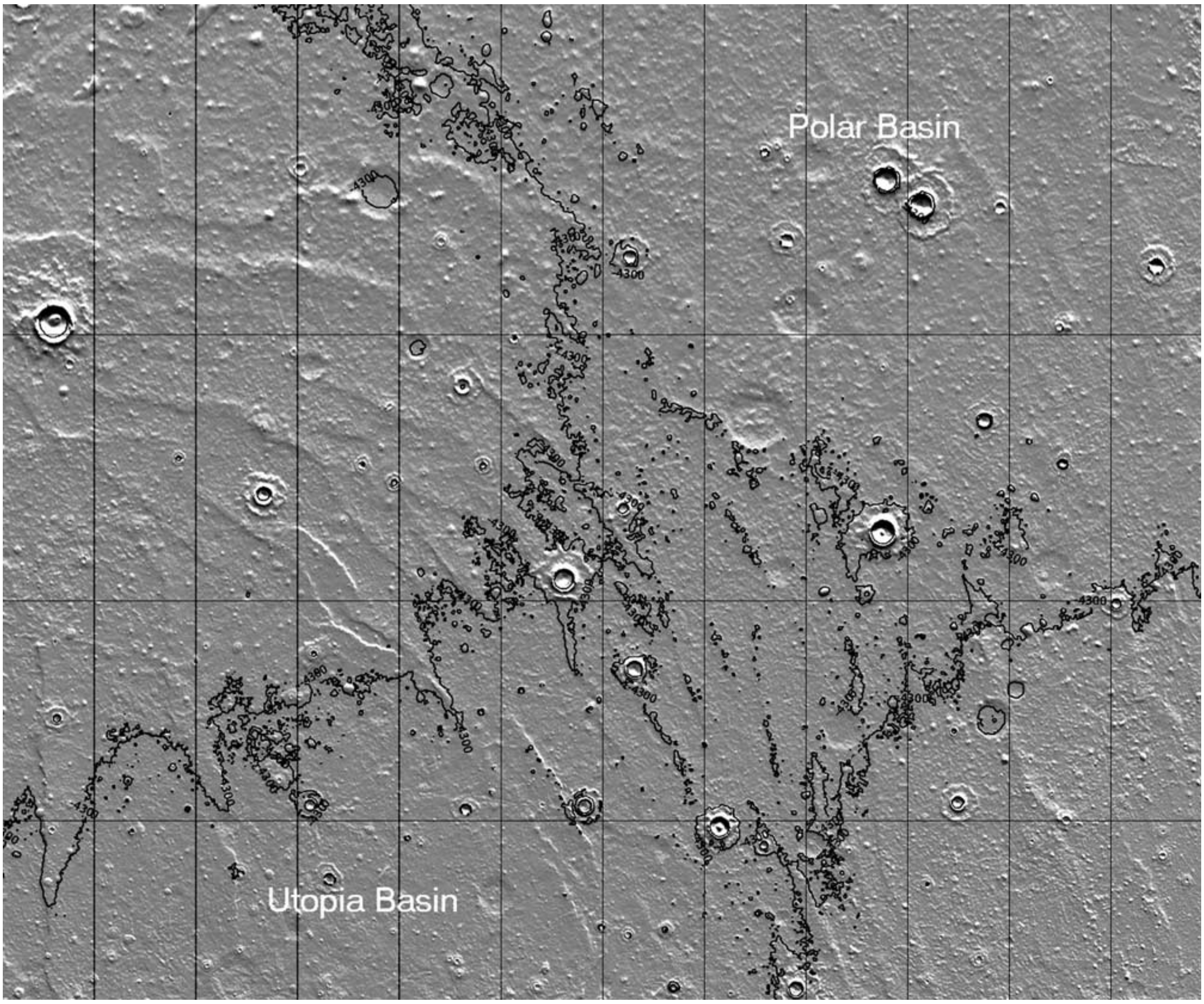

Figure 18. MOLA-based image of the divide between the North Polar Basin and the Utopia Basin. The area shown is from 55° to 75°N, and from 100° to 160°E. The divide is outlined by the −4300 m contour. There is no evidence of erosion along the spillway between the two basins as would be expected if one of the basins overflowed rapidly into the other. Textures typical of the Vastitas Borealis Formation cover the entire area.

[*Christensen et al.*, 2001] despite the inevitability of seepage of salt-rich groundwater onto the surface in such a scenario. We accordingly assume that large amounts of CO_2 were not repeatedly injected into the atmosphere. Thus any ocean that formed would have done so under conditions similar to those that prevail at present.

[49] Several authors have examined what would happen to a frozen body of water on Mars under present climatic conditions [*Carr*, 1983; *Moore et al.*, 1995; *Kargel et al.*, 1995; *Kreslavsky and Head*, 2002a]. *Kreslavksy and Head* [2002a] identified three stages in the emplacement of a large body of water: a warm convecting stage, a freezing stage, and a sublimation stage. If the floodwaters were initially above freezing, as would be the case if they were derived from groundwater well below the cryosphere, then rapid heat losses by evaporation and radiation from the surface would initially cause convective overturn [*Lane and Christensen*, 2000], thereby keeping the surface warm, preventing an ice cover from forming, and causing the ocean to be stirred and sediment suspended. Rapid evaporation (3–9 mm per day) would result, and the water would condense over and downwind of the ocean. Heat would also be lost into the ocean floor. Convection would cease when the temperature fell to 277 K, the temperature at which water reaches it maximum density. *Kreslavsky and Head* [2002a] estimate that a 100 m deep ocean would cool at 7–20 K per year so that the convecting stage would last only a few years, depending on the ocean depth and its initial temperature. If the temperature of the water were initially close to 273 K as would be expected if the water erupted from just below the cryosphere, then this stage would be very short or non-existent.

[50] In the second stage, when convection ceased, an ice cover would form and heat losses from the surface would be rapidly reduced. *Moore et al.* [1995] and *Kargel et al.* [1995] estimate that, as a result of heat losses

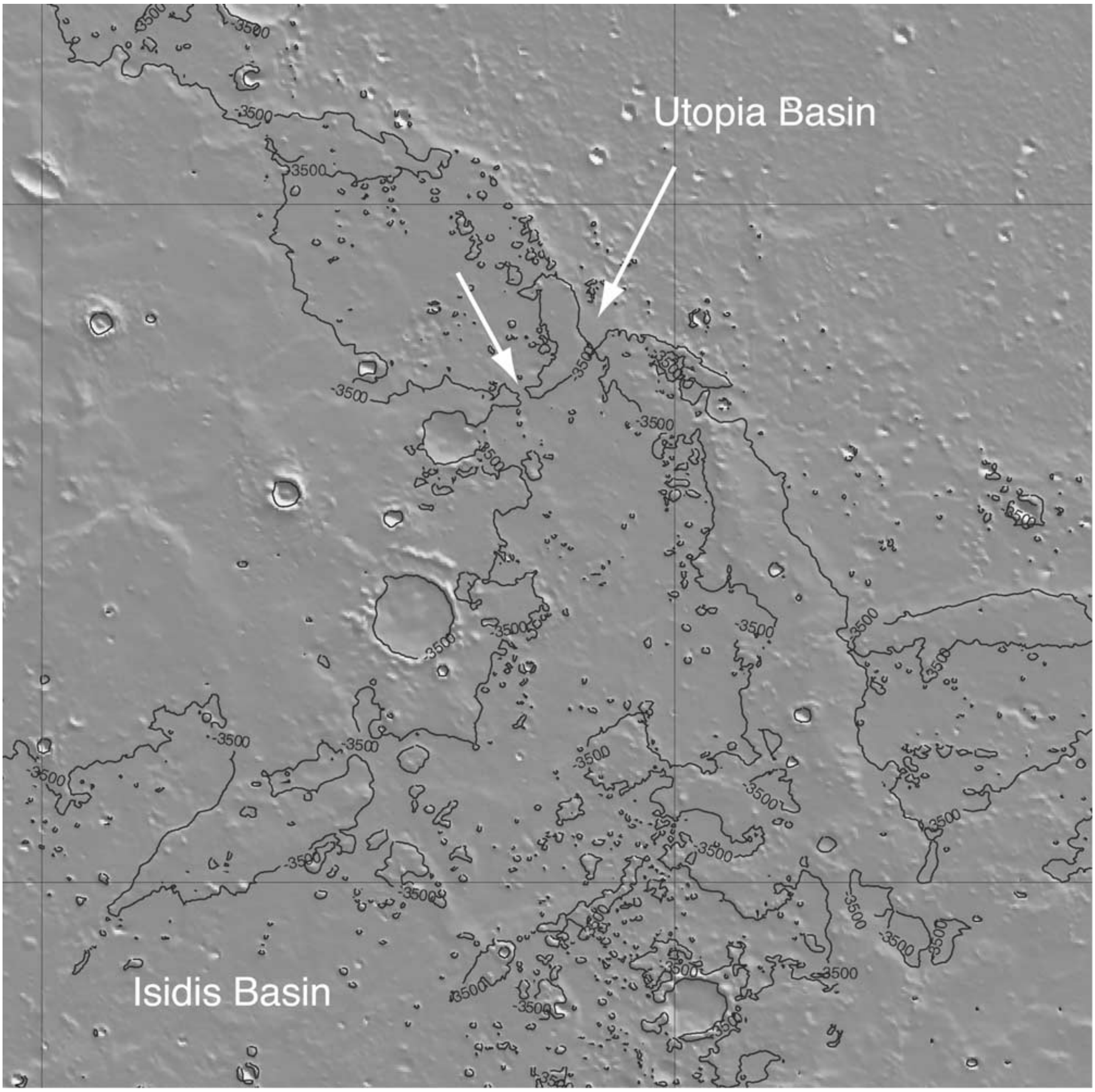

Figure 19. MOLA-based image centered at 23°N, 94°E of the divide between the Isidis Basin and the Northern (Utopia) Basin. Typical Vastitas Borealis Formation textures occur on both sides of the divide. The arrows point to narrow gaps in the divide as defined by the −3500 m contour, but there is no evidence of erosion as might be expected if one basin rapidly overflowed into the other. For scale the two latitude lines are 300 km apart.

through the surface alone, a 1 km deep lake would take roughly 10^5 years to freeze solid, the precise time depending on factors such as the ice albedo and wind speed. *Kreslavsky and Head* [2002a], taking into account heat losses both through the ice cover and into the lake floor, derive a significantly shorter time of $1-2 \times 10^4$ years. During this time any sediment load kept suspended during stage 1 by convection would be deposited on the floor.

[51] In the final sublimation stage, the ice deposit slowly sublimates and the water condenses elsewhere on the planet. The rate at which this occurs is extremely sensitive to whether or not the ice was covered with debris, such as eolian deposits or a lag. Clean polar ice under the present obliquity may sublimate at rates as high as 0.8 mm per year [*Jakosky and Haberle*, 1992]. For a high obliquity with strong winds, *Toon et al.* [1980] estimate that polar sublimation rates for bare ice could be as high as 0.5 m per year. In contrast, at high latitudes under the present obliquity, ice buried below a few tens of centimeters of rock or soil is permanently stable because temperatures never get above the frost point [*Farmer and Doms*, 1979]. Sublimation occurs only at high obliquities

and then probably at rates of only 10^{-6} to 10^{-4} cm per year [*Carr*, 1990]. Thus, if the ice remains clean, a 1 km thick ice sheet could sublimate in a few hundred thousand years. If covered with a few tens of centimeters of debris, the ice could remain for the lifetime of the planet. Neither extreme is likely.

[52] Support for long sublimation phases after each injection of water into the northern plains is the difference discussed below between the amount of water estimated to have been involved in individual floods as compared with the total volume of the possible ocean. Successive floods could have flowed over ice from previous floods to progressively fill the basin over a long period of time. Once flooding ceased then the ice sublimated away leaving the VBF covering the ridged plains. *Kargel et al.* [1995] note that during the sublimation phase, net sublimation at the more southerly parts of the former ocean and net accumulation at the pole would have resulted in a transition from a frozen ocean to a polar cap. The amount of water in today's north polar cap (1.6×10^6 km^3) is, however, much smaller than the volume enclosed even by the Deuteronilus "shoreline" (1.9×10^7 km^3) (Table 1). In summary, recent models provide plausible explanations for the evolution of large standing bodies of water that resulted from the formation of the Late Hesperian outflow channels and of the emplacement sediment rich effluent into the northern lowlands. In the following section we address the relationship of this scenario to other aspects of the history of Mars.

6. Reconciliation With Other Aspects of the Evolution of Mars

[53] We have just concluded from observational evidence that a plausible case can be made for the former presence in the northern plains of a body of water that covered the Lower Hesperian ridged plains over an area roughly equivalent to the present outcrop area of the Upper Hesperian Vastitas Borealis Formation. In this section we assess how plausible this conclusion is in light of other aspects of the planet's evolution. The main reasons for concluding that the VBF was deposited from water that filled the northern plains as a result of the large floods are (1) the similarity in ages between the floods and the VBF, (2) the similarity in volume of the VBF and the volume of material eroded by the large floods, and (3) the location of the VBF in low areas at the ends of the large flood channels. The average elevation of the outer boundary of the VBF is −3660 m. If the northern plains were filled to this level they would enclose 2.3×10^7 km^3 of water, the equivalent of 156 m spread over the whole planet (Table 1). Is this a plausible volume to have been introduced into the basin by the large floods?

[54] The large floods likely formed either by violent eruption of groundwater under high pressure or rapid release of water from groundwater-fed lakes [*Carr*, 1983, 1996; *Baker*, 2001]. *Clifford* [1993] estimated that the groundwater holding capacity of the megaregolith was in the range of $8–20 \times 10^7$ km^3. The ocean volume needed to cover the area of present topographic boundaries of the VBF represents 11–28% of the estimated holding capacity of the megaregolith. While the volume is well within the estimated holding capacity, it is unlikely that the entire capacity of the megaregolith was utilized during individual filling events. A significant fraction must have been left in the megaregolith after the flood event. It would, for example, be difficult to extract water from the megaregolith under the northern plains to form floods, such as those that cut Kasei Vallis, which start at much higher elevations than the northern plains. Nevertheless, there is no conflict between the smaller estimates of ocean volumes, those based on the Deuteronilus shoreline and the outcrops of the VBF, and the megaregolith capacity. This is not true of the larger estimates of ocean volumes based on Arabia and Meridiani shorelines [e.g., *Edgett and Parker*, 1997; *Clifford and Parker*, 2001] and the Olympus Mons aureole. These volumes are comparable to or exceed the estimates of the total holding capacity of the megaregolith (Table 1). If they are true, it would imply that the estimates of the megaregolith holding capacity are grossly in error, or that there was already a large ocean in place at the time of the Late Hesperian floods, or that there were large bodies of ice on the surface that melted to supplement the oceans.

[55] The eroded volume around the Chryse basin is roughly 4×10^6 km^3 [*Carr et al.*, 1987], which gives an acceptable 14% for the sediment load assuming no recycling of water through the flood channels. Any recycling would reduce the ratio, so that there is no difficulty in reconciling the ocean volumes with the observed erosion. The smaller estimates of the size of a northern ocean appear compatible with formation by the large floods that cut the outflow channels. Estimates of flood sizes are very uncertain. Calculations of peak discharges depend on extrapolations over two orders of magnitude from empirical data on terrestrial rivers to the much larger Martian channels, and assumptions must be made about the depths of water within the channels [*Baker*, 1982; *Komar*, 1979; *Robinson and Tanaka*, 1990; *Carr*, 1996]. Published estimates for the larger channels range from 10^7 to 4×10^9 km^3 s^{-1}. To estimate the total volume of water involved in a single flood is more difficult. Floods are typically short-lived, with discharges that decline exponentially. If formed by eruption of groundwater, the hydraulic pressure within the aquifer will drop; if formed by drainage of a lake, the lake level will fall. If we arbitrarily assume, for example, that the discharge declines by a factor of 1/e every week, then a flood with a peak discharge of 4×10^9 km^3 s^{-1} would create a lake with a volume of 2.4×10^6 km^3, or approximately one tenth of the ocean volume needed to cover the area of the VBF. This volume is also comparable to the postulated lakes in the canyons, whose catastrophic release could have been the cause of some floods [*McCauley*, 1978]. These considerations suggest that filling by one flood is unlikely and that if the northern basin ever filled, it was more likely to have been filled gradually from successive floods; the uncertainties, however, are large. The floods would have had to occur sufficiently close together that the water (or more likely, ice) did not disappear between floods (e.g., see

discussion by *Kreslavsky and Head* [2002a]). *Clifford and Parker* [2001] suggest, in addition, that the Late Hesperian floods were not the sole source of the northern ocean but rather added to the frozen remnants of an earlier Noachian ocean, so that the size of the frozen ocean need not necessarily be constrained by the size of the dominantly Late Hesperian floods. We conclude from these general arguments that there is no inconsistency between what little we know about flood sizes and mechanisms, and the formation of a 2.8×10^7 km^3 size ocean, but the larger the volume of the ocean the more difficult the reconciliation.

[56] A major issue with respect to the formation of large floods and oceans is where the water ultimately went. The polar caps, even if they consist solely of H_2O, represent only a small fraction of the volume of any ocean (Table 1). *Clifford and Parker* [2001] proposed that a significant part of the ocean volume might still be preserved in the northern lowlands as an ice layer below an insulating surface sediment layer. *Head et al.* [2002] and *Kreslavsky and Head* [2002a] argued, however, that the water is unlikely to be present as massive ice deposits below the present surface because the Lower Hesperian volcanic ridged plains are clearly visible just below the surface, being covered by only a thin veneer of later deposits (the VBF). Thus any standing bodies of water that were emplaced after deposition of the lower Hesperian ridged plains must have evaporated or sublimated into the atmosphere, and then been lost from the atmosphere either to space or to the ground.

[57] Losses to space since the end of the Noachian appear inadequate to account for a missing ocean. Photochemical modeling suggests that the losses of oxygen and hydrogen are balanced over geologic timescales. From oxygen losses by sputtering, solar wind pick-up and dissociative recombination, it is estimated that, since the end of the Noachian, Mars had lost to space the equivalent of 7.25×10^6 km^3, or 50 m of water spread over the whole planet (GEL) [*Kass*, 2001; *Hodges*, 2002]. Thus the polar caps and losses from space can account for approximately 10^7 km^3, about half of the estimated volume within the Deuteronilus shoreline or covering the area of the Vastitas Borealis Formation (Table 1). If these estimates are correct, any volume of ocean in excess of 10^7 km^3 (70 m global equivalent) must be sequestered elsewhere on the surface or in the ground. Other suggested reservoirs for such water include volatiles in units such as the Hesperian-aged Dorsa Argentea Formation (possibly as much as 20 m GEL) [*Head and Pratt*, 2001], and as a water/ice component in the Amazonian-aged Medusae Fossae Formation [*Head*, 2001], whose total volume is $\sim 1.4 \times 10^6$ km^3 [*Bradley et al.*, 2002]. The geologically recent, latitude-dependent, water-dust-rich mantle [*Carr*, 2001; *Mustard et al.*, 2001; *Malin and Edgett*, 2001; *Kreslavsky and Head*, 2000, 2002b] has a volume that is too small to be a significant reservoir (<1 m GEL [*Kreslavsky and Head*, 2002b]).

[58] If formation of the oceans caused significant global climate change, as suggested by *Baker et al.* [1991] and *Baker* [2001], then returning the water to the ground presents no problem. The water simply evaporates into the thick warm atmosphere, is precipitated out, and infiltrates into the ground. However, as noted above, significantly changing the climate of Mars probably requires injection of several bars of CO_2 into the atmosphere [e.g., *Pollack et al.*, 1987; *Gulick et al.*, 1997; *Haberle*, 1998]. The lack of observational evidence for carbonates on the surface [*Christensen et al.*, 2001] casts doubt upon any model that invokes a thick, post-Noachian atmosphere. While some significant fraction of this may simply have been dissolved in rainfall and infiltrated into the surface, a few bars of CO_2 would likely still remain in the atmosphere after global temperatures had fallen below freezing [*Haberle*, 1998] and this would be much more difficult to eliminate. In addition, with warm conditions and an active hydrological cycle, evaporite deposits would be expected within the numerous closed basins with convergent drainage that are present throughout the uplands, and no evaporites have been detected.

[59] At least two alternative scenarios exist for getting rid of the water in the ocean under cold conditions. In one scenario described above, the water sublimates and is deposited elsewhere on the surface such as in the present polar caps, in circumpolar deposits such as the Dorsa Argentea Formation, or possibly in volatile-rich parts of the Medusae Fossae Formation. In another scenario, suggested by *Clifford* [1987], under climatic conditions similar to those existing at the present, and despite the presence of a thick cryosphere, water from the atmosphere could have reentered the global aquifer system as a result of basal belting of the south polar ice cap. Observational support for this mechanism is the presence of esker-like ridges, suggestive of basal melting of an ice sheet, near the south pole, and also in Argyre and Hellas [*Kargel and Strom*, 1992; *Metzger*, 1992; *Head and Pratt*, 2001; *Head and Hallet*, 2001a, 2001b; *Milkovich et al.*, 2002]. As noted above, for this to occur, thick ice and/or a high heat flow are needed, as for example, 2 km thick ice and a heat flow of 0.075 W m^{-2}. Such a high heat flow may, however, be possible in the late Hesperian (>3.2 Gyr ago, according to *Hartmann and Neukum* [2001]). Ultimately, much of the groundwater could have been progressively cold-trapped at the base of a thickening cryosphere [*Clifford and Parker*, 2001].

7. Summary and Conclusions

[60] Large bodies of water must have episodically been left in the northern plains of Mars if the large outflow channels were cut by water, as appears likely. Pioneering work by *Parker et al.* [1989, 1993] identified several possible shorelines around the northern plains. However, large ranges in elevations and geologic relations along some of the proposed shorelines, cast doubt upon the interpretation of some of these features as shorelines. Further doubt is raised by the large volumes of water that would have been enclosed by the higher "shorelines," volumes that, when normalized to unit area, approach values for the present Earth oceans (Table 1).

[61] Stronger support is found for prior conclusions [*Lucchitta et al.*, 1986; *Parker et al.*, 1989, 1993; *Kargel et al.*, 1995] that many of the features internal to the northern plains are the result of the former presence of large bodies of water. Lower Hesperian ridged plains,

largely predating the age of the outflow channels, constitute most of the post-Noachian fill within the northern basin. By analogy with similar plains farther south, with which they are laterally continuous, these plains are likely volcanic in origin. Over much of the northern basin the ridged plains are covered with a thin veneer of material, of Upper Hesperian age, that subdues the underlying topography of the ridged plains. This veneer, which has an easily recognizable knobby surface texture, has been called the Vastitas Borealis Formation (VBF). The veneer has been interpreted as the sublimation residue of the effluent brought into the basin by the large floods [*Kreslavsky and Head*, 2002a]. Supporting this interpretation are the similarity in the ages of the outflow channels and the VBF, the similarity in volume between the VBF and the materials eroded to form the outflow channels, and the presence of the VBF at the ends of the channels. To cover the area over which the VBF is found would require the equivalent of at least 150 m of water spread evenly over the whole planet (Table 1). Under present climatic conditions any body of water at the surface would freeze on a geologically short timescale, then sublimate into the atmosphere. The ultimate fate of the water is uncertain. Approximately 50 m could have been lost to space since the late Hesperian, and about 30 m could reside in the present polar caps. The rest may be elsewhere on the surface of Mars and/or have re-entered the groundwater system by polar basal melting during the Hesperian, when the heat flow was significantly higher than at present. Although we have not been able to confirm most of the previously identified shorelines, we have found support for the former presence of a large body of water in the northern plains suggested by *Parker et al.* [1989, 1993].

[62] The main concern of this paper has been the post-Noachian era. The implications for the Noachian are uncertain. *Clifford and Parker* [2001] conclude that the nature of the Late Hesperian outflow channels requires that early Mars (the Noachian) must have been characterized by at least one third of the surface being covered by standing bodies of water and ice, including specifically, an ice-covered ocean in the northern lowlands (see their Figure 10). The great preponderance of valley networks in Noachian terrains certainly indicates a more active hydrologic cycle during this period. This same high level of surface activity has also resulted in very high surface degradation rates during the Noachian [*Arvidson et al.*, 1979; *Carr*, 1992; *Golombek and Bridges*, 2000]. As we show in this analysis, erosion and postemplacement geologic events and processes conspire to modify and obscure evidence for such subtle features as contacts and shorelines. We found that the most compelling evidence for former standing bodies of water lies in the deposits themselves, not in the marginal relations of the deposits. Applying these same criteria to test for the presence of hypothesized Noachian-aged oceans [e.g., *Clifford and Parker*, 2001] will be difficult because subsequent events during the Hesperian have repaved much of the northern lowlands, where the greatest expanses of a Noachian ocean are predicted to occur [*Clifford and Parker*, 2001, Figure 10]. Among the potentially important lines of investigation to test the hypothesis of Noachian-aged northern lowland oceans are: 1) Looking for the geological context of present surface water/ice, and minerals indicating aqueous alteration, with gamma ray and neutron spectrometer instruments, and with thermal emission and visible-near-infrared spectrometers; 2) Assessing the three-dimensional stratigraphy with ground-penetrating radar instruments, and searching for buried deposits and possible frozen water layers; 3) Using moderate and high-resolution visible, multispectral and thermal emission images to provide new views of surface units, their characteristics and their relationships, and 4) Undertaking surface exploration and sample return missions to specific areas in which well-stated tests of the hypothesis can be assessed.

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M. H. Carr, U.S. Geological Survey, Menlo Park, CA 94025, USA.

J. W. Head III, Department of Geological Sciences, Brown University, Box 1846, Providence, RI 02912, USA. (james_head_III@brown.edu)