

Chasma Boreale, Mars: Topographic characterization from Mars Orbiter Laser Altimeter data and implications for mechanisms of formation

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[1] Chasma Boreale, a large reentrant in the north polar cap of Mars, is distinct in scale, detailed topography, and orientation from the spiraling troughs that characterize the majority of the polar cap. We use new, high-resolution Mars Orbiter Laser Altimeter (MOLA) data and Mars Orbiter Camera (MOC) and Viking images of the chasma region to assess hypotheses of origin of Chasma Boreale. These hypotheses include formation by glacial flow and ablation, by eolian processes (such as katabatic winds) and sublimation, by outflow of meltwater, or by a combination of two or more of these processes. We find that these new data support initial formation by outflow of meltwater with later modification by katabatic winds and sublimation. On the basis of our analysis we suggest a possible scenario in which outflow has occurred in several stages. The outflow appears to have begun near an enclosed depression at the head of the chasma; meltwater migrated within and below the ice down the regional slope and eventually broke out to the surface. Removal of material by melting caused subsidence and erosion of the polar deposits forming the chasma, which has subsequently undergone modification by eolian and sublimation processes. The outflow deposited most of its sediment in the form of a lobe that stratigraphically overlies the polygonal plains mapped at the mouth of the chasma and scoured some of the circumpolar sediment mantle in the surrounding region. The lowest portions of the North Polar Basin received the rest of the sediment as a deposit a few meters thick. MOLA data also reveal evidence for similar events of smaller magnitude elsewhere on the margins of the polar cap. *INDEX TERMS:* 6225

Planetology: Solar System Objects: Mars; 5462 Planetology: Solid Surface Planets: Polar regions; 5416 Planetology: Solid Surface Planets: Glaciation; 1827 Hydrology: Glaciology (1863);

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1. Introduction and Background

[2] The northern polar deposits of Mars, consisting of residual frost and ice (Apl) and of layered materials (Apl) [Thomas *et al.*, 1992], exist as both a continuous cap of polar materials (Apl and Apl) and as an arc of outliers [Dial, 1984; Tanaka and Scott, 1987; Fishbaugh and Head, 2000]. Troughs spiraling around the north rotational pole expose the layered terrain [Howard *et al.*, 1982; Zuber *et al.*, 1998]. One unusual feature of the continuous cap is Chasma Boreale (Figure 1) [Dial and Dohm, 1994], a large reentrant distinct from the troughs in scale and orientation. Nearby troughs appear to curve in toward Chasma Boreale; thus their formation has been influenced by the presence of the reentrant. The chasma is ~520 km long, with an average width in the main section of ~60 km, an average depth of ~1300 m (using the lowest wall height), and an average wall slope of ~4°–7°.

[3] One purpose of this study is to characterize the structure and morphology of Chasma Boreale, primarily using new, detailed topographic data from the Mars Orbiter Laser Altimeter (MOLA) [Smith *et al.*, 1999]. In addition to MOLA data we have analyzed numerous high-resolution Viking images and all released MOC images of Chasma Boreale, though many of them contain abundant frost cover and dunes that can obscure primary features. We find that the new gridded MOLA data (polar stereographic projection, 200 pixels/deg) reveal more detail, as they are unobstructed by cloud and/or frost cover. The second purpose of this study is to

review proposed formation mechanisms and to assess their viability in light of the new data. We feel that these new data are crucial and beneficial to furthering our understanding of Chasma Boreale beyond what was revealed through Mariner 9 and Viking data.

[4] Several theories have been proposed for the origin of Chasma Boreale. Wallace and Sagan [1979] suggested that direct sunlight would be able to melt near-surface ice and thus that lakes could exist within a few meters of the surface. According to the authors, an impact event released meltwater in one of these lakes, causing an outflow that carved the chasma. However, later Viking observations revealed that the crater thought to be observed in Mariner 9 images did not exist. In addition, Clifford [1987] has pointed out that the inferred presence of dust in the ice would cause attenuation of sunlight, therefore precluding the presence of a near-surface lake.

[5] Howard [1980, 2000] proposed that the chasma was carved by concentration of katabatic winds created by cold air flowing from the top of the cap down a topographic low and that the other polar troughs were formed by a combination of sublimation and eolian processes. Evidence for katabatic wind erosion of Chasma Boreale includes the presence of yardangs, dunes, and erosional scarps within the chasma. The orientation of the chasma is favorable for formation by downslope winds directed by Coriolis forces. Zuber *et al.* [1998] have cited the fact that the floor does not continuously slope downward to the surrounding plains as being inconsistent with a fluvial origin.

[6] Clifford [1987] proposed that the chasma was carved as a result of a jokulhlaup triggered by basal melting. In his model, impermeable material underlying part of the main cap allows basal meltwater to collect in craters, forming basal lakes. The buildup of

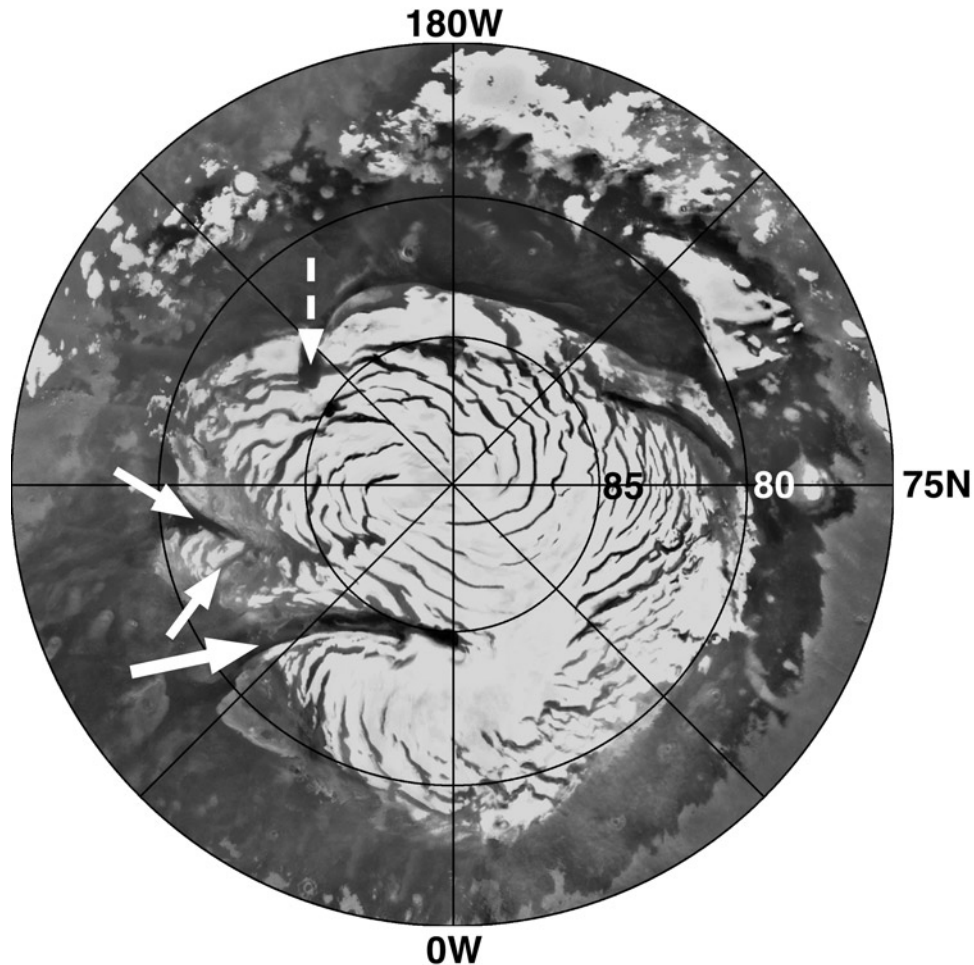


Figure 1. Viking mosaic of the North Polar Region of Mars from 55° to 90°N. Resolution is ~500 m/pixel. Heavy arrow points to Chasma Boreale. Smaller arrows point to two smaller reentrants similar to Chasma Boreale. Dashed arrow points to another reentrant that may have been formed in a manner similar to Chasma Boreale.

hydrostatic pressure allows the lake perimeter to be breached, causing catastrophic outflow of the meltwater. The flowing water would melt the overlying ice, causing the flood to eventually break out at the surface of the ice near the cap edge.

[7] An alternative trigger mechanism would be the presence of a thermal anomaly (e.g., a volcano) beneath the ice. *Clifford* [1987] describes this mechanism as being unlikely, because it would require a hot spot placed coincidentally in a similar location in the south polar cap in order to form Chasma Australe, an analogous feature in the southern cap [*Anguita et al.*, 2000; *Fishbaugh et al.*, 2000].

[8] *Benito et al.* [1997] suggested an origin in which catastrophic outflow of meltwater is triggered by sapping caused by a tectono-thermal event. They map flow features within the northern reaches of Chasma Boreale where the flow is assumed to be the most shallow. These include inner channels, longitudinal grooves, scour marks, cataracts, and giant ripples. Flow features disappear in the distal regions of the chasma. Here, plains are observed beneath the channel wall, and polygonal and dendritic terrain occupies the channel floor. *Benito et al.* [1997] liken some of the polygonal terrain in this region to the braided channels observed in subglacial and proglacial regions. In terms of origin, *Benito et al.* [1997] suggest that at least part of the cap formed along a fault system that allowed heat to be directed to this region, thus causing sapping, which in turn caused outflow. The authors argue that this process created the linearity of the chasma, a linearity that is not seen in terrestrial glacial outburst floods.

[9] *Anguita et al.* [2000] proposed a similar origin for Chasma Australe in the Martian southern polar cap. *Fishbaugh et al.* [2000] examined Chasma Australe and adjacent smaller chasmata. They noted esker-like ridges at the mouth of one chasma and channels at the mouth of another, similar elevations of some of the reentrants and the polar cap base, and evidence of deposition and ponding within the Prometheus Basin. These observations support the findings of *Anguita et al.* [2000]. Melt-related features in the form of esker-like ridges, cavi, and drainage channels have also been observed between the southern polar cap and Argyre Basin [*Kargel and Strom*, 1992; *Head and Pratt*, 2001; *Head and Hallet*, 2001].

[10] We use Viking images and high-resolution MOLA data and MOC images obtained during the Mars Global Surveyor mission to characterize Chasma Boreale and to assess which of the modes of formation described above is/are most consistent with the morphology of the chasma and its distal deposits. We first describe the general topography of the chasma and distal deposits and then describe the detailed morphology, including descriptions of topographic profiles that provide a cross-sectional view. We assess proposed formation scenarios in light of these new data.

2. Observations of Morphology

2.1. General Topography

[11] A topographic contour map of Chasma Boreale created by *Benito et al.* [1997] using the Viking USGS Digital Elevation Model is shown in Figure 2. The authors estimated the chasma

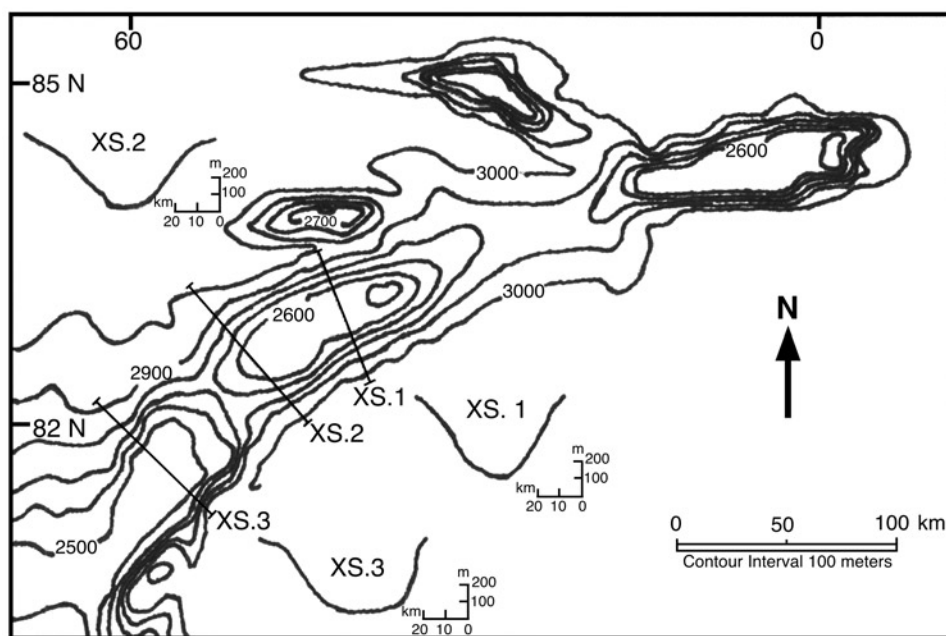


Figure 2. Topographic map of Chasma Boreale created by *Benito et al.* [1997] using the USGS Mars Digital Elevation Model. The straight labeled lines (XS.#) indicate the location of the cross sections.

length to be 600 km, the width to be 200 km at its distal end, and the depth to be 500 m. The lowest elevation in the chasma is reached both at the source (0°W) of the chasma (with steep walls), and in the middle portion of the chasma (40°W). Cross sections XS.1 and 2 show a V-shaped floor, while cross section XS.3 shows a U-shaped floor. Cross sections XS.1 and 2 exhibit symmetrical walls of equal height (350–400 m), while in cross section XS.3 the northwest facing wall is steeper than the southeast facing wall.

[12] The acquisition of new data from MOLA has allowed the production of a significantly more detailed topographic map of Chasma Boreale (Figures 3 and 4), and the topography is quite different than portrayed in earlier maps derived from Viking data (compare Figure 2 with Figures 3 and 5). The north polar cap lies within the North Polar Basin [*Head et al.*, 1999], which increases in depth with distance from the cap center in the same direction as the orientation of Chasma Boreale [*Fishbaugh and Head*, 2000]. Therefore Chasma Boreale lies downslope of the cap center.

[13] The lowest elevations within the chasma (Figure 6), which are separated by a small topographic high, lie at the chasma source (0°W) (an oval, 1775 m-deep, enclosed depression) (Figures 3 and 4c), and at 20°W (an arcuate, steep-walled depression) (Figures 3 and 4d). These depressions are much more distinctive than they appear in the previous topographic map in that the walls are steeper and the depressions are deeper and more enclosed. The bottoms of these depressions appear to have the same texture as most of the northern circumpolar plains (compare Figures 4c and 4d with 4a and 4b). This observation, along with their low elevation, clearly suggests that these depressions reach to the substrate underlying the layered deposits.

[14] The slopes on either side of the chasma wall are notably asymmetric in an opposite sense to that in the previous map. The asymmetry in the overall wall slopes (Figures 3 and 5) could be due to the preferential sublimation of the southwest facing continuation of the east wall as is hypothesized to be associated with the formation of troughs in polar layered terrain [*Howard et al.*, 1982].

[15] The chasma floor slopes very slightly downward toward the cap margin (200 m in 110 km; 0.1° ; Figures 6 and 7) and shows small, local variations in topography (Figures 3, 4d, 4e, 6, and 7). The slope varies across the chasma floor, with a negative slope

from east to west toward the second depression and a positive slope from west to east toward the chasma mouth (Figure 3). The floor also exhibits a few small craters, some of which have been postulated to be volcanic cones [*Garvin et al.*, 2000a, 2000b]. Along half of the chasma length lies a narrow, elongated feature (Figure 4e) that is now covered by dunes or completely composed of dune material.

[16] The chasma floor extends into the surrounding lowlands (Figures 3 and 4b) as a lobate structure. This structure is higher in elevation than the surrounding plains and is characterized by a marginal $\sim 250\text{-m}$ high scarp. The southeast facing wall ends in a scarp that continues around to the west. It should be noted that this scarp appears vertically exaggerated in the topography and has a slope of only $\sim 5^{\circ}$. The distal lobe deposits are probably composed mostly of sediment that was removed from the polar layered deposits [*Thomas et al.*, 1992] as the Chasma was formed.

[17] These lobate deposits overlie polygonal plains, part of the grooved member of the Vastitas Borealis Formation (Hvg) [*Tanaka and Scott*, 1987; *Lucchitta et al.*, 1986; *Dial and Dohm*, 1994]. Polygons extend to the south throughout the North Polar Basin but are manifested as ridges instead of grooves (Hvr) and also appear as Hvg on the other side of the cap near 270°W . The appearance of the polygonal plains in several widely spaced areas throughout the north polar region and their elevation below the polar cap, as seen in profile, has led *Fishbaugh and Head* [2000] to conclude that these polygonal plains lie stratigraphically beneath the polar cap and are therefore older than the polar cap itself. In mapping of this region using Viking images, *Dial and Dohm* [1994] also found that the floor of the chasma and the plains at its mouth overlie Hvg.

[18] *Benito et al.* [1987] and *Dial and Dohm* [1994] noted that some of these polygons resemble proglacial braided channels. Drainage of glacial meltwater can form channels either subglacially or proglacially. Depending on several factors, including hydraulic conditions, these channels can have several forms: braided, anastomosing, cut into sediments or bedrock, low and wide or narrow and deep, much like any stream [*Benn and Evans*, 1998]. However, unlike subaerial streams, subglacial streams need not follow the topographic gradient because their flow direction is governed by hydraulic head. Indeed, the topography in Figure 4b, which shows the lobate deposits and immediately adjacent polygonal plains,

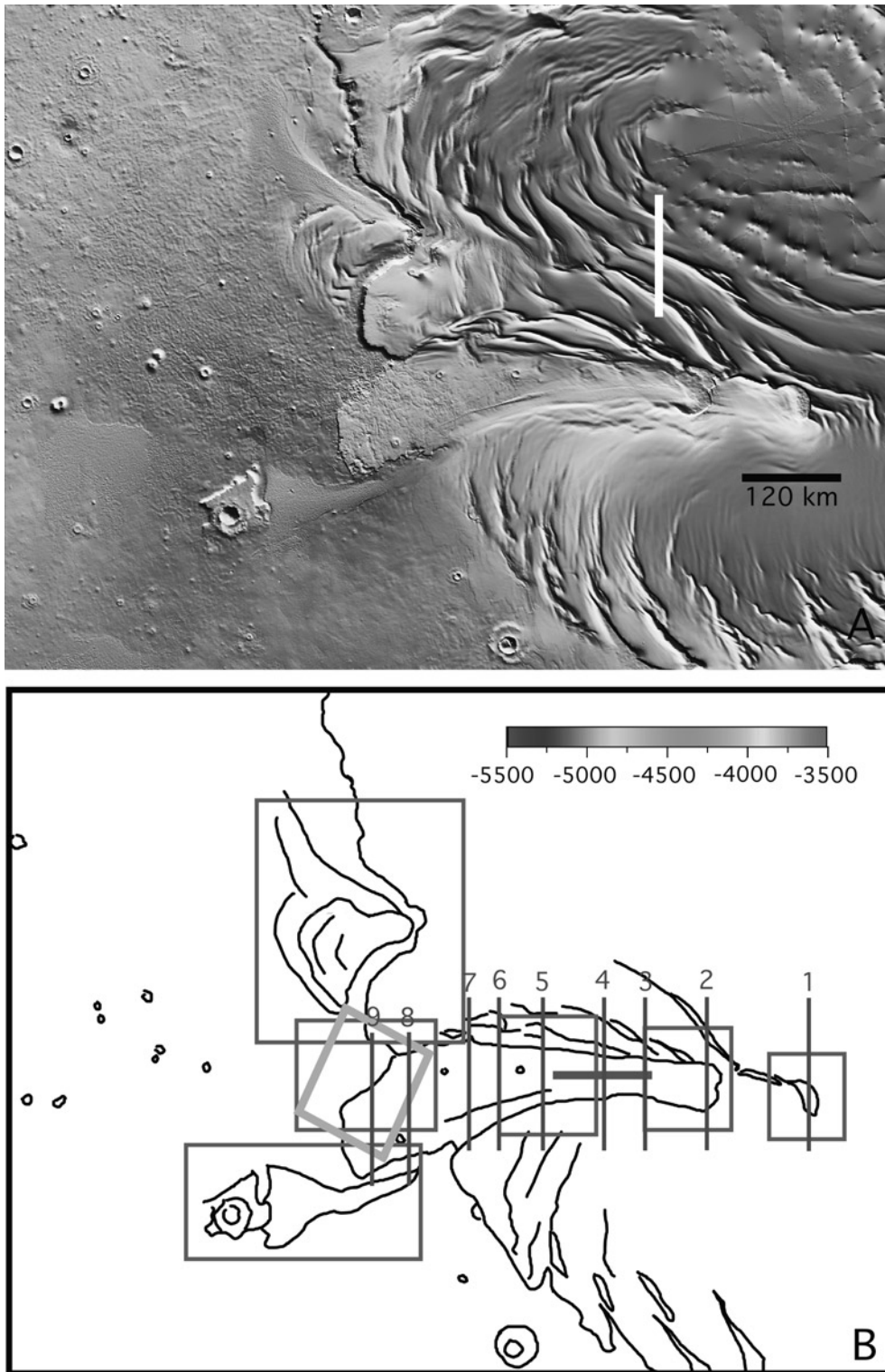


Figure 3. (a) Topographic, shaded-relief map of Chasma Boreale in polar projection using MOLA data. The white line indicates the position of the profile in Figure 10. (b) The green numbered lines indicate the position of the profiles shown in Figure 5. The orange box indicates the location of the Viking Orbiter image shown in Figure 7. The gray boxes indicate the positions of the high-resolution insets shown in Figure 4. The red line indicates the location of the profile shown in Figure 6. See color version of this figure at back of this issue.

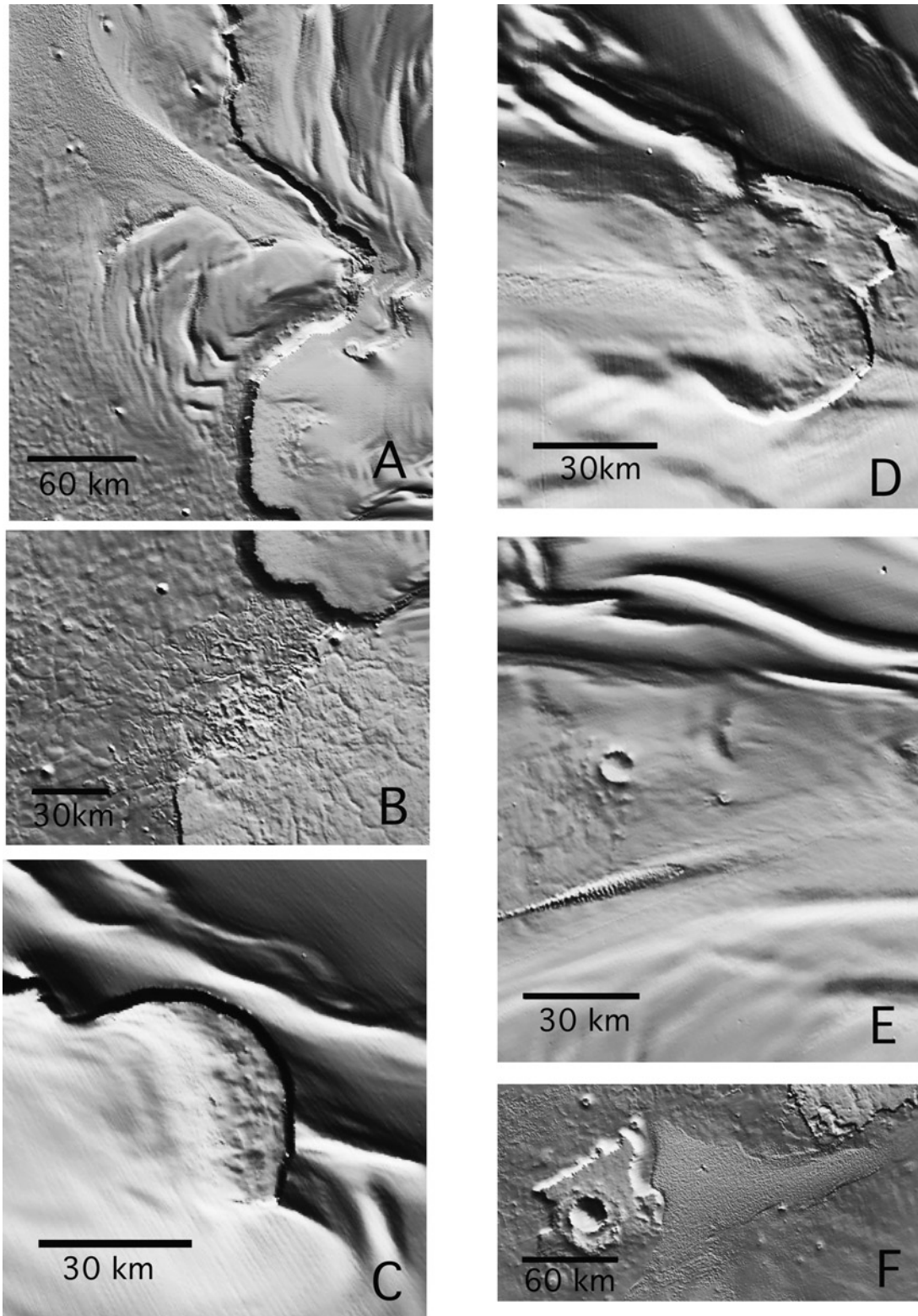


Figure 4. High-resolution insets of portions of the topographic map shown in Figure 3a. Locations of these close-ups are indicated by the gray boxes in Figure 3b. (a) Similar, smaller chasmata to the west of Chasma Boreale. (b) The western portion of the lobate deposits at the chasma mouth, showing the slump and channel-like features (see also Figure 7). (c) The deep, enclosed depression at the chasma head showing texture at the bottom. (d) The second deep, enclosed depression also showing texture at the bottom and a trough entering at nearly the same elevation as the bottom. (e) The middle portion of the chasma floor showing the elongated structure on the floor that is covered by dunes. (f) Mesa beyond the chasma mouth and streamlined dune field. See color version of this figure at back of this issue.

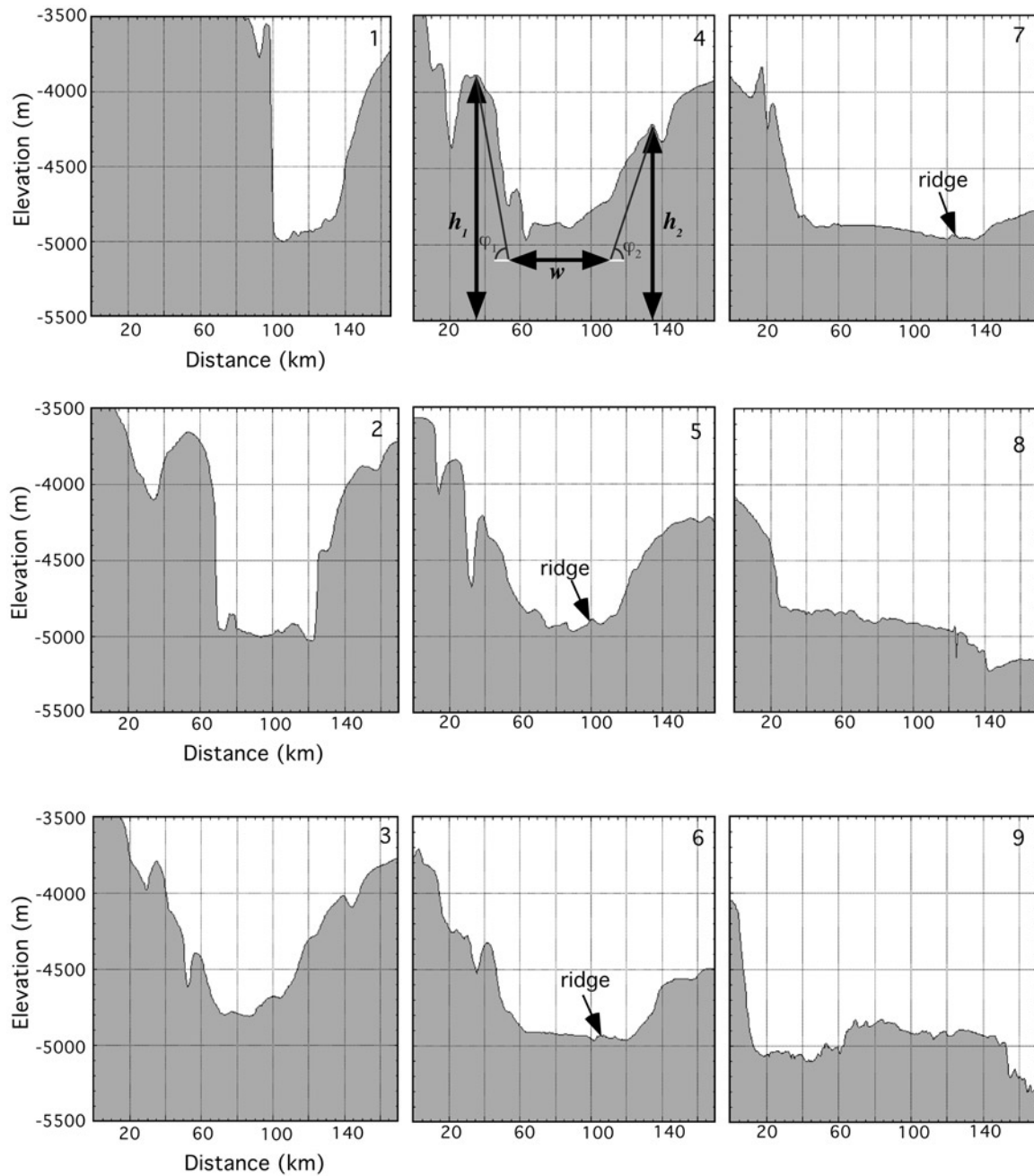


Figure 5. Representative MOLA topographic profiles transecting the chasma from gridded topographic data at a resolution of 200 pixels/deg. Locations shown in Figure 3b. These profiles are stacked in order to give a cross-sectional view running down the chasma from the origin to the distal terminus (1–9). Vertical exaggeration is $80\times$. Profiles 1–6 cross the main section of the chasma, while profiles 7–9 cross the western wall and lobate deposits. Profile 4 has been labeled to show how the chasma’s dimensions were measured. See text for further details. These profiles show that the chasma has a U-shape and widens along its length. The chasma is also not symmetrical in that one wall is steeper than the other. Profiles 5, 6, and 7 cross the elongated ridge on the chasma floor (See Figures 3 and 4e).

does resemble a braided pattern more than a strictly polygonal pattern. Other theories of polygonal plain formation also abound. *Hiesinger and Head* [2000] have reviewed the range of suggested origins of large polygons throughout the northern lowlands and on the basis of MOC and MOLA data have suggested an origin that involves tectonic deformation due to unloading of a former standing body of water within the North Polar Basin [*Parker et al.*, 1993; *Head et al.*, 1999]. *Dial and Dohm* [1994] list several further possibilities for the formation of this unit: (1) extension due to frost action, (2) compaction and shrinkage from degassing of volatiles

and melting of ground ice by intrusions or volcanic flows, or (3) grabens formed in response to a nearly isotropic, horizontal tensional stress with an unknown source [*Pechmann*, 1980].

[19] A mesa lies ~ 140 km from the chasma mouth within the North Polar Basin (Figures 3 and 4f). Prevailing wind directions inferred from local dune orientation are to the southeast [*Dial*, 1984]. Winds may thus account for the western side of the mesa being steeper than the eastern side. The mesa may be an erosional remnant of polar materials or an armored, eroded crater. If the mesa is a remnant of a formerly larger cap [*Fishbaugh and Head*, 2000],

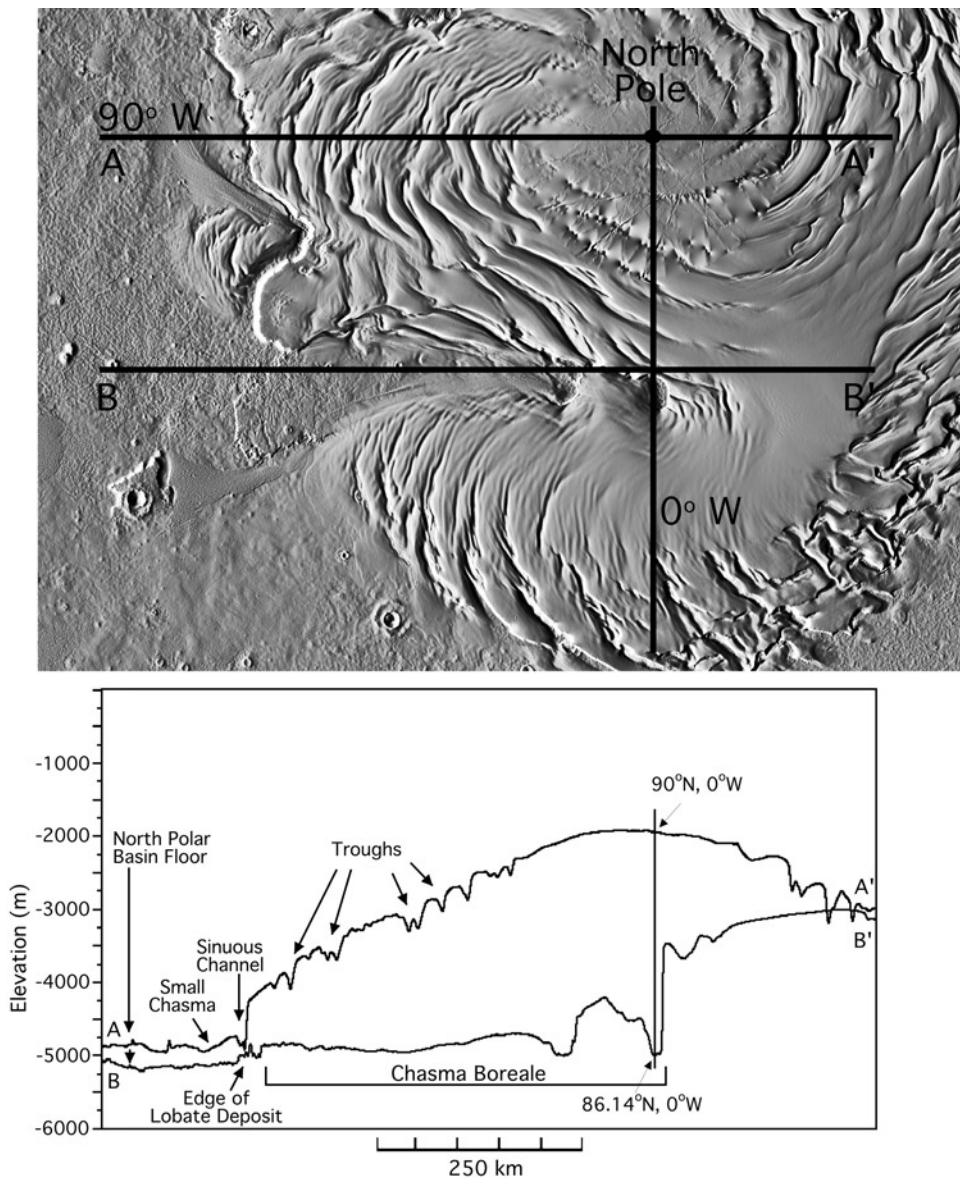


Figure 6. Topographic profiles across the summit of the north polar cap (Profile A-A') and across the portion of the cap containing Chasma Boreale (B-B'). (top) Location of profiles. (bottom) Annotated profiles. Note 3-km difference between pole summit and Chasma Boreale floor. Also note the scale differences between the troughs and Chasma Boreale, and the similar elevations of the headward Chasma Boreale depressions and the North Polar Basin floor. Profiles from gridded MOLA topography at a resolution of 200 pixels/deg.

then the former, larger extent of the cap must have preceded the formation of Chasma Boreale. Between the lobate structure and the outlying mesa lie thick sediments that have a streamlined appearance and are either dune-covered or consist completely of dune material (Figure 4f).

[20] Two narrow valleys emerge from a concave-outward arcuate structure in the left-lower middle of the map (Figures 1, 3, 4a, and 8). These reentrants can be distinguished from the typical polar cap troughs nearby by their depth, width, and opposing directions of curvature. In addition, they do not follow the same spiral pattern, centered at the high point of the cap, as do the nearby troughs. The eastern valley is ~ 14 km wide at its floor and arches southeastward and then eastward over a distance of ~ 155 km, finally flaring out into the northern lowlands near the edge of the lobate deposits extending out from Chasma Boreale. A second valley extends over

a distance of ~ 175 km from the west of the arcuate structure, broadening rapidly, extending out into the northern lowlands, and bounded by dune deposits to the south. The floor of this valley contains streamlined-appearing structures and a major dune field along its eastern margin.

[21] Formation of these small chasmata has left an isolated remnant of the polar-layered terrain whose sides form one wall of each chasma. The troughs on this remnant do not appear to be aligned with any troughs on the main cap; thus they appear to have been formed after the chasmata were carved. This is the same relationship as observed between Chasma Boreale and nearby troughs.

[22] The head of the valleys and the floors of the two valleys lie at the same elevation as the surrounding northern lowlands (Figure 4a). At the head of the valleys, two sinuous scarps mimic

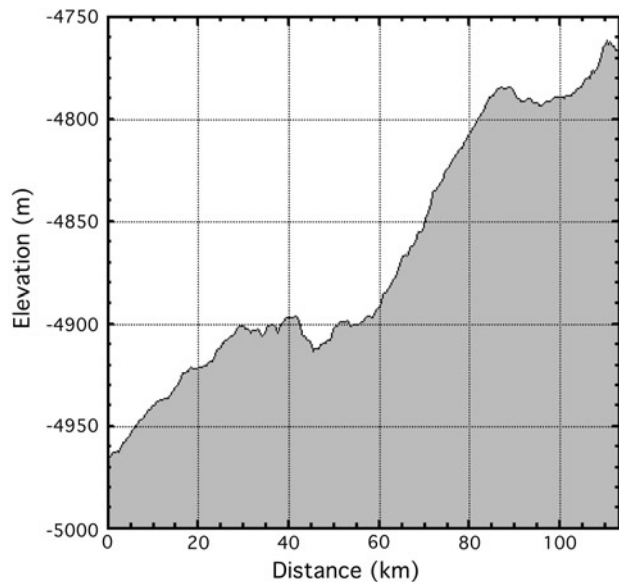


Figure 7. Elevation along the chasma floor. Vertical exaggeration is $454\times$. Profile location shown in Figure 3b as red line. In this profile the chasma floor generally slopes very slightly downward (200 m in 110 km; 0.1°) but also shows smaller-scale, local variations in topography. The chasma floor thus does not have a uniformly negative slope.

the outline of the poleward bounding scarp (Figure 8), suggesting that subsidence and slumping may have occurred.

[23] A narrow (~ 7 km wide), sinuous valley extends along the western margin of the western valley for a distance of ~ 280 km and opens out into the northern lowlands (Figures 3, 4a, and 8). The floor of this sinuous structure is at the same elevation as the surrounding northern lowlands. It too is bounded by a relatively steep wall and a shallow wall. Some evidence of collapse can be seen within the polar ice deposits along the curves of the valley. The sinuosity of this feature is unlike any other feature associated with the north polar cap.

[24] The topography (Figures 3, 4a, and 6) of these smaller reentrants share several similarities with Chasma Boreale, such as the following (Table 1). (1) There is evidence of an arcuate collapse feature and scarp near the head of these smaller reentrants. (2) These reentrants are bounded by a relatively steep wall and a shallowly sloping wall. (3) The floors of these chasmata are at the same elevation as and have a texture similar to the surrounding plains. (4) The dune deposits on the western side of the remnant are streamlined in a similar fashion to the dune deposits extending from the mesa beyond the mouth of Chasma Boreale. No lobate deposits, such as those seen in Chasma Boreale are apparent, however.

[25] These chasmata show many similarities to Chasma Boreale and may therefore have been formed by the same mechanism. If the smaller reentrants along the rest of the cap edge (Figure 1) are of a similar origin to the chasmata, the process that created Chasma Boreale may have operated on a scale affecting the entire polar deposit margin. The topographic characteristics of these features have been summarized in Table 1.

2.2. Detailed Cross Sections

[26] Individual MOLA profiles provide more detailed topographic information about Chasma Boreale in cross-section form. We have examined 50 profiles that transect the chasma and the plains just beyond the chasma mouth. We have chosen nine profiles (Figure 5) to represent the general geometry of the main

section of the chasma. The locations of these representative profiles appear in Figure 3.

[27] The main section of the chasma is generally U-shaped, similar to the shape shown in Figure 2 (XS.1). We define the height of the chasma walls as the greatest height reached by the wall before the topography either flattens or exhibits another trough (parameters h_1 and h_2 in Figure 5). The heights of the walls vary along the length, from nearly 1500 m (tallest wall in Profile 1, Figure 5) to nearly 500 m (shortest wall in Profile 6, Figure 5). Average slopes of the eastern and western wall (parameters φ_1 and φ_2 in Figure 5) are $\sim 4^\circ$ and $\sim 8^\circ$, respectively.

[28] The chasma floor is not flat across the width of the chasma. The topography in Figure 3 and the profiles in Figures 6 and 7 show that the chasma floor slopes downward on average (0.1°) with local, small variations and lies much closer to the elevation of the surrounding plains than to the elevation of the surrounding polar layered deposits. The maximum and minimum floor elevation in these profiles is -4800 and -5000 m, respectively.

[29] Using the average height of the eastern wall (~ 1300 m), the average width (~ 60 km), and the length (~ 520 km) of the chasma and assuming a rectangular profile, the volume of the chasma is $\sim 4 \times 10^4$ km³. If the chasma was initially formed by melting and outflow as suggested by Clifford [1987] and Benito *et al.* [1997], then this volume is probably an overestimate of the volume at the time of initial formation of the chasma due to later enlargement by sublimation and wind erosion. If the chasma was formed purely by wind erosion and sublimation as suggested by Howard [1980, 2000], then the initial volume is irrelevant as these processes are ongoing and have presumably, under this scenario, been gradually enlarging the chasma through time. The dust content of the polar layered terrain is poorly constrained and could range anywhere from less than 1% by volume [Malin, 1986] to over 60% by volume [Hofstadter and Murray, 1990]. We use an estimate for the dust content of the polar layered terrain in the middle of this range (40%) and calculate that the amount of sediment within the volume of layered deposits comprising the chasma volume is $\sim 1.6 \times 10^4$ km³, and the amount of ice is $\sim 2.4 \times 10^4$ km³. This amount of ice and sediment must have been removed by chasma formation and deposited elsewhere.

2.3. Lobate Deposits

[30] The floor of Chasma Boreale ends in a lobate structure that extends beyond the Chasma mouth (Figure 3). Description of this feature, its relationship to Chasma Boreale, and its context in the history of the surrounding plains may help to elucidate how this feature was formed and whether it has any genetic connection to Chasma Boreale.

[31] Figure 9a shows Viking image frame 560 B63. The location of this image is shown in Figure 3b. Visible in this image are the edge of the polar-layered deposits and part of the lobate deposits and surrounding terrain. A scarp delineates the western side of the lobate deposits and is disrupted in the center of the image by what appears to be a slump feature.

[32] Distinguishable in the Viking image are polygonal features [Lucchitta *et al.*, 1986; Tanaka and Scott, 1987; Dial and Dohm, 1994], part of the grooved member (Hvg) of the Vastitas Borealis Formation [Tanaka and Scott, 1987]. As explained above, Hvg lies stratigraphically beneath the polar materials (Api/Apl). From the profile extending across this image, it is clear that the polygons at the base of the scarp, like the rest of Hvg, lie below the lobate deposits, slump feature, and the polar materials. The Hvg grooves in this area are in several states of degradation or mantling. The theories of their formation have been discussed in section 2.1. The mantled polygons are slightly mantled by enough material that they do not appear as clear as the more defined grooves. On the surface of the lobate deposit exist grooves in subdued form. The defined grooves (as named in Figure 9b) lie at a slightly higher elevation

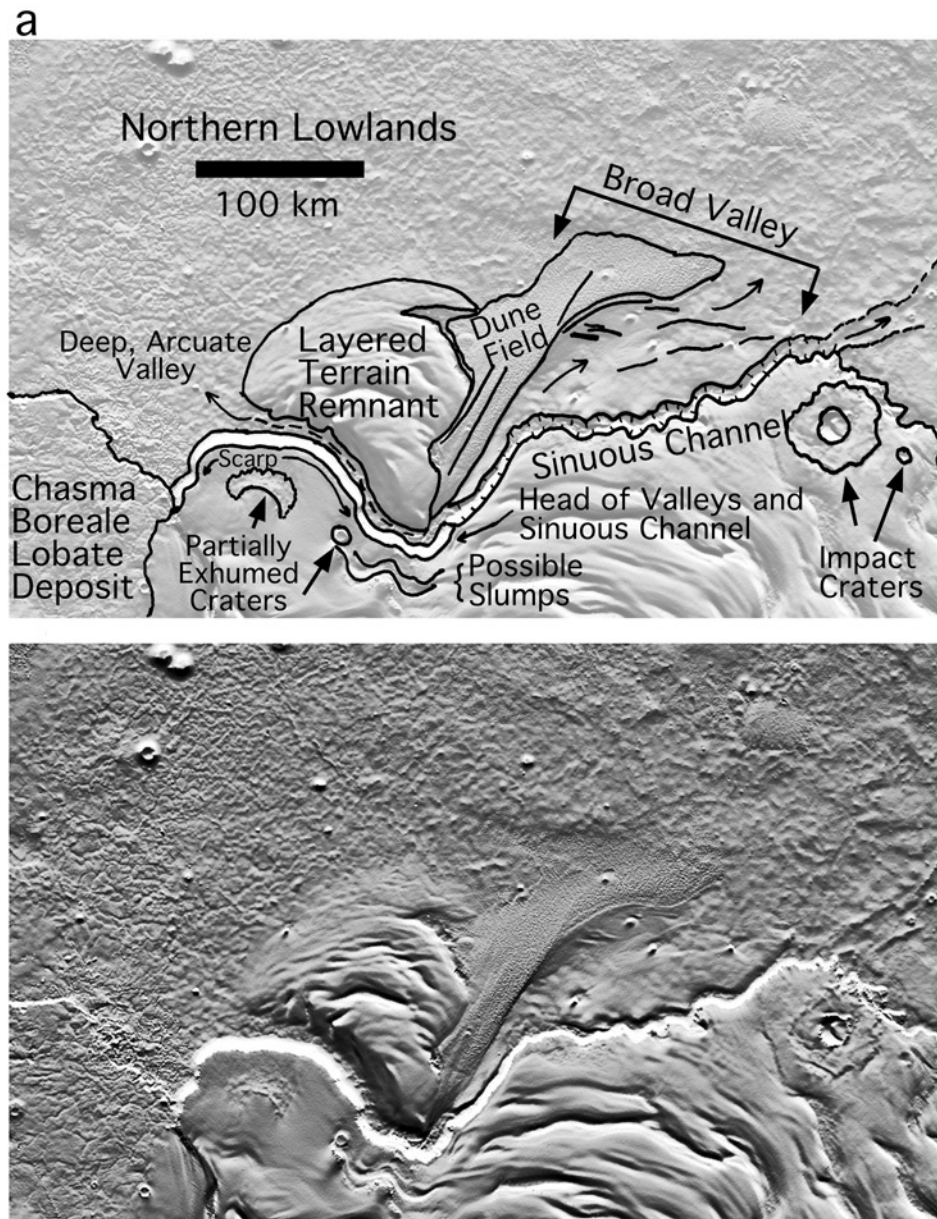


Figure 8a. Structure and relationship of valleys and a sinuous channel in the layered terrain at the margin of the north polar cap near Chasma Boreale (lower left). (bottom) MOLA topographic gradient map showing the area just to the east of Chasma Boreale and (top) an annotated sketch overlain. North (poleward) is to the bottom. The lobate deposit of the floor of Chasma Boreale can be seen on the lower left. Two valleys can be seen to emerge from a location at the poleward apex of a layered terrain remnant. The valleys are distinctive in their topography, shape, and structure from the polar troughs, and the western valley is broader than the eastern. A dune field occupies the eastern part of the western valley. Possible slumps are seen where the two valleys meet. A distinctive sinuous channel emerges at this point and extends to the west. The sinuous nature of the channel suggests that possible flow velocities were lower than for the other two valleys. Arrows indicate interpreted flow direction.

than the mantled polygons but at a lower elevation than the slump or lobate deposits. As illustrated in Figure 3b, the grooves within the lobate deposits are continuous with some of the grooves in the defined polygons, and some of these continuations even crosscut the slump feature. The grooves within the lobate deposits, slump feature, and just below the slump feature look more like quasi-sinuuous valleys than polygons.

[33] From these observations we suggest the following scenario for the history of the grooved terrain near the mouth of Chasma Boreale. The polygonal plains (Hvg, Hvr) of Vastitas

Borealis were formed as summarized by, for example, *Hiesinger and Head* [2000] and *Dial and Dohm* [1994]. Later activity, probably colian, slightly mantled these polygons. Subsequently, Chasma Boreale formed by one or several of the processes outlined above. The lobate deposits were formed as a result and laid down on top of the polygonal plain, greatly subduing the polygons beneath them. Mass wasting of the scarp created the slump feature that now overlies the polygons. Continued activity associated with Chasma Boreale, either simultaneous with or after the deposition of the lobate deposits, deepened some of these

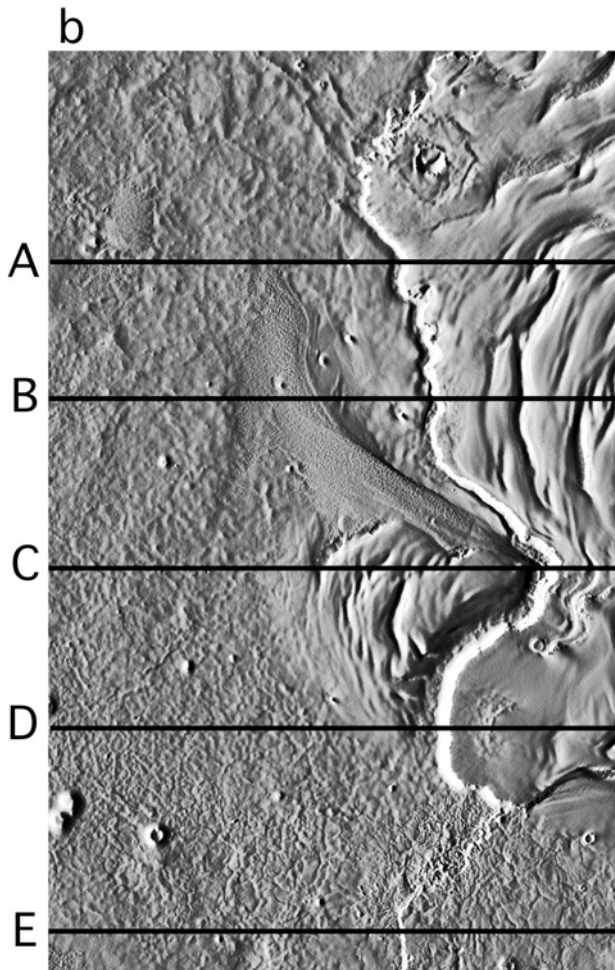


Figure 8b. Location map for the profiles shown in Figure 8c. Letters and lines show location of profiles.

grooves on the lobate deposits, across the slump feature, and within the defined polygons.

2.4. Summary of Chasma Boreale Topographic Characteristics

[34] In summary, any proposed sequence of events for the formation of Chasma Boreale must account for its main topographic characteristics (Table 1). (1) Chasma Boreale is by far the largest reentrant in the north polar cap; all others are much smaller. (2) Chasma Boreale is oriented in a direction downslope from the cap center and as predicted by the Coriolis effect. (3) Deep, enclosed depressions lie near the chasma head. The floors of these depressions are at an elevation similar to and have a texture similar to the surrounding plains. (4) One wall of the chasma is steeper than the other. (5) The slope of the floor varies across and slightly along the length of the chasma but has an average negative slope toward the North Polar Basin. (6) A lobate deposit forming an extension of the chasma floor lies on top of already modified polygonal ground and has even further modified polygons within and near it. (7) A scarp and gradational, slump-like features are on one side of the lobate structure. (8) A streamlined, dune-capped or dune-filled deposit occurs near the outlying mesa. (9) Similar but smaller chasmata and associated valleys and streamlined features lie to the west. (10) The floor of Chasma Boreale lies at essentially the same elevation as the surrounding basin. (11) There are distinctive

topographic differences between Chasma Boreale and typical polar cap troughs.

[35] In Table 1, we have listed the major characteristics of Chasma Boreale, as identified by us in MOLA topography and MOC and Viking images, and have assessed the possible origins of these features in relation to proposed formation mechanisms for Chasma Boreale. We have also included comparison with typical polar troughs. Clearly, the complexity of this analysis cannot be wholly summarized in a table; it is meant as a point of reference for the following discussions.

2.5. Comparison to Polar Troughs

[36] *Howard et al.* [1982] have described the formation of polar cap troughs. In their model the surface of the ice initially contains undulations; these later grow into troughs and migrate poleward by sublimation of the equatorward facing wall and insulation of the poleward facing wall. These troughs may also be modified and deepened by wind action [*Howard*, 1980]. Could Chasma Boreale simply be a large polar trough?

[37] There are similarities between polar troughs and the chasma. The asymmetry of the chasma wall slopes is similar to that of the troughs. Modification of the chasma walls through sublimation (either during or after initial formation), similar to what has been proposed to form the troughs [*Howard et al.*, 1982; *Howard*, 2000], could account for this. *Fishbaugh et al.* [2000] have noted that at least one trough in the exposed southern polar layered deposits appears to extend toward Chasma Australe. This may suggest a genetic link between Chasma Australe and that trough. However, this does not make a strong connection between Chasma Boreale and the northern polar troughs, because the southern troughs within the exposed layered terrain are actually often manifested as scarps [*Schenk and Moore*, 2000] and do not spiral in a manner similar to the troughs within the southern Api or the troughs within the north polar cap; thus, this trough near Chasma Australe may not be a typical polar trough.

[38] As mentioned above, Chasma Boreale is quite distinct from the typical polar cap troughs. Examination of the troughs near Chasma Boreale helps to elucidate the relationship between these features. Several differences between troughs and Chasma Boreale are noted and far outweigh the similarities.

1. The two troughs adjacent to the chasma begin at a higher elevation than the chasma floor. The chasma does not seem to crosscut the troughs. Rather, the troughs curve toward the chasma on one end and begin to spiral in the same manner as the other polar cap troughs on the opposite end (Figures 1 and 3). Thus the presence of Chasma Boreale appears to have influenced the orientation of the troughs. This observation suggests either that these troughs are younger than Chasma Boreale as noted by *Thomas et al.* [1992] or that they share a genetic connection.

2. The chasma is 15 times deeper and 50 times wider than the example trough in Figure 10 (see also the troughs in Figure 6). If the same process has created both the chasma and the trough, then it is unclear why only one trough has been deepened and widened by so much more than the others. Given the fact that most polar troughs are similar in size to each other, it appears that whatever process is creating them is uniform across the cap. One would expect locally greater insolation values farther south and east of Chasma Boreale, for these are the southernmost troughs on the cap. In addition, if the troughs and the chasma are related, it would require a mechanism that would enhance winds in one particular trough that would then form Chasma Boreale.

3. The troughs have a clear clockwise spiraling pattern, while Chasma Boreale curves in the opposite direction.

4. The troughs, for the most part, extend and spiral from the high point of the cap (near the rotational pole) and have an approximately uniform width along their length. The chasma, on the other hand, extends from a deep enclosed depression south of the rotational pole and widens along its length.

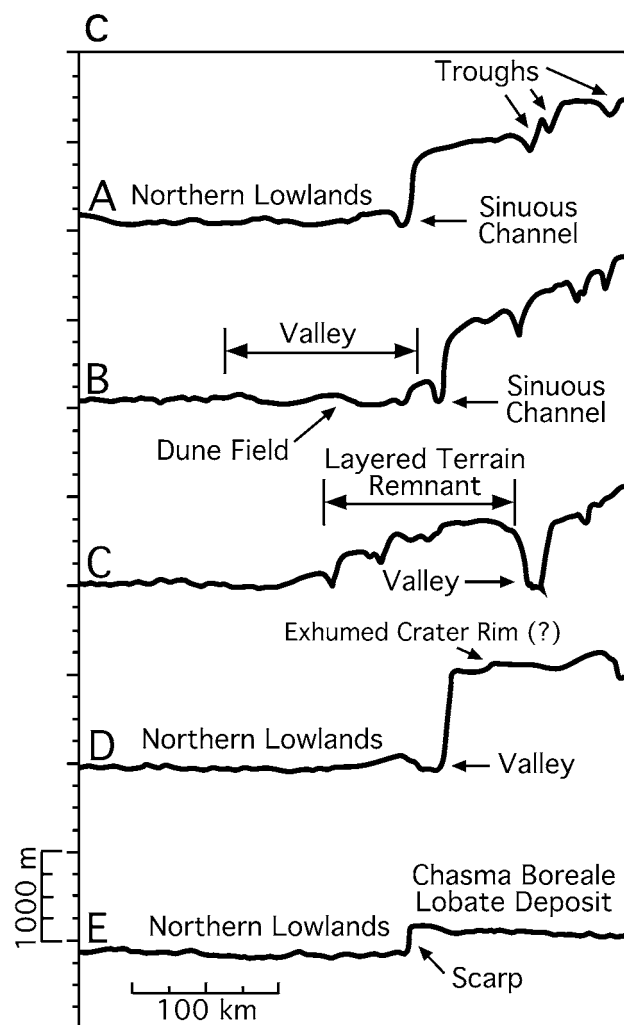


Figure 8c. MOLA altimetric profiles show details of relationships of these features, such as the characteristics of the floor of the northern lowlands and the contrast in the nature of the valleys, sinuous channel, and polar troughs. Note that the floors of the valleys and sinuous channel are at nearly the same elevation as the surrounding northern lowlands.

5. The chasma has a much more complex cross-sectional profile than that of a typical polar trough (compare Figure 5 with Figure 10).

6. The entire chasma floor lies at nearly the same level as the surrounding terrain, unlike typical polar troughs (e.g., those near the chasma).

[39] Given these strong differences between the polar troughs and Chasma Boreale, we find it unlikely that Chasma Boreale can be definitively described as merely a larger version of the typical polar troughs (Table 1). Rather, the origin of Chasma Boreale and similar, smaller reentrants is possibly much more complex.

3. An Assessment of Chasma Boreale Formation Mechanisms

3.1. Glacial Flow and Ablation

3.1.1. Large-scale cap flow. [40] One possibility is that Chasma Boreale was not formed by sublimation and eolian erosion as has been hypothesized for the polar troughs but rather formed in a constructional manner. The portion of the cap to the south and west of the chasma could have resulted from flow of polar

materials to form a lobe of deposits distinct from the main cap dome, leaving a gap (Chasma Boreale) between the main dome and the lobe. Chasma Boreale ends near the lowest point of the North Polar Basin; thus ice flow from the highest point of the cap (near the rotational pole) would follow this downhill direction. We are aware of no perfect terrestrial analog to such a scenario. The closest example on Earth would be an outlet glacier. Outlet glaciers radiate from ice caps or ice sheets, move rapidly with respect to the main ice sheet [Benn and Evans, 1998], and have a less steep gradient than the main dome [Bentley, 1987]. These features are channelized, mostly surrounded by bedrock, except near their terminus. Their flow characteristics are governed by conditions at the glacier bed such as pressurized water, deforming till, etc. [Benn and Evans, 1998; Alley et al., 1986, 1987a, 1987b, 1987c].

[41] Formation of the chasma in this way would require quite large-scale flow of the cap that at least in the present environment appears unlikely and would not be able to account for the relatively steep slopes of the chasma walls [Zuber et al., 1998]. Maximum estimates of possible flow rates of the northern cap at high obliquity are on the order of meters per year [Fisher, 2000; Pathare and Paige, 2000]. At a flow rate of 5 m/year it would take 1.2×10^5 years to form this lobe, a length of time that is longer than the current estimates of the surface age ($<100 \times 10^3$ years) of the north polar deposits [Herkenhoff and Plaut, 2000]. In addition, the similarity of Chasma Boreale in the north and Chasma Australe in the south (Figure 11) suggests a similar origin and would thus coincidentally require quite similar bed conditions at both poles. Evidence for flow of the south polar materials has been found [Head, 2001] in the form of polar materials extending into a fresh crater, but this may represent only local, small-scale flow. Given the great differences in underlying topography between the two poles [Smith et al., 1999], similarity in bed conditions does not seem probable. In summary, it appears unlikely that Chasma Boreale was formed by flow of polar materials to form a distinct lobe (Table 1).

3.1.2. Accretion model. [42] Fisher [1993, 2000] described a model of polar cap trough evolution that he calls "accretion." This model involves flow on a lesser scale and may explain the presence of large reentrants. In his model the polar troughs migrate toward the pole by sublimation of the sun-facing slope. This ablated material is partly lost to the atmosphere and partly added to the north facing slope of the trough. As the troughs migrate toward the pole, the deeper layers of the cap flow away from the center of flow (e.g., the pole). Depending on where the center or centers of flow are placed, the troughs will in some places diverge and in other places converge. Because the troughs are ablation features, increased ablation occurs where they converge. If Fisher [1993, 2000] chooses two centers of flow, one near the pole and the other on the lobe south of Chasma Boreale, he would thus attain two centers of trough convergence, located at Chasma Boreale and at the nearby, smaller chasmata. Thus increased ablation occurs at the positions of the chasmata, enlarging these features. If he chooses only one center of flow, at the center of the cap, there is no trough convergence, and hence no increased ablation at the location of the chasmata.

[43] The Fisher [1993, 2000] model may predict a current modification process affecting the chasmata and polar troughs but does not readily account for the initiation of chasma formation. To have two centers of flow (the condition necessary to induce increased ablation at the chasmata) requires the previous existence of something similar to Chasma Boreale, albeit in a possibly smaller form. A further test of this model would be a comparison with Chasma Australe. Chasma Australe is a reentrant in the southern cap similar in size and morphology to Chasma Boreale [Tanaka and Scott, 1987; Anguita et al., 2000]. Because these chasmata are so similar in form, it is reasonable to assume that they have formed through similar if not identical processes. Thus, if large chasmata are formed by convergence of troughs in the

Table 1. Major Characteristics of Chasma Boreale and the Smaller Reentrants, Comparison With Polar Troughs, and, Relevance to Possible Formation Mechanisms^a

Characteristic	Polar Troughs	Glacial Flow and Ablation	Katabatic Wind and Sublimation	Meltwater Outflow
		<i>Chasma Boreale</i>		
(1) Largest reentrant in polar cap	much smaller than CB	would require extreme amounts of flow and has not enlarged troughs to size of CB	has not enlarged any other troughs to size of CB	meltwater may have higher initial erosive capacity
(2) Oriented downslope from cap center	no such orientation	consistent	consistent for katabatic winds	consistent
(3) Orientation predicted by Coriolis Effect	oriented opposite to Coriolis	not applicable	consistent	consistent
(4) Deep, enclosed depressions near head	not observed	not applicable	unlikely to erode such deep depressions even with some associated collapse	observed on Earth above point of melting in jökulhlaups and at heads of sapping valleys
(5) Floor has average negative slope	not applicable	not applicable	possible, but not necessary	consistent
(6) Floor has similar elevation to surrounding terrain	not observed	consistent	not likely/ should show gradational slope from top of cap to plains	consistent; flow acts from base
(7) Lobate deposit at mouth	not observed	not applicable	would be more gradational without scarp	consistent; possible delta or alluvial fan deposit
(8) Modified polygons within lobate deposit	not applicable	not applicable	not known to carve braided channels; would not preferentially erode preexisting troughs on flat ground	consistent with drainage of meltwater; forms braided channels and would follow preexisting troughs
(9) Streamlined dune deposits	not applicable	not applicable	streamlined shapes not consistent with wind direction ^b	consistent
(10) Ubiquitous presence of dunes on floor	not observed	not applicable	consistent	consistent; postformation eolian deposition would mask fluvial features
		<i>Smaller Chasmata</i>		
(1) Floors at same elevation as surrounding plains	not observed	nonsistent	not likely; see above	consistent
(2) Streamlined dune deposits	not applicable	not applicable	consistent	consistent
(3) Collapse near head	not observed	not applicable	winds not known to cause collapse; much deeper than that caused by sublimation on southern cap ^c	consistent (see above)
(4) Sinuous channel to west	not applicable	not applicable	inconsistent	consistent
(5) Opposite orientations	not observed	possible	possible (?)	possible

^a CB refers to Chasma Boreale.

^b *Tsoar et al.* [1979].

^c *Thomas et al.* [1992].

manner described by *Fisher* [1993, 2000], there should exist a trough pattern in the southern cap similar to that in the northern cap. Yet spiraling troughs similar to those in the north only exist within the residual ice portion (Api) of the southern cap and not within the exposed layered terrain (Apl), which is where Chasma Australe and other, smaller chasmata are found [*Fishbaugh et al.*, 2000]. Ablational features exist mostly as scarps, not troughs in the exposed southern-layered deposits [*Schenk and Moore*, 2000] and do not spiral as do northern troughs. Thus, while similar reentrants exist in both caps (Chasma Boreale and Chasma Australe), the trough patterns are quite different. *Fisher's* model does not account for the original formation of Chasma Boreale or for the similarities between reentrants in caps with quite different trough patterns. In addition, this model provides no prediction of the expected

morphology of Chasma Boreale. However, this model may illustrate a mechanism of post-formation modification.

3.2. Katabatic Winds

3.2.1. Katabatic winds model. [44] *Howard* [1980, 2000] has suggested that the chasmata were formed gradually, and contemporaneously with, the polar cap troughs by katabatic wind erosion. Katabatic winds are strong glacial winds created by the downglacial movement of cold air from the top of an ice mass to the warmer air below. Effects of these winds grow stronger as they approach the edge of the glacier [*Benn and Evans*, 1998]. *Zuber et al.* [1998] find that the orientation of Chasma Boreale, the steep slopes of the chasma walls and the outlying mesa, and the lack of a monotonically decreasing floor slope suggest that the cap once

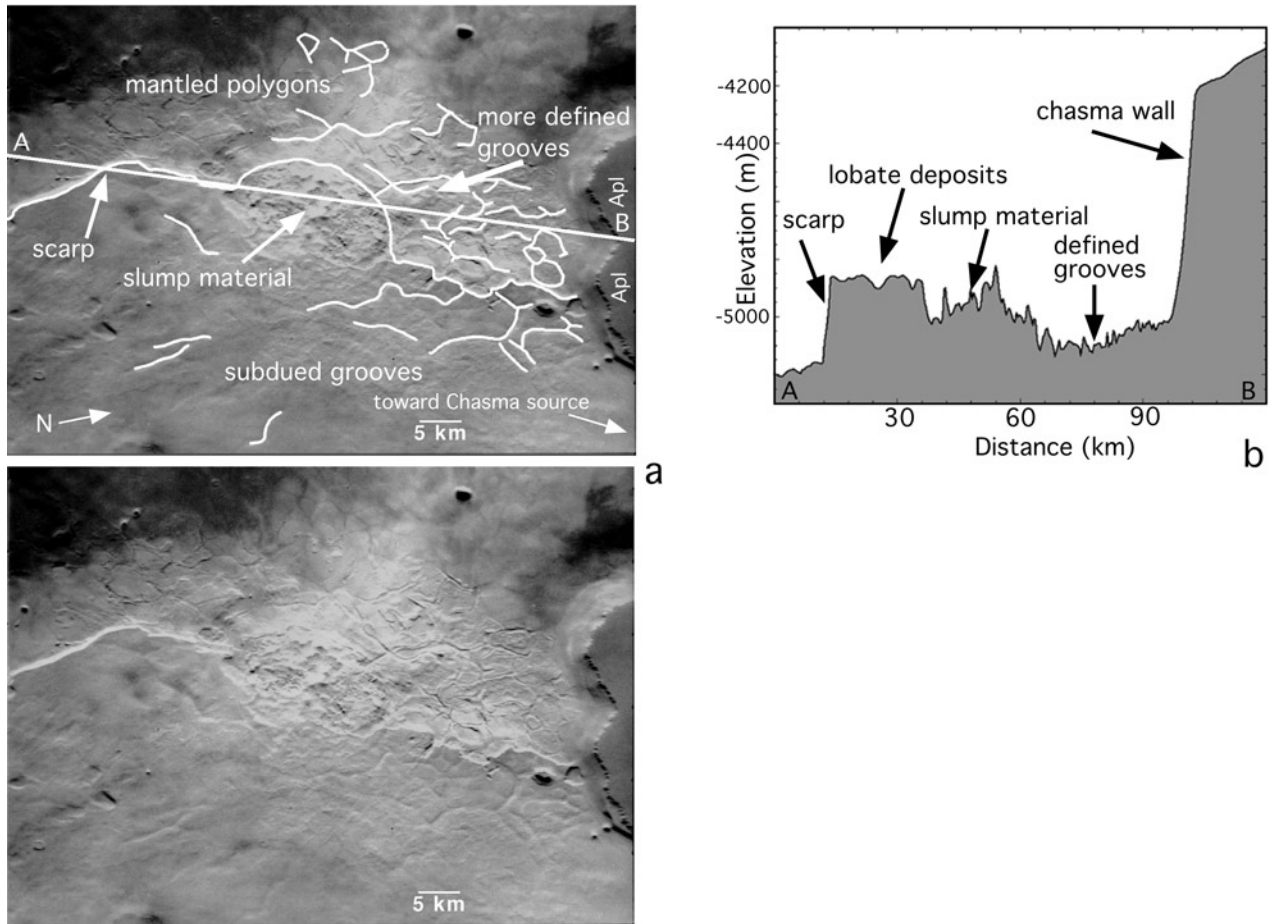


Figure 9. Lobate deposit margin. (a) Viking image 560 B63 (115 m/pixel), which shows the distal end of the southeast facing wall of the chasma, the edge of the scarp at the mouth of the chasma, and the polygons mapped at the chasma mouth. See Figure 3 for orientation of this image with respect to the chasma, but note that the rectilinear projection of this image is different from the polar projection of Figure 3. The scarp visible on the right side of the image is that which curves west from the chasma wall (direction up the chasma indicated by an arrow). A smaller scarp runs southwestward from the chasma wall scarp, becomes gradational in the center of the image, then becomes a scarp again. This scarp divides a region of subdued and more defined polygonal terrain. Material mass wasted from this scarp overlies some of the defined polygons and defines the gradational portion of the scarp. Subdued polygons also lie to the west of the defined polygons. The troughs of these polygons may have been utilized as drainage channels by the late stages of a flood. (b) MOLA profile 255, which shows a profile crossing the Viking image as indicated. Vertical exaggeration is $270\times$. The cap edge has a slope of $\sim 9^\circ$. The polygons form a rough surface at this scale. The profile then slopes upward to a region of material probably slumped from the scarp. The profile then drops off, becoming a scarp with a slope of $\sim 9^\circ$. Below the scarp, the surface is smoother as the MOLA track does not cross any polygons there.

extended out to the mesa and was eroded back by eolian processes, forming Chasma Boreale. The presence of eolian features on the chasma floor such as dunes, the widening of the chasma toward its mouth, the chasma's orientation, and the necessary presence of katabatic winds in association with a large ice mass are all consistent with formation of Chasma Boreale by this mechanism (Table 1). An additional advantage of this mechanism is that katabatic winds most certainly exist, while melting requires a trigger mechanism and a combination of specific circumstances.

3.2.2. Problems with the katabatic winds model. [45] It is likely that katabatic winds have had a large influence on the shaping and erosion of, and morphology of floor features in Chasma Boreale. Yet, on the basis of the new data (Table 1) we consider it unlikely that katabatic winds could have been the singular and dominant formation mechanism for several reasons.

[46] First, Howard [2000] argues that the ability of the wind to transport frost and sediment within polar troughs and to erode the

layered deposits and basement materials favors eolian erosion. Indeed, these observations do support an element of eolian erosion but do they favor formation of Chasma Boreale solely by this process, and do they exclude other processes? While the wind may be able to move frost and dust and erode yardangs and stripped layers into the layered deposits [Howard, 2000], these relatively minor erosional features do not necessarily account for the wind's capacity to erode the entire chasma, including an isolated depression reaching to the cap base (see Figure 6). Could these depressions have been formed by lowering due to wind erosion aided by sublimation? Because wind and sublimation act from the surface, we find localized lowering on such a large scale due to these processes unlikely. Sublimation of overlying ice would also expose the sediment in the layered deposits; this could hinder sublimation if the sediment cover is more than a few centimeters thick [Carr, 1983], halting formation of a depression unless constantly removed. MOC images show that sediment layers visible at

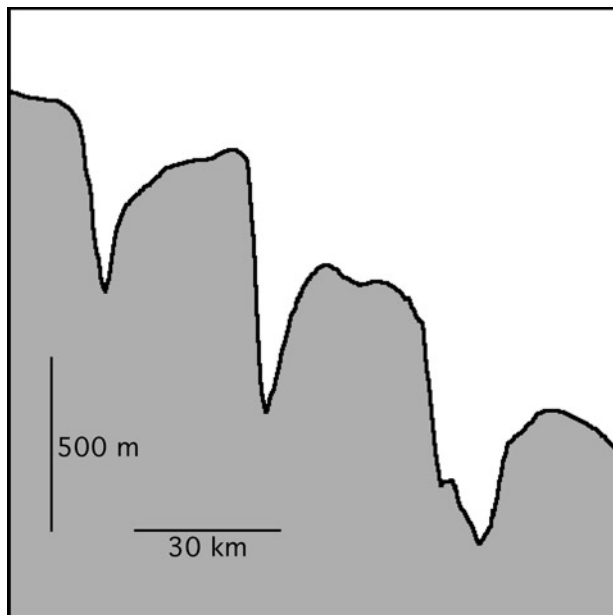


Figure 10. Profile across typical polar cap spiraling troughs. Vertical exaggeration is 73 \times . Location of this profile is shown in Figure 2. Compare to profiles in Figure 5. Note (in contrast to Chasma Boreale) the smaller size, V-shaped profile, smoother smaller-scale topography, differing floor levels between troughs, and floor levels above the surrounding basin.

MOC resolution may be meters thick [Edgett and Malin, 2000]. Collapse due to sublimation of the CO₂ ice on the southern cap has created depressions on the order of only a few meters deep, not hundreds of meters as in the case of Chasma Boreale [Thomas *et al.*, 2000]. There are other processes with a much higher erosional

capacity than wind, such as outflow of meltwater, and this erosional agent acts from the glacial base upward, making it more likely to induce collapse at the base and to enhance large-scale erosion.

[47] Second, Howard [2000] addresses the erosional power of the wind by pointing out that on the Antarctic ice cap, katabatic winds are enhanced in topographic swales and thus that enhancement of katabatic winds could serve to maintain and deepen the chasmata, eroding collected sediment. Katabatic winds are enhanced when a topographic low already exists, and the steeper the gradient, the greater the enhancement of wind. Formation of Chasma Boreale would thus seem to require an initial topographic low, with topographic relief large enough to enhance the katabatic winds, a problem not addressed by Howard. While katabatic winds are enhanced in places on the Antarctic polar cap where topographic swales exist (e.g., Adelie Land) [e.g., Ball, 1957; Kodama *et al.*, 1985], no features similar to Chasma Boreale exist on the Antarctic polar cap. Continued erosion by strong katabatic winds has not produced a chasma.

[48] Third, if the troughs have formed from eolian processes and have undergone the same continued erosion by katabatic winds, then why have other chasmata as large as Chasma Boreale not formed elsewhere on the cap? Is it possible that there has been no mechanism to form a topographic low to initiate concentration of katabatic winds or that katabatic winds do not have the erosive power to create such a large chasma on their own? Perhaps an enclosed topographic low, such as Chasma Boreale, is needed to strongly concentrate the off-cap winds.

[49] Fourth, according to analysis of the dune forms in Viking images, there are two wind directions during the summer (easterly off-pole and westerly on pole), and during the winter and spring, there are only on-pole winds [Isoar *et al.*, 1979]. It is possible that if katabatic winds operated with such efficiency on the north polar cap, then they might disrupt this balance of seasonal winds which has shaped the Olympia sand sea, and they might even remove the expansive ergs. If katabatic winds are removing the sediment and

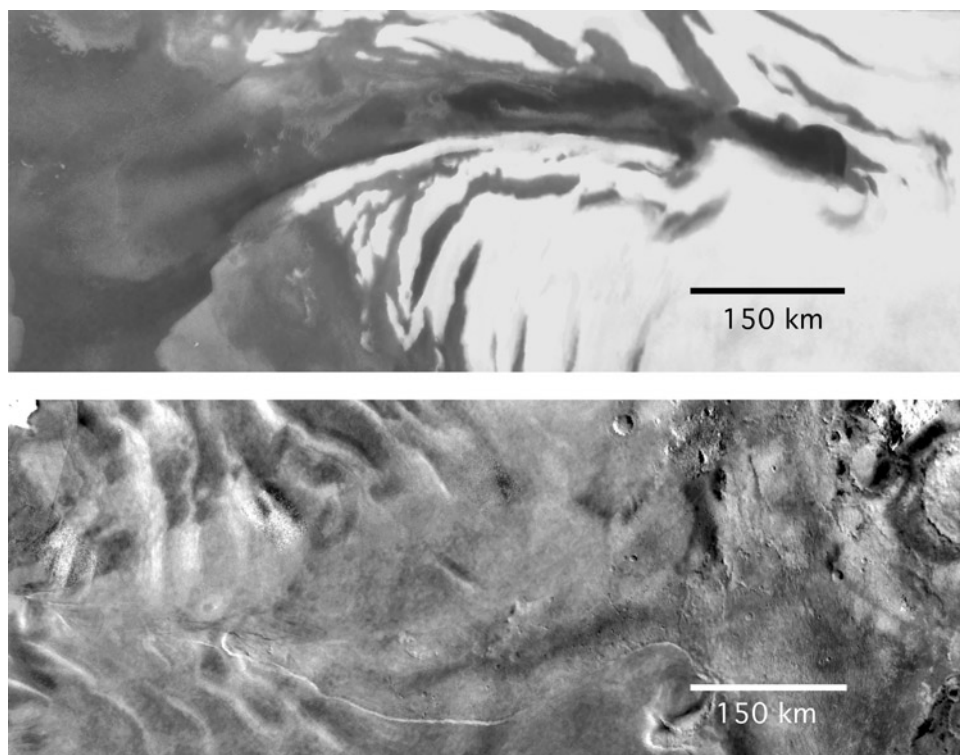


Figure 11. Portions of Viking north and south pole image mosaics showing (top) Chasma Boreale and (bottom) Chasma Australe. Note the morphological similarities of the two chasmata, suggesting similar origins.

ice from the polar deposits to form Chasma Boreale, then why was the bulk of the sediment deposited as a flat, lobate unit with a steep-scarped margin, rather than as an extensive erg, as in the large concentration of dunes in Olympia Planitia? Sediment has since formed into dunes on the floor of the chasma, and dunes probably continue to form today, just as they do in Olympia Planitia [Thomas and Weitz, 1989], as eolian erosion of the layered deposits continues. It seems more likely that katabatic winds strong enough to erode the entire chasma would also disperse the removed sediment. Even if the sediment was deposited in a distinctly localized accumulation by katabatic winds or other eolian forces, then it should have been reworked into dunes by those same forces, just as have the sediment accumulations associated with the outlying cratered mesa and the polar material remnant near the smaller reentrants. The amount of dune material on the floor of Chasma Boreale cannot account for all of the sediment removed from the chasma.

[50] Finally, Howard [1980, 2000] does not address exactly how winds would erode the layered deposits. How does formation of a chasma initiate? How will the shape of the chasma evolve? What features would develop on the floor of the chasma, at its mouth, and in the surrounding plains? One might expect that because wind erosion operates first on the ice cap surface, then there should be a more gradual decrease in slope from the top of the cap to the chasma mouth, without abrupt scarps and depressions, which is not what is observed (see Figure 8). As the winds continue to operate, gradual headward erosion of the chasma should ensue. As explained above, the winds should either have dispersed the removed sediment or reworked it into dunes. Sublimation could aid wind in carving the chasma. However, because sublimation has not enlarged any of the polar troughs to sizes approximating that of Chasma Boreale, sublimation itself does not seem to add an erosive power that is large in relation to wind erosion, and thus does not appear to explain the large size of the chasma. The wall slopes of Chasma Boreale and polar troughs are nearly the same, and thus the insolation on the walls of Chasma Boreale is probably not any larger than that on typical trough walls.

[51] The presence of eolian features, such as dunes and yardangs, associated with Chasma Boreale, and the inevitable presence of katabatic winds in such a chasma points toward wind erosion as having had an influence on the chasma. However, the evidence presented thus far is not sufficient to support katabatic winds as the sole formation mechanism (Table 1).

3.3. Outflow of Meltwater

3.3.1. Outflow model. [52] As discussed previously, outflow of meltwater has also been proposed as a mechanism for carving the chasmata [Clifford, 1987; Benito et al., 1997; Anguita et al., 2000]. If, indeed, these chasmata were formed by outflow or even a jökulhlaup-type event, what types of features should we expect to see associated with Chasma Boreale and how should the morphology of the chasma evolve as it is forming? Jökulhlaups are catastrophic floods emanating from subglacial lakes, meltwater drained from volcanic eruptions beneath a glacier, or from marginal ice-dammed lakes [e.g., Björnsson, 1992]. Since single flood events can show a variety of flood conditions [Maizels, 1989], predicting exactly what features or morphology should result from such a flood is difficult. In addition, since the rushing meltwater can travel great distances beneath the glacier in subglacial tunnels that increase in size with time as the flood level is reaching its maximum value [Blown and Church, 1985], much of the flood activity is hidden from observation. For example, flood waters travel 50 km beneath Vatnajökull from the Grimsvötn lake to Skeidararsandur in Iceland [e.g., Björnsson, 1974, 1975, 1992; Gudmundsson et al., 1995]. There are some telltale signs of past jökulhlaup events that could be observed on aerial photographs (or with orbiter images in the case of Mars). Geothermal heat causes melting, which creates subglacial lakes and

depressions in the glacier surface above these lakes [Björnsson, 1992]. These depressions mark the geographical location of the beginning of the flood. Small reentrants at the edge of glaciers are associated with the ends of some, but not all, jökulhlaup-carved tunnels. Watery debris flows caused by catastrophic outflow often form lobate deposits (depending on sediment load) [Maizels, 1989b; Brennand and Shaw, 1996]. Jökulhlaups drain onto gently sloping outwash plains, commonly called sandurs, which have been built-up by deposition of suspended load and bed load from proglacial drainage rivers. The catastrophic floods can sculpt [Kor and Cowell, 1998] and scour [Shaw et al., 1996] bedrock, add sediment to the sandur [Maizels, 1989a, 1989b, 1993], deposit icebergs that later melt and form kettles [Tómasson, 1996], create drumlins [e.g., Kor and Cowell, 1998; Shaw et al., 1996] carve new channels, and create various flood morphologies [e.g., Shaw et al., 1996; Rains et al., 1993]. As with any stream, the effect of the jökulhlaups on the surrounding plains depends on the severity of the flood itself, on the sediment load, etc. The details of the stratigraphy and sedimentary deposits resulting from a jökulhlaup [Maizels, 1989a, 1989b, 1993] would not be possible to observe on Mars owing to limits in image resolution.

[53] In summary, possible features created by a jökulhlaup that would be visible on Mars given the current data resolution restraints would be the following: (1) collapse above the point of melting in the ice cap (unless the jökulhlaup resulted from drainage of a proglacial lake), (2) evidence of subglacial water drainage (in the form of now exposed subglacial channels, a reentrant, sculpted bedrock, channeled scablands, hummocky terrain, etc.), (3) deposition of sediment in the surrounding plains, in the form a sandur-type deposit, drumlins, and/or debris fan. In the case of the Mars north polar cap, this sediment would come from that contained within the layered deposits and from sediment from the surrounding and subjacent plains entrained within the flood.

[54] It is important to note that meltwater does not always drain in discrete channels, even during jökulhlaups [Björnsson, 1992], but can also be distributed in a film, or cavities, or other means, and then collect at the glacier terminus. Therefore, in relation to point 2 above, evidence of subglacial drainage may not necessarily be straightforward, or even observable. Analysis of past fluvial activity in the Martian north polar cap is further complicated by the fact that, unless this event occurred quite recently, subsequent eolian activity (ubiquitous in the north polar region [e.g., Tsoar et al., 1979; Greeley et al., 1992]) could partially or even wholly mask any remaining evidence of the event. Dunes, in particular, could cover the area, as they have been known to emanate from arcuate scarps in the layered terrain [Thomas and Weitz, 1989]. Even with these limitations, several authors have put forth a jökulhlaup hypothesis for Chasma Boreale, primarily based on candidate fluvial features observed in Viking images.

[55] Clifford [1980a, 1980b, 1993] first proposed that Chasma Boreale and Chasma Australe were possibly formed by a jökulhlaup-type event. He noted the large size of these reentrants and the fact that they crosscut typical polar troughs and are geomorphologically similar to Ravi Vallis [see Clifford, 1993, Figure 15], an outflow channel that has a well-accepted flood origin. Clifford hypothesized that basal melting in the past history of the polar cap was possible and that meltwater could collect within and be catastrophically released from craters beneath the cap, resulting in a jökulhlaup. Heat generated by turbulence and viscous dissipation within the flowing water and by friction between the flowing water and surrounding ice could then serve to enlarge the drainage tunnel, forming a reentrant.

[56] Benito et al. [1997], using the Viking Digital Elevation Model and images, further elaborated on this mechanism and observed many features that they interpreted as having a fluvial origin, such as inner channels, longitudinal grooves and scour marks, and giant current ripples. Such features have since been found, according to MOLA data, to lie above the floor of the

Chasma, and Howard [2000] has suggested alternative eolian origins for these. However, Benito *et al.* [1997] noted other morphologies such as an elongate deposit on the Chasma floor (Figures 3 and 4e), which they interpreted to be a hydrodynamically shaped pendant bar and whose large shape they felt argued for a flood origin. Other authors [e.g., Dial and Dohm, 1994; Tanaka and Scott, 1987; Howard, 2000] interpret this dune-covered deposit to be wholly of eolian origin. However, there does not appear to be any obvious topographic obstacle in the upwind direction of this deposit which would cause deposition of a large lee dune [e.g., Greeley and Iversen, 1985]. In addition, Benito *et al.* [1997] note that postformation eolian sediment has probably masked many possible fluvial features.

[57] Benito *et al.* [1997] also noted that some of the polygonal terrain at the Chasma mouth resembles pro-glacial braided channels formed from drainage of meltwater and that polygonal terrain has been found at the mouths of outflow channels [Lucchitta *et al.*, 1986] and is thought to result from contraction and sediment compaction.

[58] Anguila *et al.* [2000] report on a similar study of Chasma Australe. This reentrant has an arcuate scarp at its head similar to that of Chasma Boreale, and they interpret this scarp to have been formed by headward recession due to outflow of meltwater, noting its similarity to cliffs at the heads of sapping channels on Earth. According to them, there are no known terrestrial eolian processes that form such cliffs. Anguila *et al.* [2000] also found evidence of eddy deposits, pendant accumulation, and back-flooded areas on the chasma floor. According to their estimates, the hydraulic parameters of Chasma Australe are similar to those of outflow channels, and the scale of the flood hydrograph is similar to those for terrestrial jökulhlaups.

[59] We find that many of the topographic data and relationships outlined in previous sections and in Table 1 are broadly consistent with processes that might have involved generation and outflow of meltwater to form Chasma Boreale. We list these reasons here.

1. Chasma Boreale is by far the largest reentrant in the polar cap. The hypotheses of origin with the greatest capacity to create such a feature would be those which act from the base upward and have the highest erosional capacity. Meltwater outflow acts from the base of the cap, and, as stated previously, can erode large amounts of ice through the heat of the meltwater itself and through heat generated by friction and turbulence.

2. The Chasma is oriented downslope from the cap center (Figures 3, 6, and 7). Meltwater collected beneath the cap would on average ultimately flow downslope from the point of melting. Of course, this orientation is also consistent with a glacial flow origin and with katabatic winds. The orientation also follows that of water or wind directed by the Coriolis effect. However, one of the smaller chasmata does not follow this direction (Figures 4a and 8).

3. Chasma Boreale begins at a deep, enclosed depression (Figures 3 and 4c), and the smaller chasmata show evidence of collapse at their head (Figures 3, 4a, and 8). As described earlier, katabatic winds, even aided by sublimation, are unlikely to induce such large-scale collapse. Outflow of meltwater on the other hand, is known to be associated with collapse at the point of melting. In addition, this process acts from the base upwards, rather than from the surface downward as is the case for katabatic winds, so that a depression reaching to the base would be expected.

4. The floor has an average negative slope (Figures 6 and 7). Water would, on average, ultimately follow a negative slope.

5. The floors of both Chasma Boreale and the smaller chasmata have elevations close to that of the surrounding plains (Figures 3 and 6). This is not observed in any polar troughs except those on the extreme periphery of the cap and is not expected (see above discussion) with katabatic wind erosion.

Outflow of meltwater, on the other hand, occurs at the base. Therefore it forms a tunnel, which may later grow into a reentrant, that begins at the base of the polar cap.

6. There are lobate deposits at the mouth of the chasma. We have not found any examples of comparable steep-sided lobate or fan-shaped eolian deposits on Earth or elsewhere on Mars. If katabatic winds slowly carving the chasma were to carry enough sediment to form such lobate deposits, then one would expect more gradually sloping and more dispersed sediments as the wind loses speed relatively slowly, since katabatic winds increase in speed and strength as they flow from the top of the ice. Regardless, we would expect winds to form dunes of these lobate deposits if they were eolian in origin, just as has been formed elsewhere in the north polar region and has been found within the chasma itself. Rather, the origin of these deposits that we favor is one of deposition from meltwater that, when it reached the ice cap terminus and dispersed laterally, unloaded its sediment in a fan. As described above, this behavior has been observed in association with jökulhlaups.

7. Streamlined deposits are associated with the smaller chasmata (Figures 4a and 8) and the mesa beyond the mouth of Chasma Boreale (Figure 4f). While eolian processes may streamline deposits, wind direction maps produced by Tsoar *et al.* [1979] do not show directions consistent with the particular shape of these deposits. Winds have modified these deposits, however, as there are dunes on top of them, and they may have even been deposited by wind. Outflowing meltwater could initially mold these deposits into streamlined shapes.

8. Examination of all available MOC and high-resolution Viking images of Chasma Boreale shows that dunes of all forms are ubiquitous on the floor of Chasma Boreale. No obvious fluvial features were found. As noted by Benito *et al.* [1997], it is likely that eolian depositional features would mask any existing fluvial features.

9. The sinuous channel extending to the west (Figures 4a and 8) from the westernmost chasma seems to require outflow of water. Eolian processes seem highly unlikely to form such sinuosity or such narrow and deep a valley.

[60] In summary, the characteristics discussed above and outlined in Table 1 are interpreted to be most consistent with outflow of meltwater playing a major role in the formation of Chasma Boreale and the smaller chasmata. This mechanism has probably acted in conjunction with katabatic winds and sublimation producing the chasma morphology we see today. However, there are also problems with the outflow hypothesis.

3.3.2. Problems with the outflow model. [61] The size of Chasma Boreale (60 km in width) is obviously much larger than the typical size (tens to hundreds of meters in width and kilometers in length) of channels, tunnels, and reentrants carved by typical terrestrial subglacial melt drainage and outbursts [Maizels, 1989a; Maizels, 1989b; Russell, 1993; Clarke and Matthews, 1981]. Large subglacial sheet floods with widths of at least several hundred kilometers and depths of tens of meters, probably occurred beneath the Laurentide ice sheet [Shaw *et al.*, 1989; Shaw and Gilbert, 1990; Kor *et al.*, 1991; Rains *et al.*, 1993]. The Livingstone Lake flood event may have even stretched ~1600 km from The Northwest Territories, Canada to northern Montana [Rains *et al.*, 1993]. These latter examples are closer in size to Chasma Boreale. The size difference between Chasma Boreale and terrestrial floods may be due to the differing environments between Earth and Mars in one or more of the following ways. (1) Dowdeswell and Siegert [1999], using radar sounding, have estimated a total volume of 4000–12,000 km³ for proposed subglacial lakes beneath the Antarctic ice sheet. The substrate beneath the Mars north polar cap may have an even higher water storage capacity than beneath Antarctica because of the numerous craters that serve as ready-made reservoirs, a point hypothesized by Clifford [1992]. (2) Successive flows may have followed the weakness already created by the

presence of the chasma, enlarging it with each flow. (3) The timescale of orbital parameters that might cause polar cap evolution and recycling is much shorter on Earth than on Mars [e.g., *Thomas et al.*, 1992] so that the chasma is probably older than any terrestrial jökulhlaup feature and may have been enlarged by sublimation and other processes since its formation. (4) The trigger mechanism that began this flow, such as a subglacial volcanic eruption, may have been much larger in magnitude than any terrestrial trigger mechanism.

[62] In favoring formation by katabatic winds, *Howard* [2000] outlines three main problems with an origin by outflow of meltwater for Chasma Boreale. First, Howard has proposed alternative eolian origins for the glaciofluvial features described by *Benito et al.* [1997]. With the acquisition of MOLA data, it has become apparent that many of these actually lie at elevations above the chasma floor, decreasing the likelihood of a glaciofluvial origin. However, these particular features are not the sole evidence for an outflow origin, and because winds have modified and continue to act within the chasma since its formation, one might expect that eolian deposits would mask many existent fluvial features on the floor.

[63] We have examined over 150 MOC images of Chasma Boreale. Figure 12 shows four examples of MOC images from within the chasma. These images exhibit a variety of eolian features and frost patterns that could easily obscure any primary features that might be beneath them. In all of the images examined, the most easily identifiable features were many dune forms and frost. Figure 12d shows an image from within the lobate deposits, and it contains depressions of unknown origin. These depressions do not appear to be degraded impact craters as they have no evidence of raised rims, and some of them are irregular in shape.

[64] MOC and Viking images of the smaller reentrants exhibit less evidence of eolian activity on their floors. Figure 13 shows an image of the floor of the eastern small chasma (Figure 13a), an image of the collapse region in the polar deposits at the head of these chasmata (Figure 13b), and an image of the floor of the sinuous channel extending from the westernmost small chasma (Figure 13c). The floor of the small chasma (Figure 13a) exhibits linear groove patterns and pits, not of an obvious eolian or fluvial origin, that are similar to those formed by postchannel formation processes in fretted terrain [*Lucchitta*, 1984; *McGill*, 2000; *Carr*, 2001]. Linear ridges parallel to the polar deposit wall also lie within the sinuous channel, while a small valley and hummocky terrain lie further from the wall, at the bottom of the image (Figure 13b). This small valley could be of a fluvial origin. The collapse region in the layered deposits at the head of the small chasma (Figure 13c) exhibits erosion of the surface of the cap.

[65] Second, the floor is not level and does not gradually slope downward toward the surrounding plain (Figures 3 and 6), a problem also noted by *Zuber et al.* [1998]. While this observation is correct, under hydraulic pressure from overlying ice, water is not constrained to follow only a negative slope, and indeed, most terrestrial jökulhlaup drainage occurs within subglacial tunnels [e.g., *Björnsson*, 1992]. At least some of this nonlevel floor topography could readily be due to subsidence from subsurface melting and collapse of the surface, and/or to later modification by katabatic winds. In addition, although there is irregular topography, the floor of the chasma is distinctly different than that of the cap and much more clearly related to the topographic level of the terrain surrounding the cap (Figure 6).

[66] Third, Howard notes that if the arcuate scarp at the head of Chasma Boreale were formed by fluvial erosion, then the flood must have passed beneath the bridge of layered deposits between the two enclosed depressions, or this bridge of layered deposits must have been formed after the flood occurred. We do not feel that these observations preclude formation by outflow. The bridge of layered deposits could have formed by ice flow after the carving of Chasma Boreale. Alternatively, water could have passed beneath

such a bridge. Glaciers and ice sheets often hide complex drainage networks beneath them, and jökulhlaup flood waters often travel great distances from the point of trigger beneath the glacier before outbreak at the terminus [e.g., *Björnsson*, 1992; *Thorarinsson*, 1953, 1956].

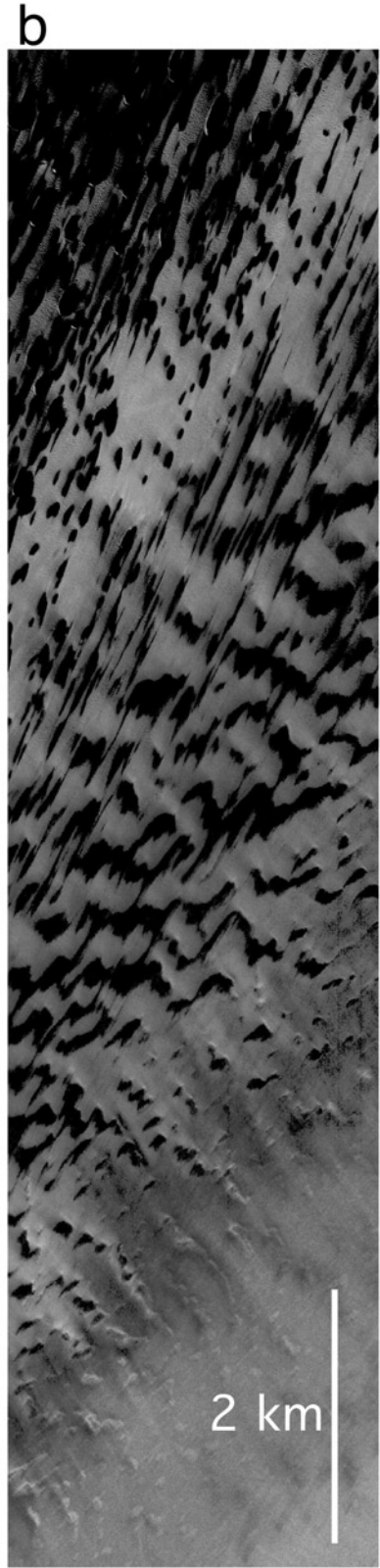
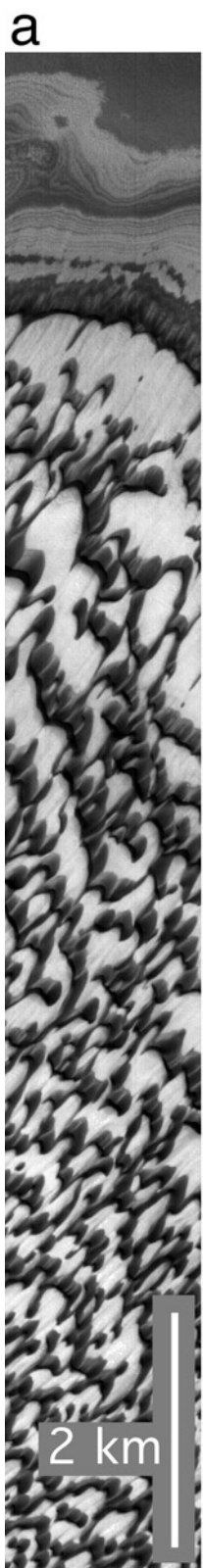
[67] *Howard*, 2000, [p. 284] states that “The wind erosion hypothesis... is economical in the sense that it involves only processes that are observed to operate under present conditions.” While true, katabatic wind erosion does not appear to form such structures on Earth today, and recent studies have shown evidence for meltwater features on Mars in the recent geologic past [e.g., *Malin and Edgett*, 2000]. Furthermore, large-scale climate change and geologic evolution have occurred throughout the geologic history of Mars. For example, while outflow channels are not being formed today, abundant evidence points toward the fact that they were carved by water in past history, some of them during the Amazonian Period [*Carr*, 1996; *Head and Wilson*, 2002]. In addition, large-scale meltwater formation and drainage has been documented around the south pole in the Dorsa Argentea Formation [*Head and Pratt*, 2001] and near the Prometheus Basin [*Head et al.*, 2001]. Candidates also exist for subglacial volcanic eruptions, melting, and drainage [e.g., *Ghatan and Head*, 2001; *Head and Wilson*, 2002]. In summary, the major problems with the outflow hypothesis as outlined by Howard do not individually or collectively refute a role for outflow.

[68] Finally, we are left with the question of what could have caused melting and triggered outflow. Possibilities include the following: (1) much thicker caps, (2) climate change, (3) obliquity change, (4) subcap volcanic eruptions, (5) the presence of a groundwater mound that reaches the cap base [*Clifford*, 1993], (6) frictional melting due to cap movement, (7) higher geothermal heat gradient in the past, (8) inclusion of dust, salts, clathrates, etc., to modify the melting point, and (9) polar wander. In section 3.3.3 we outline a plausible scenario (Table 1) for forming Chasma Boreale primarily by outflow processes.

3.3.3. A revised meltwater outflow formation scenario. [69] On the basis of the observations outlined in this paper for Chasma Boreale (Table 1), we outline the following scenario (Figures 14 and 15) as our favored hypothesis. Melting of the polar cap initially built up a reservoir or reservoirs of meltwater below the cap. That melting has taken place relatively recently geologically is supported by other evidence for north polar cap retreat in the form of distal kame and kettle topography [*Fishbaugh et al.*, 2001], candidate polar ice outliers [*Fishbaugh and Head*, 2000], and significant decrease in height and volume of the Olympia Lobe at 180°W [*Fishbaugh and Head*, 2000, 2001]. *Brennand and Shaw* [1996] have hypothesized that where meltwater flow lines converge, a surface trough is formed in the ice; since meltwater will flow toward this trough, the trough outlines the direction of meltwater flow. Such a process on Mars could have initiated the formation of a reentrant, Chasma Boreale.

[70] Following meltwater buildup, flow began, inducing subsequent collapse and melting of the polar materials and forming the depression. Note that, as discussed above, the meltwater need not have come only from the volume occupied by the depression. Water then continued to tunnel through or below the ice. The water followed the hydraulic gradient but ultimately flowed down the regional slope toward the North Polar Basin. In this scenario, the fact that the floor of Chasma Boreale does not slope continuously downward does not preclude a meltwater origin. *Brennand and Shaw* [1996] note that the Harricana glaciofluvial complex in Quebec is narrow near its source (the northern end) and wider at its southern end (similar to Chasma Boreale) and slopes upward toward the south. This complex is thought to have been formed from confined meltwater flowing beneath an ice cap that thinned toward the south, similar to the north polar cap on Mars.

[71] Most of the sediment and ice was deposited in a lobate structure at the chasma mouth. The flood also scoured the



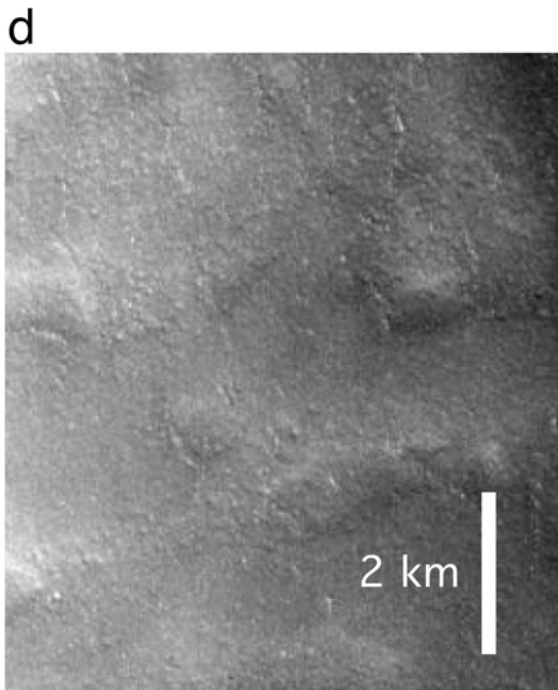


Figure 12. (continued)

surrounding plains, partially removing any eolian mantle, exposing polygonal plains, and depositing and sculpting the streamlined deposits near the outlying mesa.

[72] During the waning stages of the flow (Figure 15) we hypothesize that the water followed the lowest floor topography, eroding the eastern side of the lobate fan, and draining over the delta-like structure via the preexisting, subdued Hvg grooves. This drainage deepened these grooves, creating fluvial valleys that cross the slump feature and continued to utilize preexisting grooves at the base of the slump.

[73] Using an estimated chasma volume and layered deposits sediment content of 40%, we estimate that if the sediments carried by the flow were spread out over the area of the North Polar Basin below an elevation of -5000 m (just below the lobate deposits), they would constitute a layer less than 20 m thick. Of course, the sediments may not have been completely spread out over this area. The streamlined dune field between the lobate scarp and the cratered mesa may consist of sediment deposited by this outflow and later modified by eolian activity. On the basis of the estimated sediment content, the volume of the floor deposits and lobate deposits together account for approximately less than 2% of the volume of sediment missing from the chasma.

[74] On the basis of the characteristics outlined above and the morphologic similarity to Chasma Boreale, we believe that similar, but smaller flows carved the chasmata to the west. At the head of these chasmata is a collapse feature, similar to the depression at the head of Chasma Boreale, suggesting that the flow caused erosion and collapse of the overlying materials at this point. An obstruction (possibly a crater) or variations in hydraulic and/or topographic gradient caused the outflow to bifurcate, forming two diverging chasmata. Both chasmata open in a downhill direction. We hypothesize that due to the heat of the meltwater and the heat generated by turbulence and friction, the polar deposits were melted, and collapsed, creating these chasmata. Sublimation and eolian erosion have since enlarged and modified the reentrants.

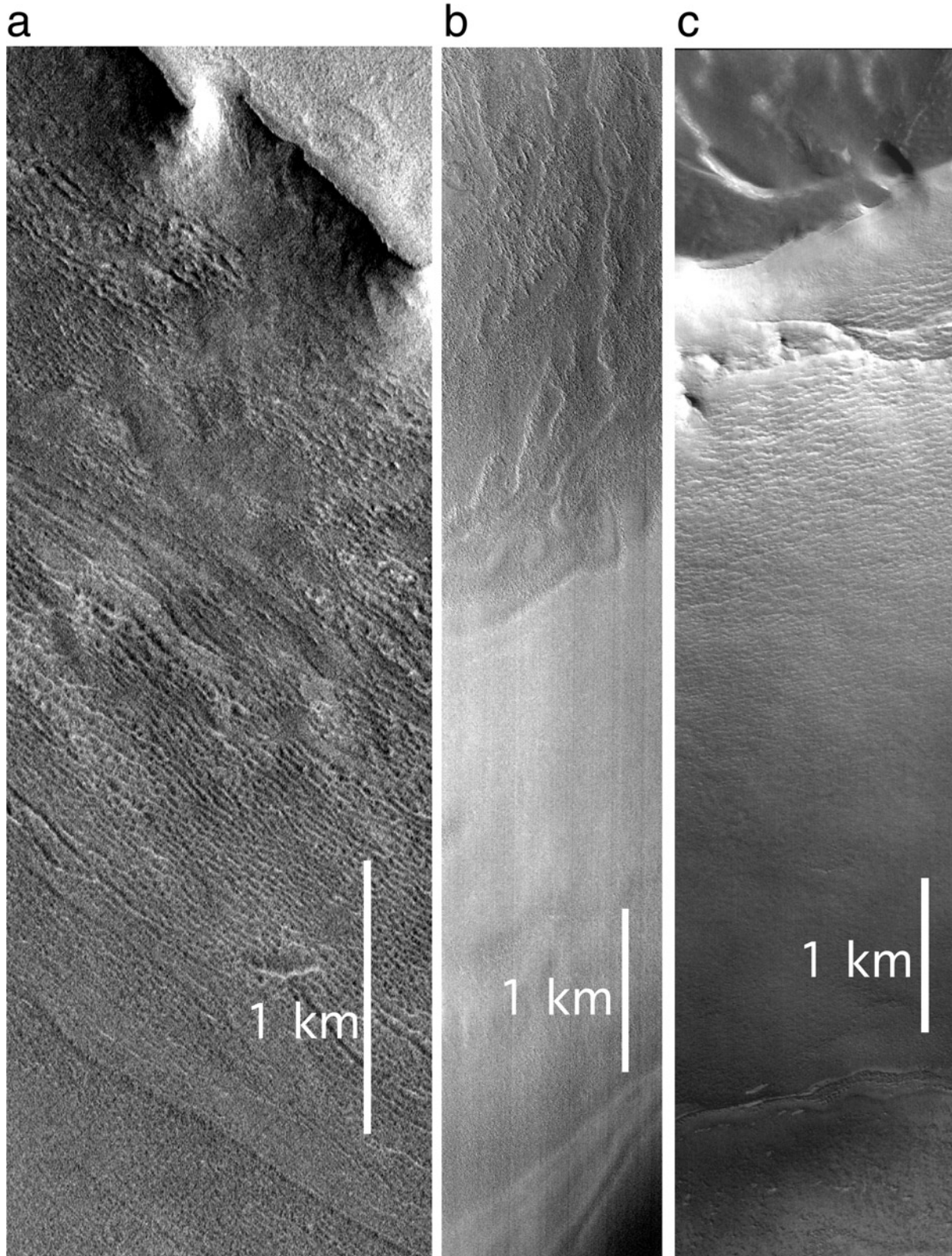
[75] One of the chasmata exhibits streamlined features near its mouth that may have been deposited and shaped by the outflow (Figures 4a and 8). The lack of such deposits at the mouth of the other reentrant could be due to the fact that either this flow was less sediment-rich or that this flow happened after that which formed Chasma Boreale. In the latter case, the flow from Chasma Boreale may have dispersed any sediment at the mouth of the smaller reentrant.

[76] Emanating from this same chasma along the cap edge is a sinuous channel (Figure 8), which we interpret to be carved during the late stages of outflow from the small chasmata by relatively slow moving meltwater. While the elevation along the channel increases in a direction away from the chasmata, this could be due to deposition of sediment during flow or to eolian deposition afterward. Alternatively, the water, if flowing beneath ice, could have been following the local hydraulic gradient.

[77] The formation of these chasmata left a remnant of the polar cap that contains spiraling troughs whose direction of spiral matches that of the main cap troughs but is tighter. They do not line up with any troughs on the main cap and thus do not appear to be troughs cut off by formation of the chasmata. Just as in the case of Chasma Boreale, these troughs seem to have been formed after the chasmata.

[78] Collapse above the subglacial tunnels created by the outflow could have contributed to the current manifestation of the chasmata. In addition, subsequent sublimation could be responsible for modifying the westward facing wall of Chasma Boreale to form a shallower slope than the eastern wall. The sublimation process could also further enlarge the chasma. Additional enlargement, shaping, and deposition would be contributed by eolian processes, as attested to by the presence of various duneforms throughout the length of the chasma (Figure 12). In particular, katabatic winds [Howard, 1980, 2000], created by the colder air above the ice cap flowing to the lower reentrants, must have subsequently played a role in shaping the chasma and in creating eolian erosional forms within the layered deposits themselves. Eolian activity has also clearly modified the smaller valleys subsequent to their formation. Several impact craters appear to be undergoing burial or exhumation (Figure 8).

Figure 12. (opposite) Example MOC images of Chasma Boreale showing a variety of eolian features and frost. (a) Part of MOC image M02-02805 (9.72 m/pixel), centered at 1.89°W , 84.63°N within the depression at the head of Chasma Boreale. Illumination is from the top right-hand corner of the image. Part of the arcuate scarp in the layered deposits is visible at the top of the image and shows complex layering. Extending from the base of this scarp to the bottom of the picture are dunes (mostly barchan) and interdune frost. Wind direction indicated by these dunes is down from the scarp toward the lower left-hand corner of the image. (b) Image M00-02149 (3.23 m/pixel), centered at 30.70°W , 84.12°N below the scarp of the second depression down-chasma from the chasma head. Illumination is from the upper right-hand corner. Complex dune forms and streaks fill this image. (c) Part of image M02-00815 (4.84 m/pixel), centered at 46.45°W , 83.28°N in the middle reaches of the chasma. Illumination is from the bottom left. Dark material, possibly dune material, fills shallow, linear grooves. Also visible are streaks within the frost, some of which crosscut the direction of the grooves and other streaks, indicating changing wind direction. The dark material in the lower left-hand corner fills a depression, possibly a crater. (d) Part of image M18-00816 (12.06 m/pix), centered at 51.26°W , 80.38°N within the lobate deposits at the mouth of Chasma Boreale. Illumination is from the bottom and shows some depressions of unknown origin that do not readily appear to be degraded craters. There are no obvious eolian features visible in this portion of the image, but other parts of the image do show scattered dunes.



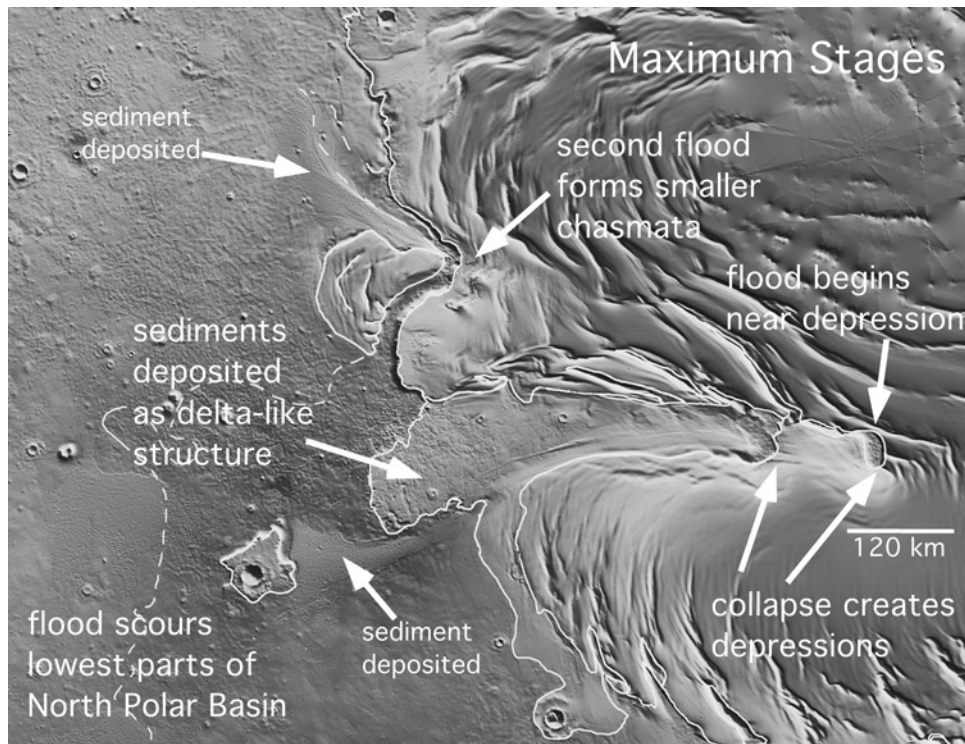


Figure 14. Outflow scenario, maximum stages. Grey-scale version of the topographic map in Figure 3, annotated to show the interpreted maximum flow stages during the formation of Chasma Boreale by outflow of meltwater.

[79] Using the new MOLA data and MOC and Viking imagery, we have characterized the topography of Chasma Boreale, furthering work done with Viking images and earlier topographic data by previous workers [e.g., Howard, 1980, 2000; Howard *et al.*, 1982; Clifford, 1993; Benito *et al.*, 1997]. We find that the data best support a significant role for meltwater outflow in the origin of Chasma Boreale and nearby, smaller reentrants (Table 1). Katabatic winds, eolian processes, and sublimation have certainly modified the chasmata and helped to give them their current form.

4. Outstanding Questions

[80] We have outlined a scenario for the history of these chasmata on the basis of the new data, but several outstanding issues remain. The relative roles of outflow, katabatic winds, and sublimation need to be quantified. Models of each process need to address their erosive power, the expected morphology of the features they produce, and under what climatic conditions they best operate. New, high-resolution quantitative data from MOLA should greatly assist in addressing these issues. Benito *et al.* [1997] and Anguita *et al.* [2000] have used Viking elevation data to

estimate discharge values for outflow through Chasma Boreale and Chasma Australe, respectively. Using Manning's equation modified for Mars conditions [Komar, 1979], Benito *et al.* [1997] estimated a discharge rate for Chasma Boreale of $1 \text{ km}^3 \text{ s}^{-1}$, comparable to Kasei and Ares Vallis [Robinson and Tanaka, 1990; Komatsu and Baker, 1997], and thus concluded that the formation of Chasma Boreale included a catastrophic flood. This discharge rate is much higher than terrestrial jökulhlaup discharge rates, such as for Grímsvötn in Iceland [Rist, 1973; Björnsson, 1992; Tómasson *et al.*, 1980; Nye, 1976; Spring and Hutter, 1981; Clarke, 1982; Fowler and Ng, 1996]. An alternative method of calculating the peak discharge, using more accurate topographic data than that available to Benito *et al.* [1997], would be to use the slope-area method used to estimate peak terrestrial jökulhlaup discharges [Benn and Evans, 1998]. This latter method may be preferred, as outflow in Chasma Boreale likely occurred beneath the ice, not in a subaerial stream. However, we currently have no means to determine the dimensions of the chasma (or tunnel through the ice) at the time of outflow because of non-flow-related modification of the reentrant (collapse, sublimation, eolian/katabatic wind erosion). We have seen hints of small terraces in the walls using MOLA data

Figure 13. MOC images in the region of the smaller reentrants (see Figure 8). (a) Part of image SP02-50604 (2.69 m/pixel), centered at 70.47°W , 81.54°N on the floor of the small reentrant closest to Chasma Boreale. Illumination direction is from the bottom right-hand corner of the image. The edge of the polar-layered deposits is visible in the top of the image. The floor shows nearly linear pits and grooves and some slight depressions near the middle of the image. There are no obvious fluvial or eolian features. Compare this image to the dune-covered images of Chasma Boreale shown in Figure 12. These linear ridges and troughs are very similar to the lineated valley fill seen in fretted channels [e.g., Lucchitta, 1984, Figure 2a; McGill, 2000, Figure 6; Carr, 2001, Figure 12], which was interpreted to be postchannel formation, late-stage, slope-related modification of ice-rich debris which has since undergone sublimation. (b) Part of image SP2-52306 (2.81 m/pixel), centered at 75.78°W , 82.93°N near the head of the smaller chasmata. Illumination is from the left. Image lies within potential collapse region within the polar cap at the head of the smaller chasmata. Erosional patterns are visible within the polar deposits at the top of the image. (c) Part of image M02-03427 (3.23 m/pixel), centered at 96.41°W , 81.32°N on the floor of the sinuous valley extending from the westernmost chasma. Illumination is from the bottom of the image. The edge of the polar cap is visible at the top. Almost linear ridges lie parallel to the base of the polar cap but disappear toward the middle of the image. Near the bottom, lies a small, possibly fluvial, valley and hummocky terrain.

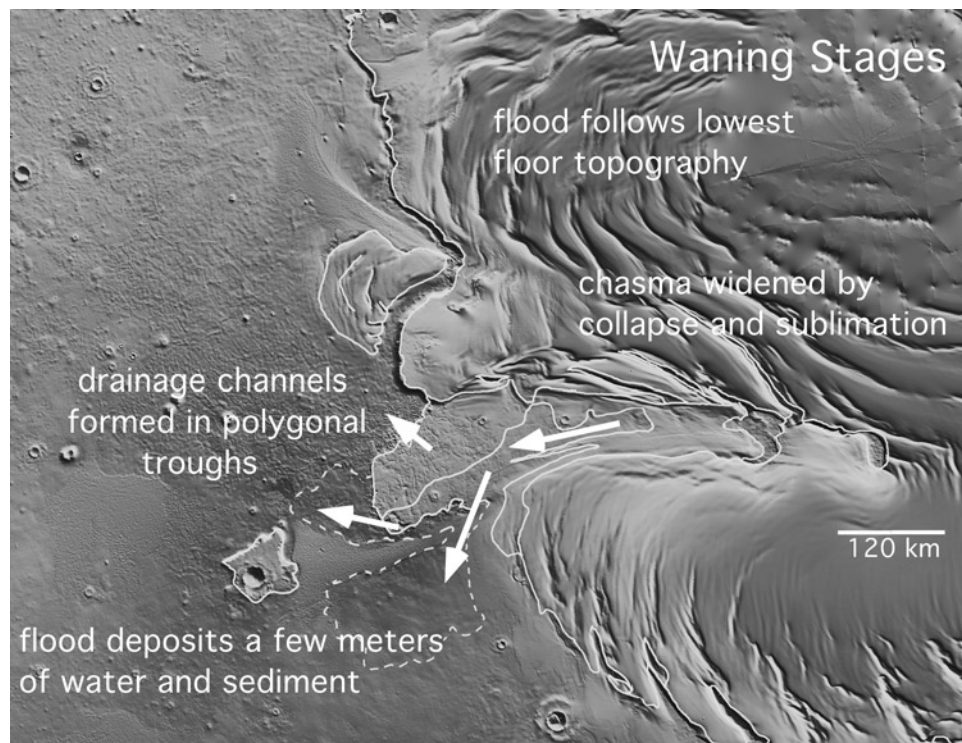


Figure 15. Outflow scenario, minimum stages. Grey-scale version of the topographic map in Figure 3, annotated to show the interpreted waning flow stages during the formation of Chasma Boreale by outflow of meltwater.

(but none using MOC or Viking images) which might indicate flow levels, but they are not consistent along the walls or across the chasma. Hydraulic parameters of terrestrial jökulhlaups are measured in the field, and even then uncertainties are incurred because of the inability to directly measure tunnel size beneath the ice. Therefore, any calculations of discharge rate using the current chasma dimensions would be greatly overestimated. Thus it is uncertain whether or not this flow was catastrophic.

[81] Determining whether or not the flow was catastrophic and how much meltwater could have been released would be aided by having a better understanding of the triggering mechanism. We have outlined a range of possible causes of melting. The contributions of each of those mechanisms and the likelihood of their occurrence need to be quantified, even if only in a relative sense. The possibility of volcanic eruption beneath the ice is receiving more attention due to the findings by *Garvin et al.* [2000a, 2000b] and *Sakimoto et al.* [2001] of possible young volcanoes on the floor of Chasma Boreale and near its mouth.

[82] If the polar caps contain a significant amount of CO₂ clathrate admixed with water ice [*Jakosky et al.*, 1995; *Hoffman*, 2000], then because CO₂ clathrate has a lower thermal conductivity and is stable under higher pressures than pure water ice, the cap would not melt as readily as it would if composed of pure water ice. Thus, obtaining an accurate estimate of the amount of CO₂ clathrate in the layered deposits would help constrain the conditions necessary for melting the deposits. *Mellon* [1996] studied the phase stability of CO₂-bearing ices under Martian heat flow and surface temperature conditions and found that the polar deposits probably contain relatively small amounts of CO₂ (less than a few tens of mbars). If, however, the polar deposits do contain a significant amount of CO₂ clathrate, this would affect the behavior of the melted polar material. Under constant pressure but increasing temperature beneath the cap, melted CO₂ clathrate would consist of liquid CO₂ (which is soluble in water at cold temperatures and high pressures), liquid water and excess, gaseous CO₂ [*Hoffman*, 2000]. This is likely to be the state of the melted

clathrate when still beneath the cap. When this melt mixture reaches the cap periphery, and pressure is therefore greatly reduced, the water would readily freeze and CO₂ would now be nearly completely insoluble, leaving unstable pockets of CO₂ gas within the ice which would be likely to burst [*Hoffman*, 2000]. Future studies should include a search for possible signs of explosive activity at the periphery of the cap near Chasma Boreale, such as pits formed from blow out of unstable CO₂ gas.

[83] Also important is the understanding of the distribution and volume capacity of meltwater storage beneath the polar cap. These parameters are needed to assess how much water can be built up before release and how catastrophic such a release might be. For example, loading and flexure beneath the cap may create a large depression capable of significant meltwater storage. Interpretation of sub-basal topography based upon MOLA data [*Johnson et al.*, 2000] and MGS gravity [*Smith et al.*, 1999] and magnetic data [*Hood and Zakharian*, 2001] will contribute to this understanding.

[84] It is crucial to link the history of these chasmata with the history of the entire north polar region. Is it possible that the formation of Chasma Boreale may have taken place during the time in which the north polar cap appears to have undergone major retreat in the 180°W direction? *Fishbaugh and Head* [2000] have interpreted the convex topography of Olympia Planitia (Figure 14) as a dune-covered extension of the north polar cap (the Olympia Lobe). Recessional features such as polar material remnants, kettles, and kame-and-kettle terrain lie just to the south of Olympia Planitia and are characterized by rough topography and irregular depressions [*Fishbaugh and Head*, 2001]. Together, these features are interpreted to represent a former extent of the north polar cap that has undergone subsequent retreat. The topographic and geographic relationships of the recessional features, Olympia Planitia, the cap, the chasmata, and the North Polar Basin are illustrated in Figure 16. In Figure 16, all elevations below -4900 m are black, showing the topographic relationships of the lowest elevations of the recessional features (black, top), chasmata, and the North Polar Basin (purple and black). The mouths and floors of the three chasmata and the

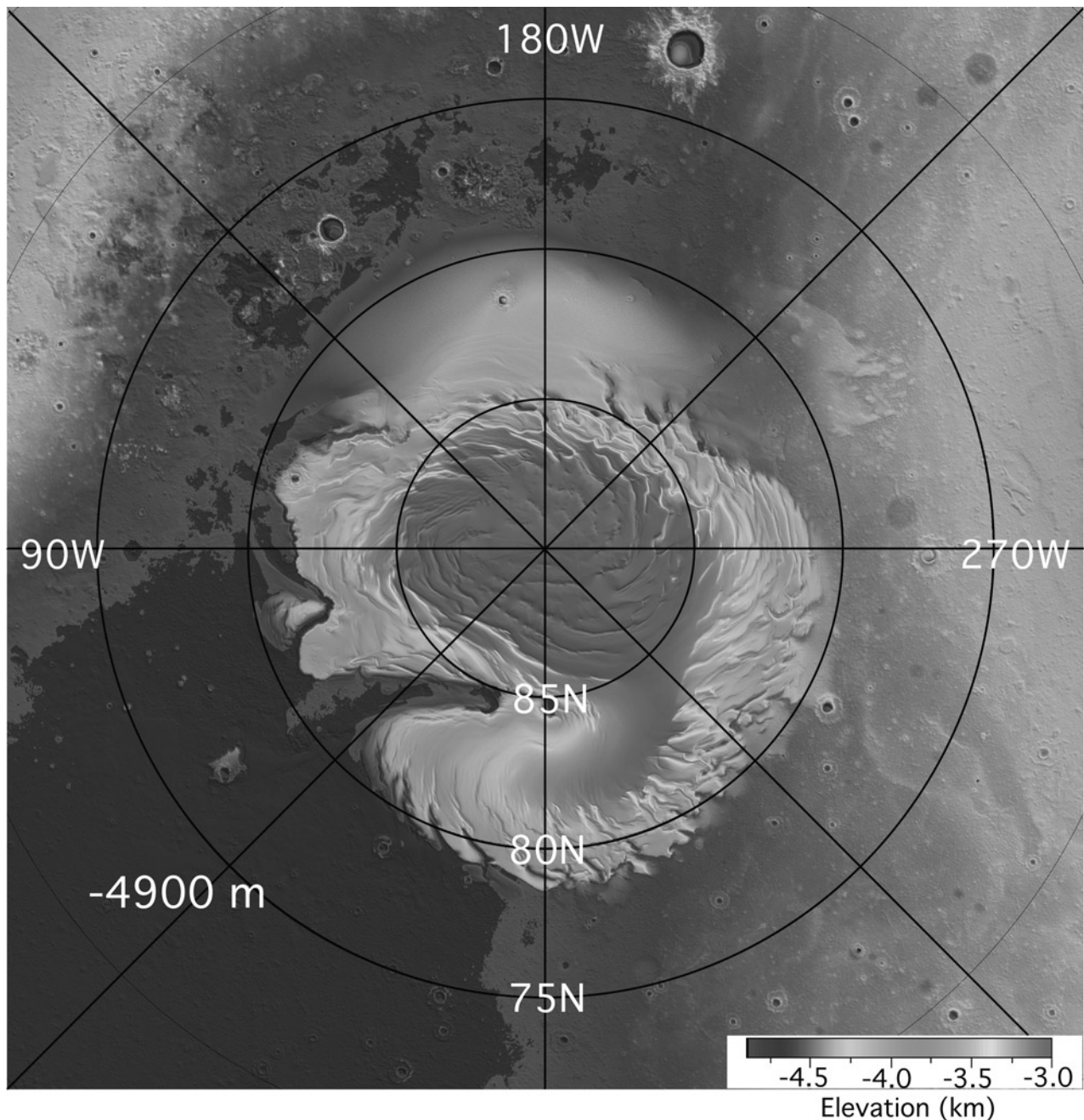


Figure 16. Topographic map of north polar region extending out to 72°N and ranging from -4900 m to -3000 m . All elevations below -4900 m are black. The North Polar Basin is the purple and black region toward the bottom and the left. Olympia Planitia is the bluish-green positive lobe extending from the cap toward 180°W . The interpreted recessional features (polar remnants, and kame and kettle terrain) lie in the arc of rough topography distal and concentric to Olympia Planitia. See color version of this figure at back of this issue.

recessional features distal to the Olympia Lobe are all at essentially the same elevation ($\sim -4900\text{ m}$). In addition, chasmata, kettles, and kame-and-kettle topography are all interpreted to involve melting of polar deposits. The observations suggest to us that the formation of these features could have occurred during a widespread period of melting of a formerly larger polar cap, with sediment-laden melt-water draining to similar, lower elevations.

[85] Examination of the troughs near Chasma Boreale and Olympia Planitia may help to elucidate the relative timing relationships between Chasma Boreale and the retreat of the polar cap

from 180°W . Polar troughs near Chasma Boreale curve in toward the chasma and therefore must have “felt” the presence of the Chasma as they were forming. This observation suggests, as pointed out by *Thomas et al.* [1992], that at least the polar troughs near Chasma Boreale are younger than the Chasma itself. MOLA topography (Figure 17) and the Viking mosaic (Figure 1) show a few troughs extending into the Olympia Lobe. The bottoms of the part of the troughs within the Olympia Lobe are deeper than the bottoms of any of the troughs within the main cap. Therefore it is unlikely that troughs extended into the Olympia Lobe when it was

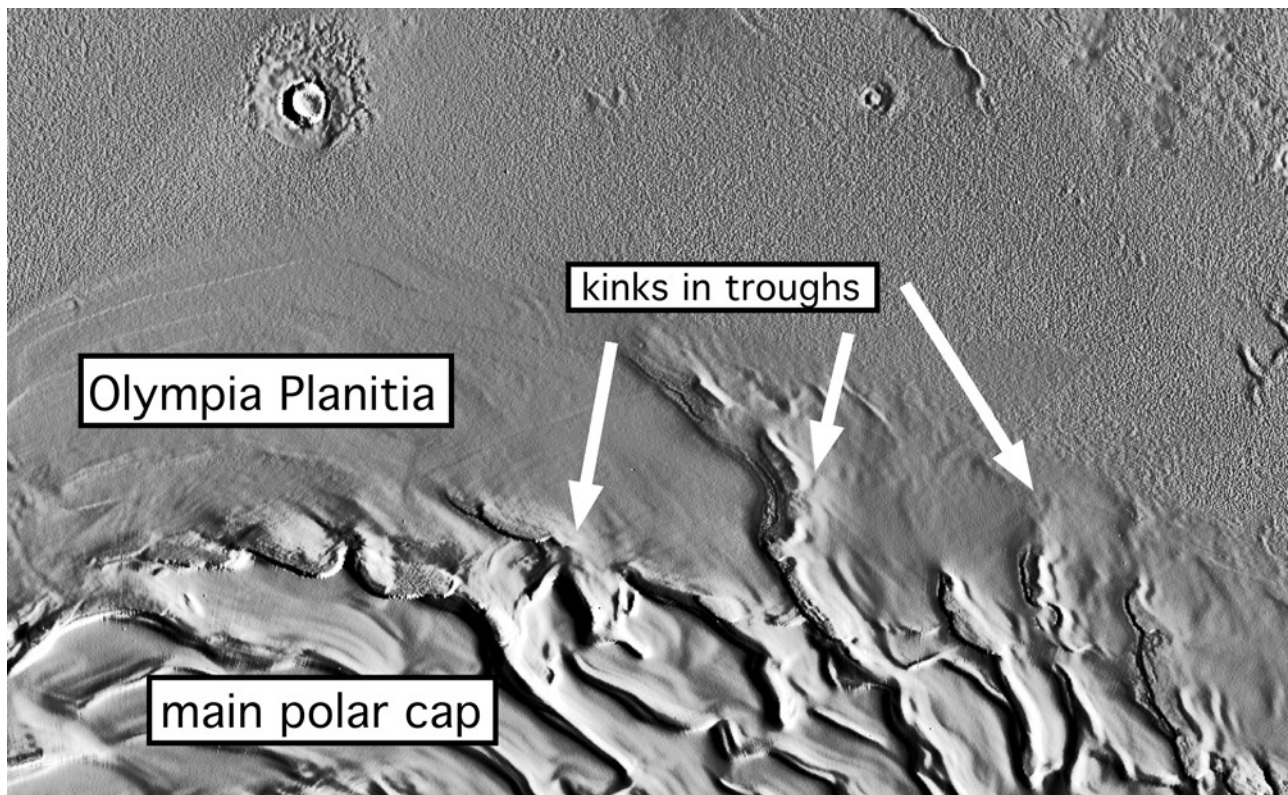


Figure 17. Topographic shaded relief map, using gridded MOLA data at a resolution of 200 pixel/deg, of polar troughs extending into Olympia Planitia, an extension of the polar cap which has undergone partial retreat and is now covered by dunes [Fishbaugh and Head, 2000]. The edge of the main cap is at the bottom of the image. Some polar troughs extend from the cap into Olympia Planitia and exhibit kinks in their structure. The fine-scale textures within Olympia Planitia are dunes.

level with the main cap, followed by the Olympia Lobe retreat and preservation of the remnants of those troughs. If this scenario were the case, the troughs should have had much shallower floors. We believe that it is more likely that these troughs extended part way into a previously retreated Olympia Lobe. In this case, they have such deep floors, because they were formed in a lobe that has a surface lower than that of the main cap.

[86] This may also account for the fact that they have a kink along their length at about the point where they enter the Olympia Lobe from the main cap. If their spiral nature is due to cap flow, as suggested by Fisher [2000] and described above, then the flow may be somewhat different in the main part of the cap than in the Olympia Lobe. The fact that there are few troughs that do extend from the main cap into the Olympia Lobe and that these troughs do not extend very far into the Olympia Lobe could be explained by the presence of the dune cover. This dune cover would inhibit sublimation of the ice, a major mechanism in creating these troughs [Howard *et al.*, 1982; Fisher, 2000].

[87] Thus, according to these observations, we speculate that the troughs near Chasma Boreale are younger than the chasma, and the troughs near and within the Olympia Lobe are younger than the retreat event that decreased the size of the lobe. If one assumes that all the troughs are the same age, then Chasma Boreale and the cap retreat event are both older than the troughs. This implies that the formation of Chasma Boreale was not the most recent event to affect the polar cap. We are continuing to investigate additional means to determine the relative dates between formation of the cap, the troughs and Chasma Boreale, and the retreat of the cap itself. The similarities between Chasma Boreale and south polar reentrants suggest that they have a genetic connection, and we are

currently exploring similarities and differences in the histories of the two polar regions [e.g., Fishbaugh and Head, 2001].

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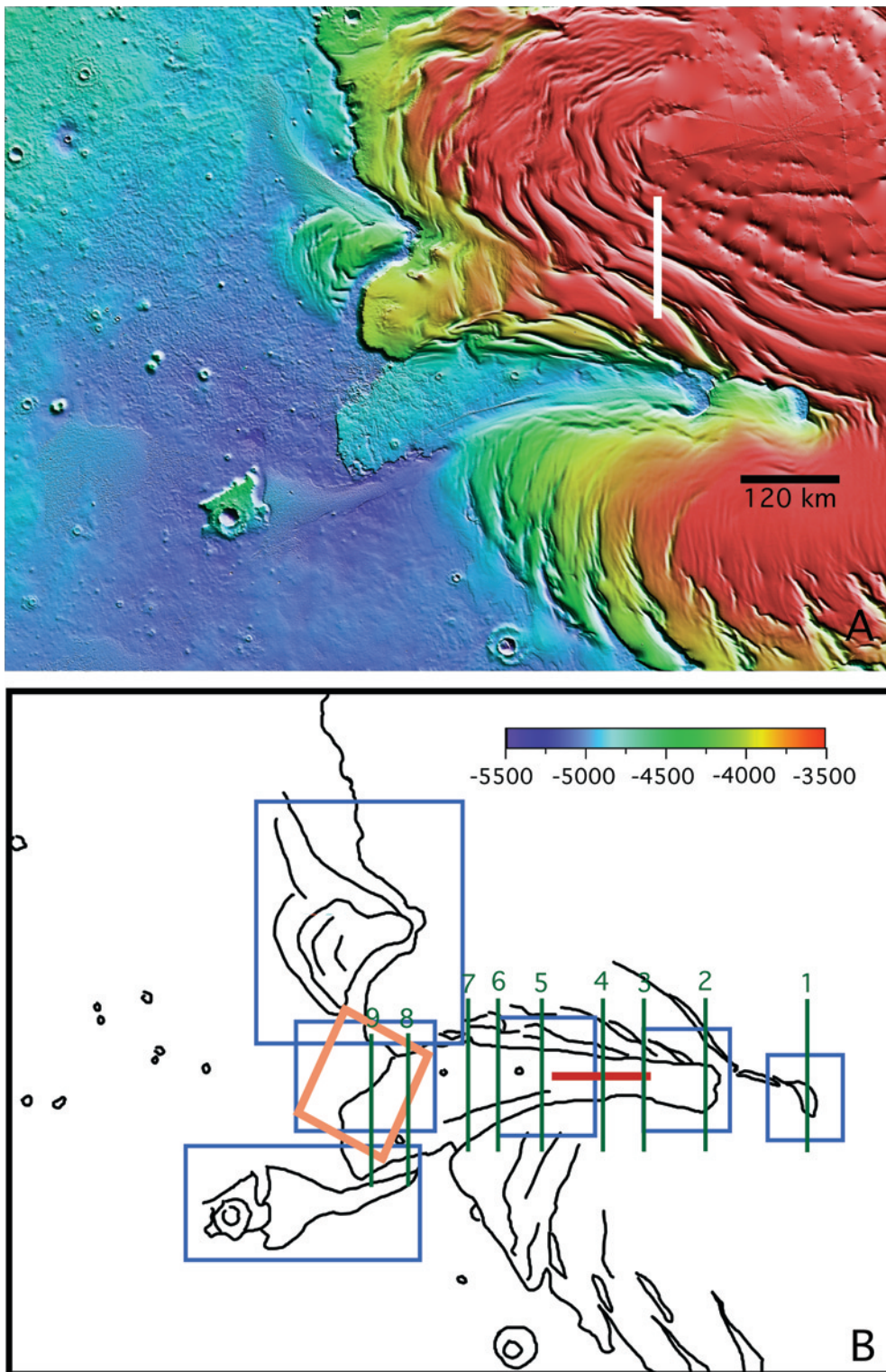


Figure 3. (a) Topographic, shaded-relief map of Chasma Boreale in polar projection using MOLA data. The white line indicates the position of the profile in Figure 10. (b) The green numbered lines indicate the position of the profiles shown in Figure 5. The orange box indicates the location of the Viking Orbiter image shown in Figure 7. The gray boxes indicate the positions of the high-resolution insets shown in Figure 4. The red line indicates the location of the profile shown in Figure 6.

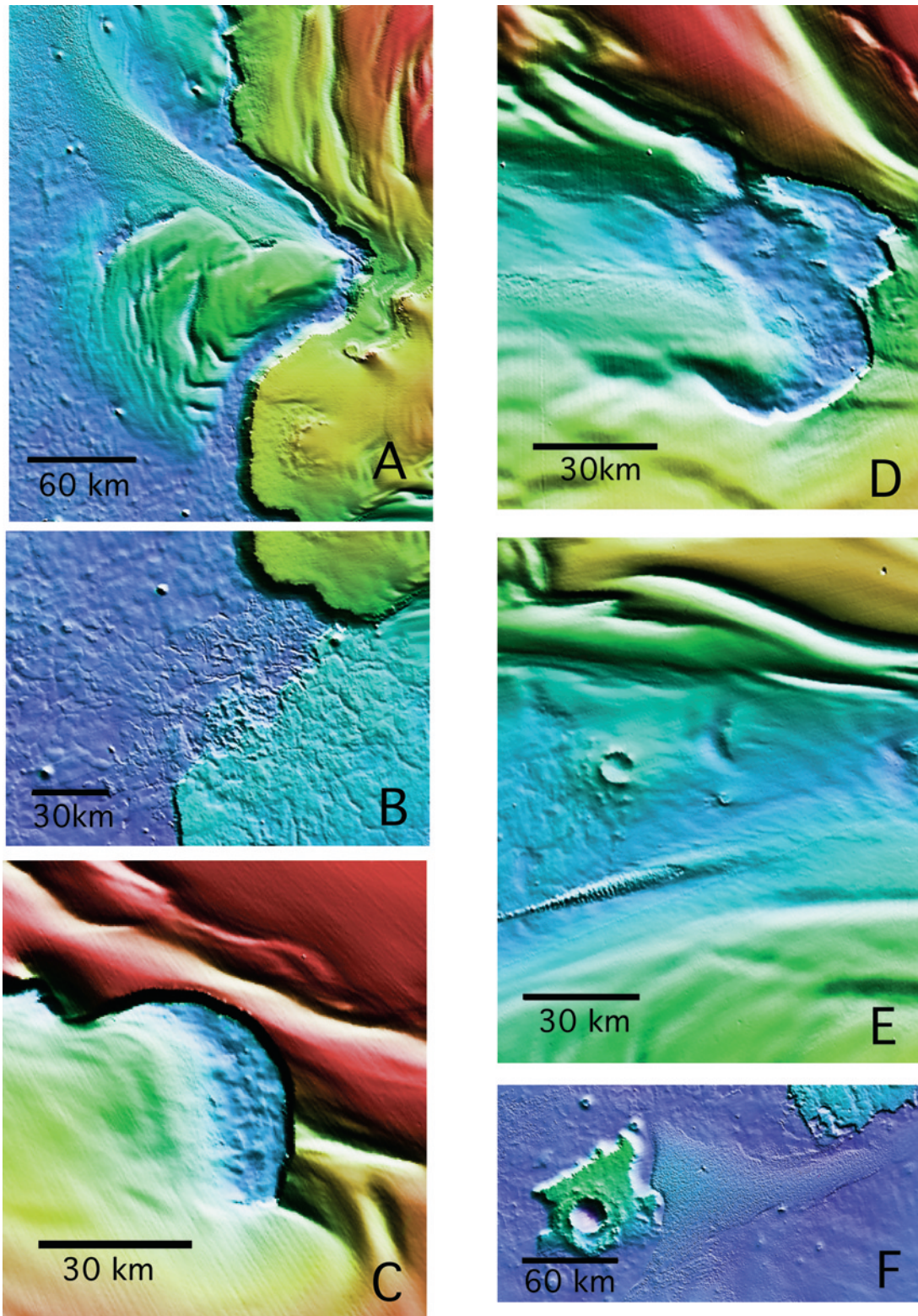


Figure 4. High-resolution insets of portions of the topographic map shown in Figure 3a. Locations of these close-ups are indicated by the gray boxes in Figure 3b. (a) Similar, smaller chasmata to the west of Chasma Boreale. (b) The western portion of the lobate deposits at the chasma mouth, showing the slump and channel-like features (see also Figure 7). (c) The deep, enclosed depression at the chasma head showing texture at the bottom. (d) The second deep, enclosed depression also showing texture at the bottom and a trough entering at nearly the same elevation as the bottom. (e) The middle portion of the chasma floor showing the elongated structure on the floor that is covered by dunes. (f) Mesa beyond the chasma mouth and streamlined dune field.

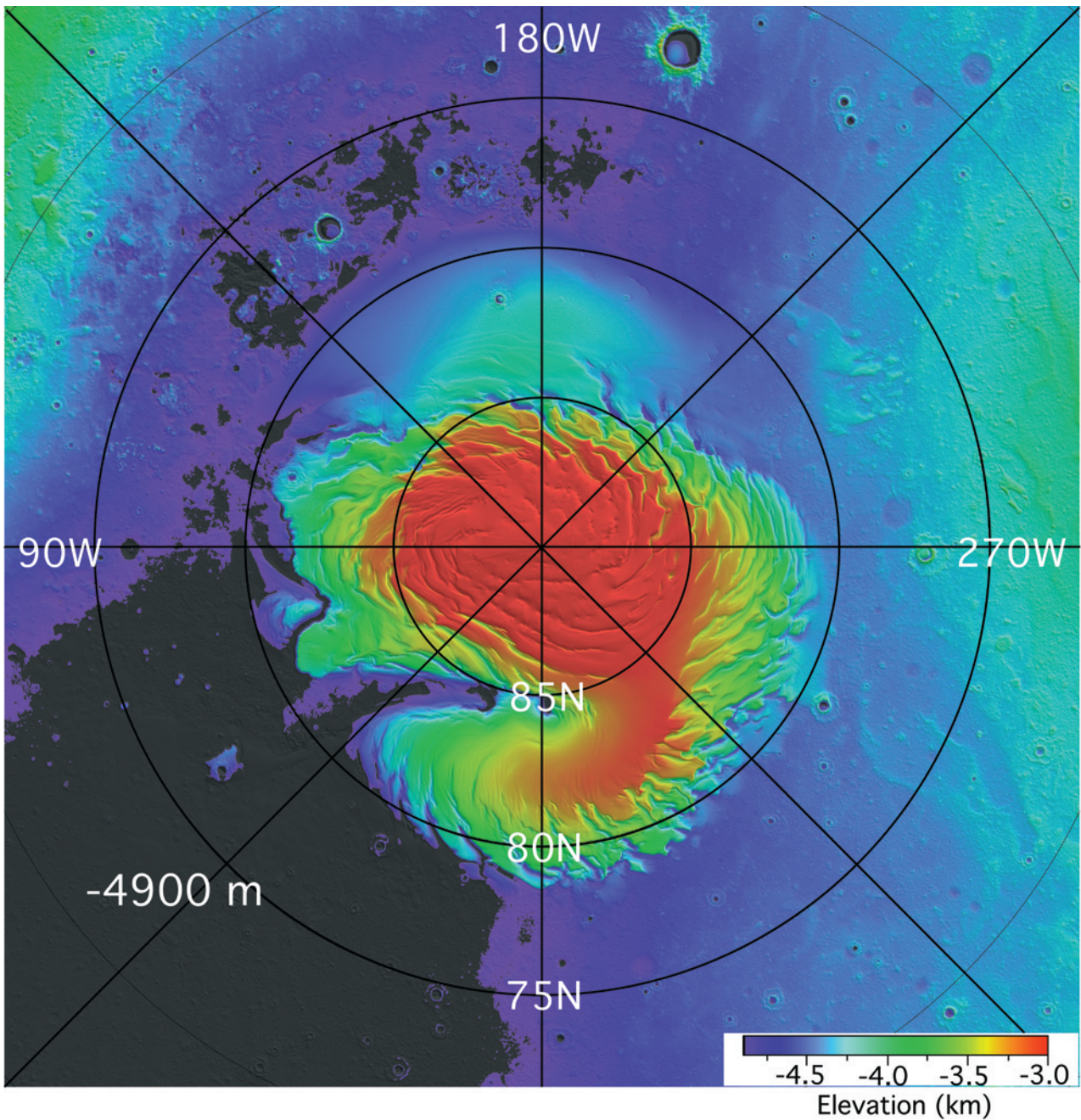


Figure 16. Topographic map of north polar region extending out to 72°N and ranging from -4900 m to -3000 m. All elevations below -4900 m are black. The North Polar Basin is the purple and black region toward the bottom and the left. Olympia Planitia is the bluish-green positive lobe extending from the cap toward 180°W. The interpreted recessional features (polar remnants, and kame and kettle terrain) lie in the arc of rough topography distal and concentric to Olympia Planitia.