JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 107, NO. E6, 5044, 10.1029/2001JE001615, 2002

North polar stratigraphy and the paleo-erg of Mars

Shane Byrne and Bruce C. Murray
Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, USA

Received 10 September 2001; revised 8 February 2002; accepted 8 February 2002; published 29 June 2002.

[1] An accurate self-consistent way of coregistering the imaging and topographic data sets of the Mars Global Surveyor mission was developed and used to begin a stratigraphic analysis of the northern polar region. A distinct change in the layering style exists at a definite stratigraphic horizon near the base of the north polar layered deposits. Occurrences of the contact between two distinct layered units can be mapped hundreds of kilometers apart at nearly the same Mars Orbiter Laser Altimeter (MOLA) elevation. The lower layered unit has a consistent association with sand dunes, leading to the conclusion that it is an eroding sand-rich deposit that predates most of the overlying north polar layered deposits, which exhibits the expected features of a dust-ice mixture. These results suggest that an areally extensive erg was in existence before the present ice cap and that the present circumpolar erg is likely composed of material reworked from this older deposit. The volume of this lower unit is estimated to be on the order of 10^5 km^3. The presence of this deposit implies that there existed a period in Mars' history when there was no icy polar cap. A dramatic climatic change leading to the deposition of the upper layered (icy) unit in the present-day polar layered deposits represents a major event in Mars' history. However, owing to uncertainties in the mechanics of layered deposits formation, such an event cannot be dated at this time. *INDEX TERMS:* 6225 Planetology: Solar System Objects: Mars; 5415 Planetology: Solid Surface Planets: Erosion and weathering; 5462 Planetology: Solid Surface Planets: Polar regions; 5464 Planetology: Solid Surface Planets: Remote sensing; 5470 Planetology: Solid Surface Planets: Surface materials and properties; *KEYWORDS:* Mars, polar, geology, history, stratigraphy, dune

1. Introduction

[2] The polar layered deposits on Mars have long been thought to contain a detailed climatic record [*Murray et al.*, 1972; *Cutts*, 1973b]. The structural model commonly accepted is that of ice with varying admixtures of dust forming layers with distinct albedo and mechanical strength [*Thomas et al.*, 1992; *Toon et al.*, 1980; *Cutts et al.*, 1979; *Squyres*, 1979; *Cutts*, 1973b]. Variations in Mars' orbital parameters, such as changes in obliquity and eccentricity, are thought to drive climate change, which in turn gives rise to the varied depositional environments needed for distinctive layer formation [*Toon et al.*, 1980; *Ward and Rudy*, 1991].

[3] The northern polar layered deposits are additionally complicated by the large sand sea encircling them [*Tsoar et al.*, 1979; *Dial*, 1984; *Tanaka and Scott*, 1987] which is mostly composed of the Olympia Planitia dunefield. Many authors have noted that erosion of the layered deposits may be a source of the dark sand-sized material [*Breed et al.*, 1979; *Thomas*, 1982; *Blasius et al.*, 1982; *Lancaster and Greeley*, 1990; *Thomas and Weitz*, 1989] which makes up the circumpolar erg. This would seem to pose a problem for the accepted formation scenario of layered deposits, which relies on aeolian deposition of fine dust in accumulating ice. Sand is not expected in the layered deposits because the polar cap rises over a kilometer above the surrounding plains and sand-sized particles (at least in the present atmosphere) cannot be carried by suspension. It has been suggested that the dark saltating material could be composed of dust aggregates originating in the polar layered deposits [*Greeley*, 1979; *Saunders et al.*, 1985; *Saunders and Blewett*, 1987]. However, *Thomas and Weitz* [1989] noted that the Viking color and albedo values derived for the north polar dunes do not differ significantly from dark dunes anywhere else on the planet. In contrast, Viking-based thermal inertia results suggest that the circumpolar erg has a lower bulk density than dunefields at lower latitudes [*Herkenhoff and Vasavada*, 1999; *Paige et al.*, 1994], which lends support to the idea that the dunes are composed of dust aggregates or perhaps unweathered, basaltic fragments.

[4] The northern cap complex, composed of the northern polar layered deposits and a partial covering of residual water ice, is nearly centered on the rotational pole and sits close to the lowest point of a large hemispheric depression [*Zuber et al.*, 1998; *Smith et al.*, 1998], which extends over much of the northern hemisphere. In many recent publications the ensemble structure of the polar layered deposits and the thin residual cap has been referred to simply as "the cap"; this is the convention which we will also adopt for this paper. Figure 1a shows the topographic situation of the cap. The cap contains many spiral troughs which have been

0148-0227/02/2001JE001615

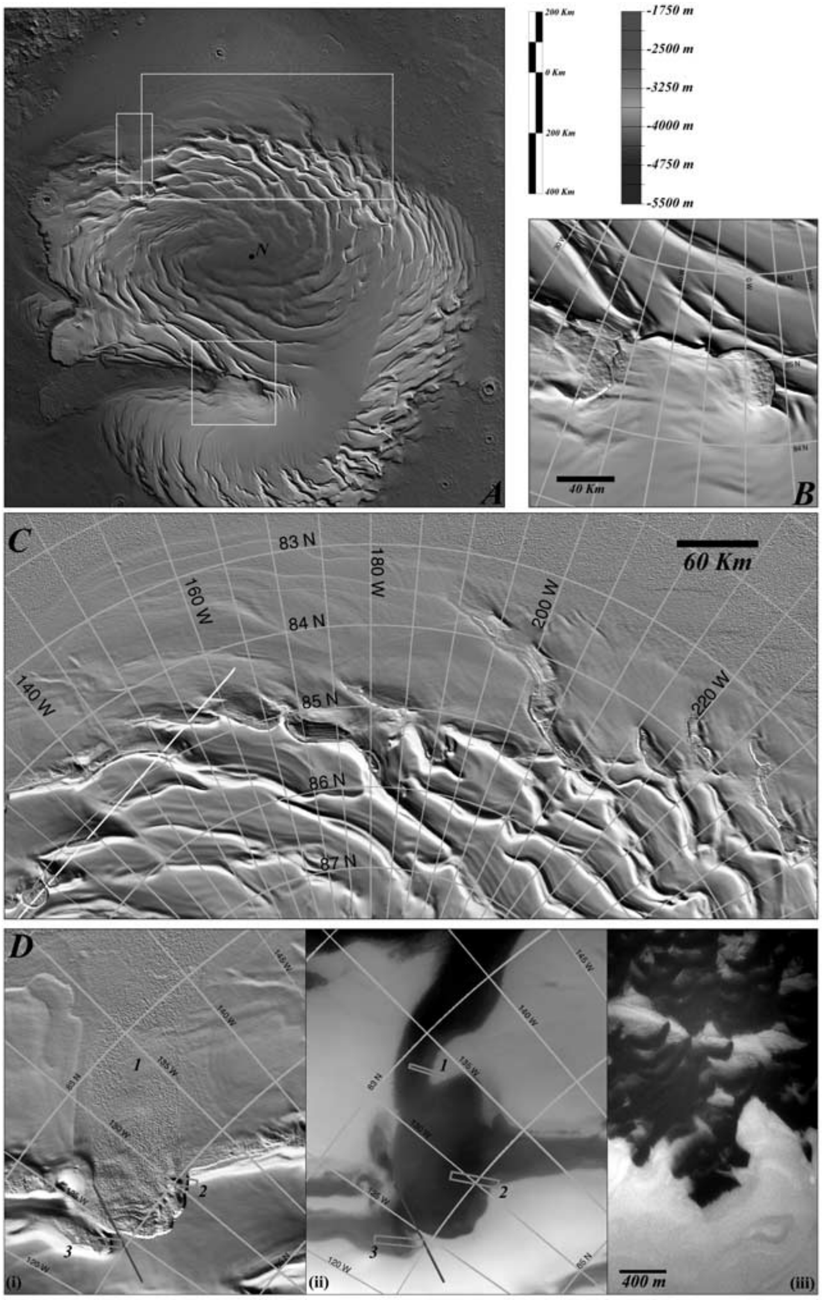

Figure 1. (a) Digital elevation model (DEM) constructed from ~28 million altimetry measurements made by Mars Orbiter Laser Altimeter (MOLA). Vertical and horizontal scales are in the upper right. The DEM extends to fully include the 80th parallel and is artificially illuminated from the upper right. White boxes indicate the positions of other subframes in Figure 1. (b) Derived shaded relief image of the region containing the head of Chasma Boreale is shown. Colored lines indicate where the contact between the finely and platy units can be mapped from the shaded relief map (red) and confirmed with Mars Orbiter Camera (MOC) narrow-angle frames (blue). (c) Derived shaded relief image showing area of residual cap edge centered on 180°W. Red and blue lines have the same meaning as in Figure 1b. The yellow line in the lower left indicates the position of the topographic profile shown in Figure 3. (d) Area of cap edge at 130°W shown in (i) shaded relief and (ii) MOC wide-angle M01/01617. This shows the correspondence of rough texture in shaded relief to dark albedo regions in the visible images, commonly associated with sand dunes. The blue line indicated in (i) and (ii) represents the position of the MOLA profile shown in Figure 7. MOC narrow-angle outlines 1, 2, and 3 represent positions of Figure 1d (iii), Figure 8, and Figure 9, respectively. (iii) Section of MOC narrow-angle image M03/01003 (illumination from the upper right) showing the contact between dark/light, textured/smooth areas, confirming the transition from a dune to nondune area. The outline of this image is shown as 1 in Figure 1d (i) and Figure 1d (ii). See color version of this figure at back of this issue.

attributed to the action of aeolian erosion [*Cutts*, 1973a; *Howard*, 2000], sublimation [*Ivanov and Muhleman*, 2000], or glacial flow [*Fisher*, 1993]. Chasma Boreale is a large radial chasm also cut into the cap that may have been formed through ablation, aeolian erosion [*Cutts*, 1973a; *Howard*, 2000], or some kind of catastrophic groundwater outburst [*Baker and Milton*, 1974; *Clifford*, 1980, 1987; *Benito et al.*, 1997]. Exposures of the layered deposits can be seen within both the spiral troughs and Chasma Boreale as well as several arcuate scarps in the vicinity of 180°W at the cap edge. These exposures have been the subject of stratigraphic study using Viking and Mariner data [*Howard et al.*, 1982; *Blasius et al.*, 1982; *Fenton and Herkenhoff*, 2000]. Work in the general area of Mars polar stratigraphy, using new Mars Global Surveyor data, has also been undertaken [*Herkenhoff*, 1998; *Edgett and Malin*, 2000; *Herkenhoff and Kirk*, 2000; *Murray et al.*, 2001; *Tanaka and Kolb*, 2001; *Kolb and Tanaka*, 2001]. The northern cap and its extensive set of deposits have been mapped by *Dial* [1984], *Tanaka and Scott* [1987], *Greeley et al.* [1992], and *Fishbaugh and Head* [2000].

[5] The Mars Global Surveyor (MGS) spacecraft has been in polar mapping orbit since March of 1999 [*Albee et al.*, 1998, 2001]. Instruments on board used in this study are the Mars Orbiter Camera (MOC) [*Malin et al.*, 1992] and the Mars Orbiter Laser Altimeter (MOLA) [*Zuber et al.*, 1992]. Over a year's worth of topography measurements and acquired images have been released to the public. Owing to the spacecraft's near-polar orbit, both the imaging coverage and the topographic measurements are densest in the polar regions. The combination of this new topographic knowledge and the ability to accurately locate high-resolution images relative to that topography makes possible for the first time a more detailed stratigraphic analysis of the stack of layers which makes up the polar deposits at both poles. It seems certain, now that this kind of detailed analysis is possible, that many stratigraphic studies, previously impossible, will be undertaken. Here a surprising result, which was apparent once the technical hurdles of precisely coregistering these data sets were resolved, is reported.

[6] The focus of this paper is to document a distinct change in the style of layering exposed in the many troughs and chasms within the northern cap at a consistent elevation. Layers above this horizon have the expected features of the canonical dust-ice mixture [*Thomas et al.*, 1992; *Toon et al.*, 1980; *Cutts et al.*, 1979; *Squyres*, 1979; *Cutts*, 1973b]. Layers below this horizon differ markedly in albedo, in morphology, and in resistance to erosion from those above. A strong association of exposures of this lower section with occurrences of dune material is demonstrated, leading to the conclusion that it is this specific section within the north polar layered deposits that is the source of the material comprising the current circumpolar erg.

2. Data Preparation

[7] To facilitate this and future work, high-resolution digital elevation models (DEM) of both polar regions were constructed following the method of *Neumann et al.* [2001] using the Generic Mapping Tools package [*Wessel and Smith*, 1998]. The northern DEM was constructed by fitting a continuous curvature surface to ~28 million independent MOLA altimetry measurements. Preprocessing of the data helped reduce the volume of points to be fit and short-scale aliasing problems. Data points were initially selected to satisfy certain quality requirements (G. Neumann, MIT, personal communication, 2001) judged by parameters such as along- and across-track shift and crossover residuals. Off-nadir tracks were excluded, leaving no topography information within ~180 km of the pole (poleward of 87° north); this region was separately dealt with. The spatial resolution was chosen to be 200 m, and the region covered is roughly 1200 × 1200 km centered on the pole. Tracks visibly offset from their surroundings were removed, and the surface was regenerated.

[8] The derived shaded relief map, at 200 m per pixel, has a higher resolution than either the MOC wide-angle camera or U.S. Geological Survey (USGS) Mars Digital Image Mosaics (MDIMS). In addition, shaded relief has advantages over visible imaging in that there is little pixel to pixel smearing and lighting and atmospheric effects are not an issue. For these reasons this shaded relief product was chosen as our basemap, although individual MOC wide-angle images continue to be used for albedo information where needed.

[9] MOLA points acquired simultaneously with a MOC narrow-angle image can be located within the image by line and sample number using spacecraft time and information on the coalignment of the narrow-angle CCD and MOLA boresight (S. Anderson, A. Ivanov, JPL, personal communication, 2000). Similarly, those line and sample positions can be related to MOLA-derived latitude and longitude points, which are superior to those obtained from normal spacecraft orbital information since they include the MOLA crossover correction [*Neumann et al.*, 2001]. This allows the narrow-angle image to be map projected in a best fit way to ensure that those MOLA points project to the correct position on the MOLA-derived basemap. In this way, MOC images can be placed relative to each other and their surroundings in an accurate self-consistent way. Where narrow-angle images overlap the mutual offset is commonly observed to be a few tens of meters. Radiometric calibration of the narrow-angle images was performed with the USGS ISIS software package.

[10] The imaging and topographic data sets were combined in a geographic information system package (Arcview, by ESRI) modified by us for use in the Martian polar regions. This makes spatial relationships between images (in three dimensions) clear, allows different data products to be overlain, and permits easier distinction of topographic and albedo effects.

3. Change in Layering Style

[11] Sections of the layered sequence within the cap and layered deposits are exposed in the many troughs and arcuate scarps both at the cap edge and in the interior. The purpose of this paper is to document a clear division of this layered sequence into two parts at a definite stratigraphic horizon. The upper, younger sequence is finely layered with smooth outcrops showing individual layers visible down to the limit of the camera resolution (herein-

after referred to as the finely layered unit). The lower, older sequence is distinctly different in layer morphology, albedo, and material properties. It has a characteristic irregular thick-plate-like structure in exposures, such that individual layers are less uniform both vertically and laterally (it is hereinafter referred to as the platy unit). This section has lower albedo than the overlying finely layered section. Layers in both sections appear to be close to flat lying; however, this is less certain in the platy unit owing to the more confusing morphology. Hereinafter, the two sections of the northern polar layered deposits described will be referred to as distinct geologic units. This division of the polar layered deposits was noted by *Malin and Edgett* [2001] in their review of the first year of MOC observations.

[12] The transition between these units is sharp and distinct. Figure 2a shows some examples of the contact between the units discussed in MOC narrow-angle images. Figure 2b shows how this contact is identifiable in MOLA-derived shaded relief maps; the lower unit protrudes out of the bottom of scarps as a prominent step. We used the shaded relief images to map the contact between available narrow-angle MOC frames. This contact is visible over a large area; Figure 1c shows where the contact can be mapped from a combination of MOC narrow-angle frames and the MOLA shaded relief map in the 120°–240°W region of the cap. Figure 1b shows that occurrences of this contact can be found as far away as the head of Chasma Boreale over 600 km distant. The minimum area of a circle needed to enclose all the mapped occurrences of this contact is roughly 0.4 million km^2, so assuming that the lower unit is continuous and has a near-circular shape, it is at least that extensive.

[13] Significantly, wherever this contact is visible in the 120°–240°W region, it is observed to occur in the elevation range from −4400 to −4200 m. The large horizontal distances and narrow vertical distribution of instances of this contact lend credence to the interpretation that it is a widespread and definite change in deposition style and material composition contained within the stratigraphic record rather than isolated patches of unusual layering with no relevance to each other. Figure 3 shows a topographic profile taken from the DEM along the line indicated in Figure 1c. This line was chosen as it crosses a number of locations where the surface intersects the elevation range mentioned and also because at these locations narrow-angle MOC frames are available to confirm the continued presence of the contact. In each case the contact appears at the expected elevation.

[14] The lower platy unit also seems to have different material properties than the overlying finely layered unit. On scarps where both units are exposed, breaks in slope are commonly observed at the contact, as illustrated in Figure 4. In other instances the lower platy unit is observed to protrude from the base of the scarp as a step; see, for example, Figure 5. In all cases a different composition for the lower platy unit, which is more resistant to mechanical or thermal erosion, can be inferred.

[15] The differences in resistance to erosion, morphological appearance, and albedo strongly indicate that the lower unit differs in both composition and deposition style. The sharp appearance of the contact could indicate that this change was rapid, at least compared to the timescale of layer formation, or that there may be an erosional unconformity separating the two units, representing an unknown amount of time.

[16] No exposures of the platy unit at the cap edge in the longitude ranges of 0°–70°W and 225°–360°W are seen, although Chasma Boreale contains exposures within these ranges. The quality of the current narrow-angle coverage was unfortunately adversely affected by a dust storm, which occurred during the M02 and M03 mapping phase (H. Wang, Caltech, personal communication, 2001). Many of the narrow angles acquired in this period contain very little surface information. Imaging conditions for the next Martian year will hopefully be clearer. It is possible that as more high-resolution imaging is acquired and released for pubic use, exposures of this unit will be discovered in other regions.

4. Correlation With Duneforms

[17] One of the most important observations of the lower platy unit is the fact that exposures of this unit are highly correlated with the nearby occurrence of dune bed forms. Dunes require saltating particles to form, which usually implies sand-sized material but conceivably could also be sand-sized aggregates of dust [*Greeley*, 1979; *Saunders et al.*, 1985; *Saunders and Blewett*, 1987]. The dunes observed here will be referred to as sand dunes; however, the possibility that sand-sized dust aggregates may play a role will be left open.

[18] Many of the exposures of the contact between the two units discussed in section 3, in the longitude range 140°–240°W and at the cap edge, occur in closed depressions next to arcuate scarps. Although these closed depressions are "uphill" from, and their bases are higher in elevation than, the main circumpolar erg, deposits of dune-forming material are present. There is no evidence of dunes in the region between these depressions and the main erg, which would have implied poleward or equatorward transport of dune material. Thus it appears that the dune material was derived in situ. Figure 6 shows some examples of dune material located adjacent to exposures of the lower platy unit. Dunes are also visible in Figures 4, 8, and 9 next to the exposed platy unit. *Thomas and Weitz* [1989] also noted that dunes appear to have restricted sources within the polar layered deposits. Although with Viking imagery they were unable to see the platy unit, they realized that the sources of dune material are probably in the stratigraphically older deposits.

[19] In another area of the cap edge at roughly 125°W (illustrated in Figure 1d), there is a large reentrant with an associated train of dunes, which are migrating southwest toward, and eventually join, the main circumpolar erg. If formed from the material eroded at the scarp, these dunes have traveled from at least where the scarp edge used to be at the time of erosion to the edge of the erg, a minimum distance of 130 km. This large minimum distance, their dark color, and the inherently violent nature of the saltation process cast doubt on the possibility of these dunes being composed of sand-sized dust aggregates which may not be strong enough to survive intact. *Saunders et al.* [1985, 1986] have suggested that dust aggre-

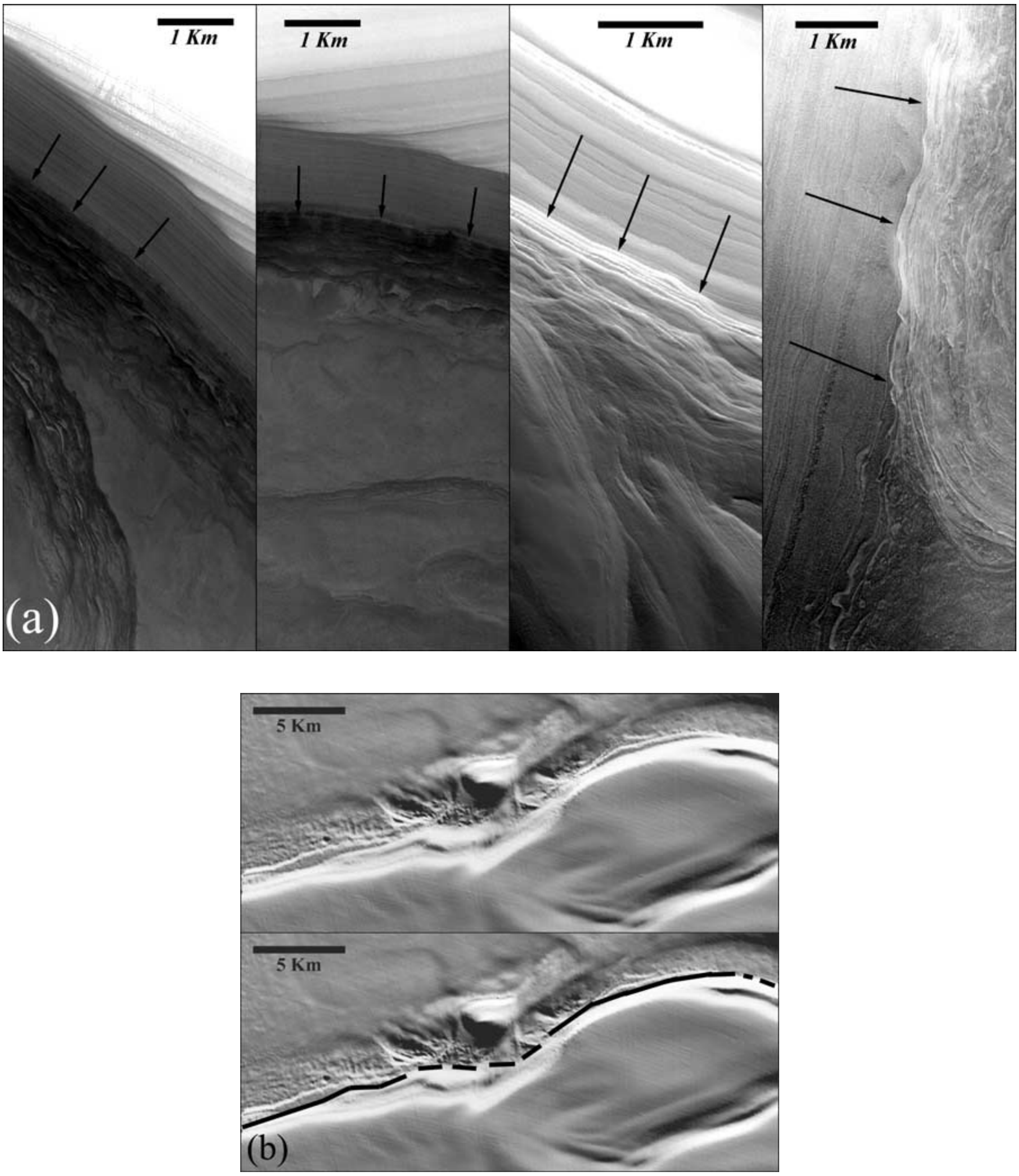

Figure 2. (a) Examples of the contact between the fine and platy layered units. MOC narrow-angle frames (from left to right) M02/00817 (85.1°N, 168°W, Sun from upper right), M03/01653 (84.9°N, 161°W, Sun from upper right), M17/01021 (84.7°N, 143°W, Sun from lower left), and M16/00329 (85.5°N, 190°W, Sun from upper right). The morphological difference in appearance between these two units is easily visible. The lower albedo of the platy unit is visible in the two left images; the two right images are still covered in seasonal frost, which masks the albedo contrast. The arrows indicate the downhill direction with the arrow heads pointing to the contact where the finely layered unit ends and the platy unit begins. (b) Section of MOLA-derived shaded relief map with illumination from the upper right. The panels are identical except the top shows an unobstructed view of where we mapped the contact (heavy line in lower panel). The lower unit is visible as a protruding layer at the base of the scarp. Narrow-angle images are used to confirm the presence of the contact at intervals along this mapped line.

gates can survive saltation up to a few tens of kilometers and that they can acquire their dark color by gathering carbonaceous meteoritic dust as they saltate. In this case, however, the minimum saltation distance exceeds their quoted survivability distance, and the amount of dark carbonaceous meteoritic dust must be low since this material saltates over an otherwise high-albedo surface. The thermal inertia results [*Herkenhoff and Vasavada*,

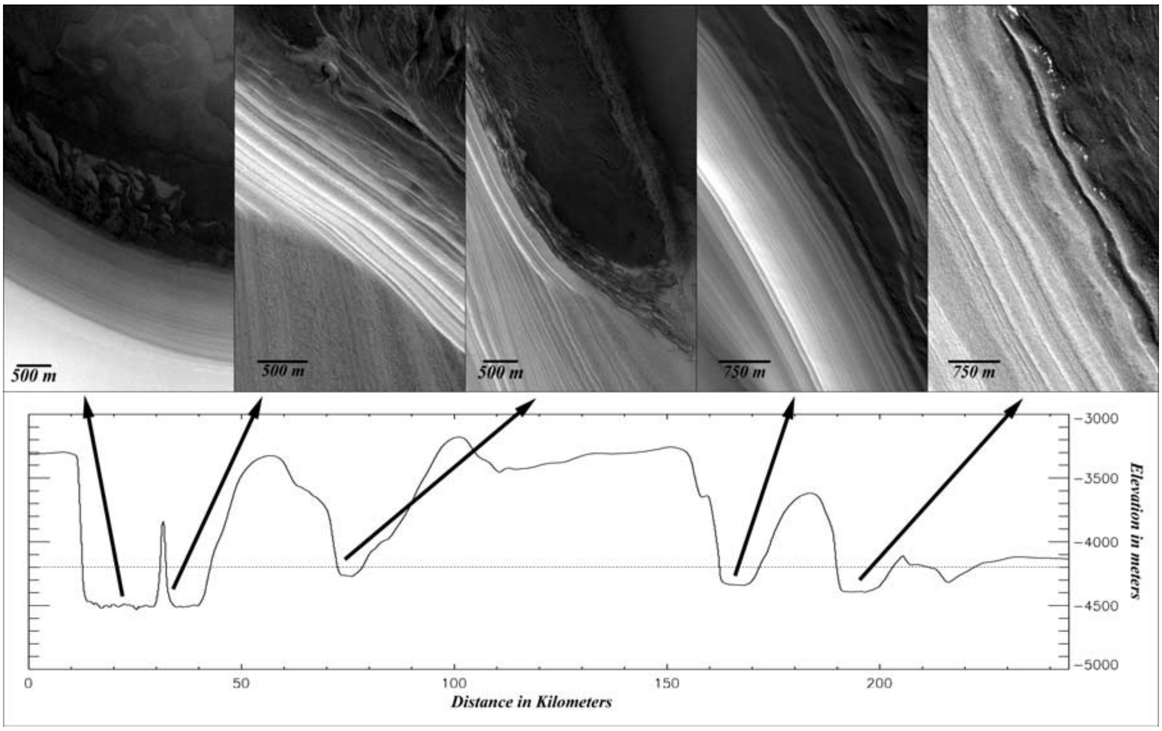

Figure 3. Topographic profile measured from DEM, the location of which is marked in Figure 1c as a yellow line. The surface intersects the level of the contact in several depressions. Example narrow angles (which are located on the profile) from each depression are shown (from left to right): M03/02389 (85.1°N, 121°W, Sun from lower left), M02/00088 (85.2°N, 125°W, Sun from upper right), M03/04603 (85.3°N, 135°W, Sun from upper right), M17/00869 (84.8°N, 148°W, Sun from upper right), and FHA/01488 (84.8°N, 157°W, Sun from upper right). The elevation of the contact in each case is −4300, −4150, −4150, −4170, and −4200 m, which is remarkably consistent considering the length scales involved. The downhill direction in each image is from bottom left to upper right.

1999; *Paige et al.*, 1994], combined with the above discussion, lend support to the idea that the dunes are composed of unweathered basaltic fragments. However, it remains unclear as to the applicability of these thermal inertia results. High local slopes within dunefields have been ignored in all thermal models, and the high emission angle of the Viking observations in this area makes it likely that thermal measurements have been dominated by the "hot" side of these dunes. These two facts combined could possibly lead investigators to infer an incorrect value of thermal inertia.

[20] Although in general dune bed forms are not resolved by the MOLA data, dunefields are easily identifiable from the derived shaded relief images as areas of apparently rough texture. Figure 1d shows the correspondence of rough texture in shaded relief maps to dark albedo regions in MOC wide-angle images commonly associated with dunes. Where higher-resolution narrow-angle images exist, they confirm that the dune-covered areas can be correctly identified from the MOLA data as illustrated in Figure 1d (iii).

[21] A section of MOLA profile 13387 over the steepest portion of the scarp is shown in Figure 7; its position relative to the scarp is shown in Figure 1d. The maximum scarp slope along the MOLA track is 60.2°. When this is adjusted to take into account the nonperpendicular strike

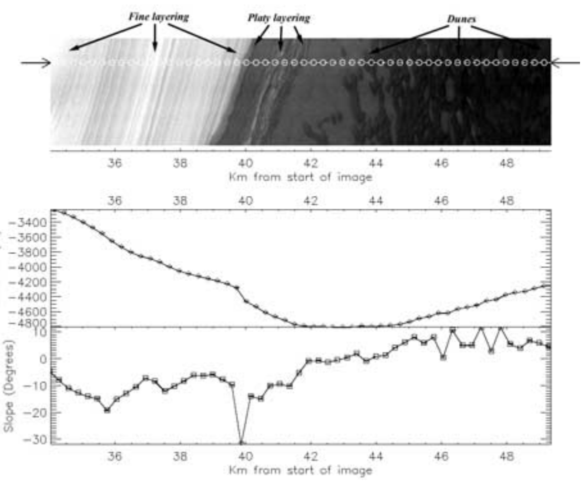

Figure 4. MOC narrow-angle image M03/05887 (84.7°N, 188°W, Sun from upper left in this orientation) along with its simultaneously acquired MOLA track. The circles in the image represent the size and location of individual MOLA shots. The shape of the scarp is clear along with the break in slope where the transition in layering style occurs. The elevation of the contact (roughly −4200 m) agrees closely with elevations recorded elsewhere (see Figure 3) in this region.

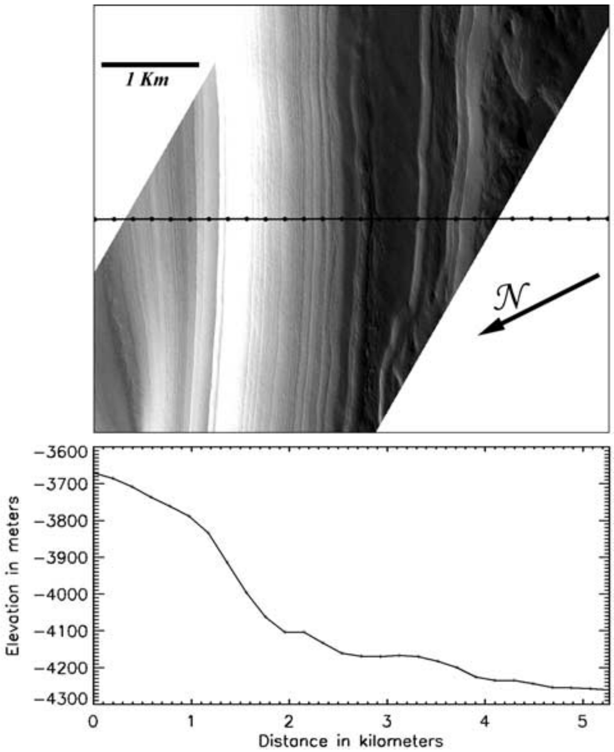

Figure 5. Section of MOC narrow-angle image M17/00869 (84.8°N, 148°W, Sun is from the right in this orientation) along with a topographic profile measured off the DEM. Here the platy unit protrudes from the bottom of the scarp by roughly 1 km; a break in slope is also visible at the contact.

of the MOLA trace to the scarp, a 67.4° downhill slope is inferred. Even higher slopes may be possible over length scales shorter than the 300 m altimeter shot separation. The extremely steep slopes, arcuate shape, and interior ridges, which parallel the scarp edge and are visible in Figure 1d (i), of the main reentrant strongly indicate an origin through successive landsliding. We interpret these interior parallel ridges to be remains of the lobate deposits expected of landslides. Why landslides should have occurred in this area is unclear to us. However, given the sharpness of the scarp and the possibility of glacial-like flow or at least relaxation discussed by many authors [*Nye*, 2000; *Fisher*, 1993; *Zuber et al.*, 1998], it seems likely that at least the last of these landslides was a recent occurrence.

[22] Figure 8 shows a fortuitously placed MOC narrow-angle frame, whose position is also marked in Figure 1d (i). Although this image is taken in poor illumination and atmospheric conditions, the platy unit can clearly be seen protruding from the base of the scarp. Also of interest and perhaps more clearly visible in the Figure 1d (i) context image is the 6.4 km crater immediately adjacent to the scarp which appears to have been uncovered recently by its retreat. Either an impact or some endogenic process may have formed the crater. The size of the feature lends support to the theory that a long period of time may be represented by an unconformity between the finely layered and platy units. In the wall of this crater is a clearly visible exposure of the platy unit. Dunes cover the eastern part of the crater, providing yet another example of the correlation between contemporary dunes and the platy unit.

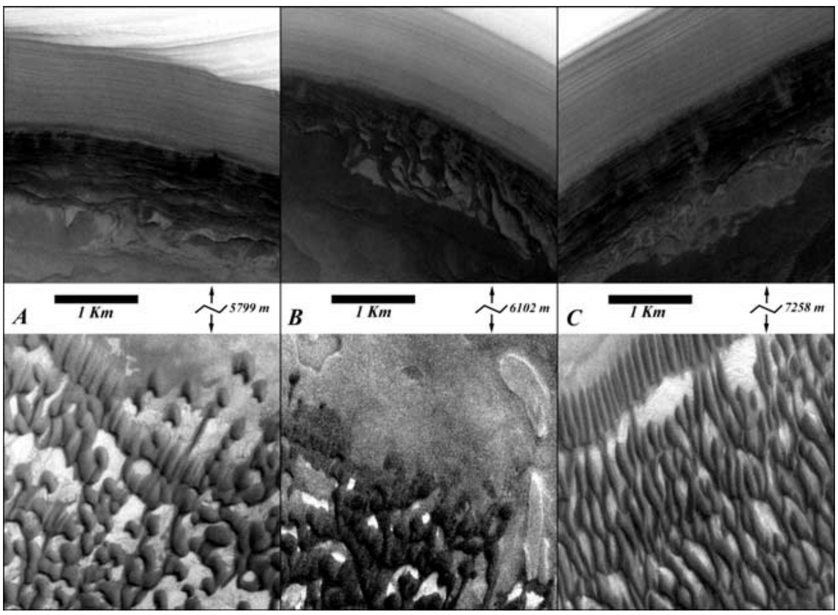

Figure 6. Examples of the association of dunes with exposures of the platy unit. These three MOC narrow-angle frames are from three separate closed depressions at the (a and c) cap edge and (b) interior. From left to right they are M03/01653 (84.9°N, 161°W, Sun from upper right), M03/02389 (85.1°N, 121°W, Sun from upper right), and M03/00596 (85.4°N, 170°W, Sun from upper right). The images have had their center portions cropped out; the amount of missing image length is indicated between the two sections of each. The downhill direction in the upper panels is from top to bottom.

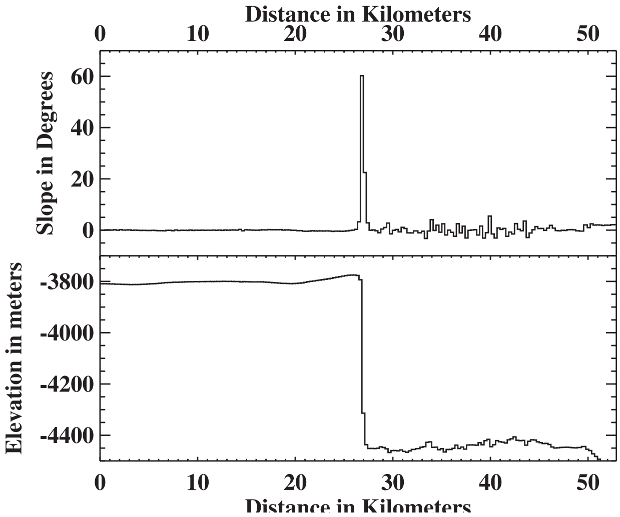

Figure 7. Section of MOLA profile 13387, the position of which is marked in Figure 1d. Slope maximum at the scarp is 60.2°. When corrected to account for the nonperpendicular strike of the profile to the scarp, a slope of over 67° in the downhill direction is inferred.

[23] Immediately to the northeast of the main reentrant is another arcuate scarp, and again the platy unit is visible along with associated dunes; see Figure 9 (outline of this image is also marked in Figure 1d). The dunes have collected in one corner of the depression. There is a ridge ~100 m high separating this depression from the main reentrant. However, there is a route where slopes are low enough so that the dunes derived from the material within this depression can climb up on top of this ridge and escape down the other side into the main reentrant and ultimately the circumpolar erg. The morphology of the dunes is consistent with saltation in this direction. Although this ridge is only a few pixels wide in the MOLA shaded relief image, it has the heavily textured appearance associated with dune cover in other locations. Wide-angle views of the same location also show a thin dark streak connecting the two areas.

[24] Chasma Boreale provides an exposure of over a kilometer of relief, cutting directly into the polar cap. It intersects the level at which one would expect to find the contact between the platy and finely layered units. Figure 10a shows the contact at the eastern head scarp of the chasam, occurring close to the expected elevation hundreds of kilometers away from the previous examples and the other side of the rotational pole. The elevation of the contact in this one image can be seen in Figure 10a to be roughly −4600 m. This is at a lower elevation than exposures at the cap edge in the vicinity of 180°W. It could be either that the platy unit is thinner here or that the basement topography is lower. Chasma Boreale provides an opportunity to probe the location of the bottom of the platy unit. Figures 10b and 10a show the platy unit continuing down to the bottom of the chasma at −4900 m, leaving the question of how deep this layer extends unresolved. Dunes fill the chasam at many locations, and while it is difficult to argue that these dunes must have been derived in situ, it is certainly consistent. The chasma contains two distinct heads (see Figure 1b); the eastern head scarp of the chasma at the higher elevation contains the contact (Figure 10a). The western head scarp also shows an exposure of the platy

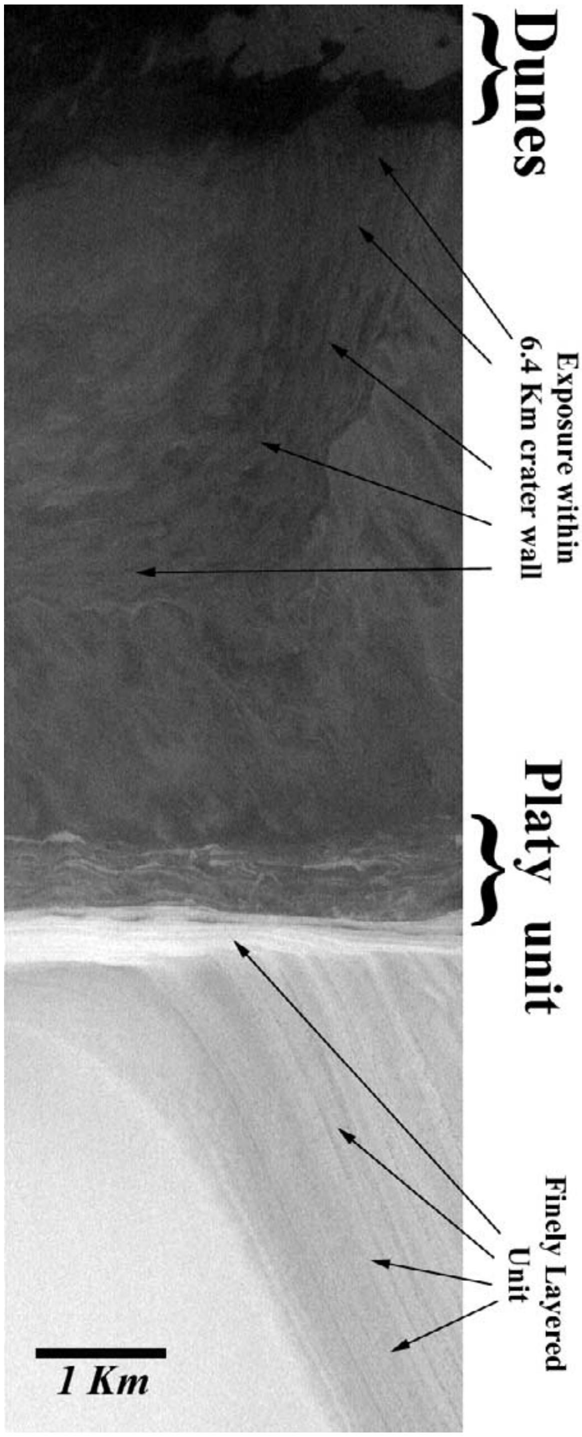

Figure 8. Section of MOC narrow-angle image M04/01575 (84°N, 130°W, Sun from upper right) showing edge of reentrant. The outline of this image is shown as 2 in Figure 1d. The contact between the platy and finely layered units is also visible here along with an exposure of the platy unit in the crater just below the scarp.

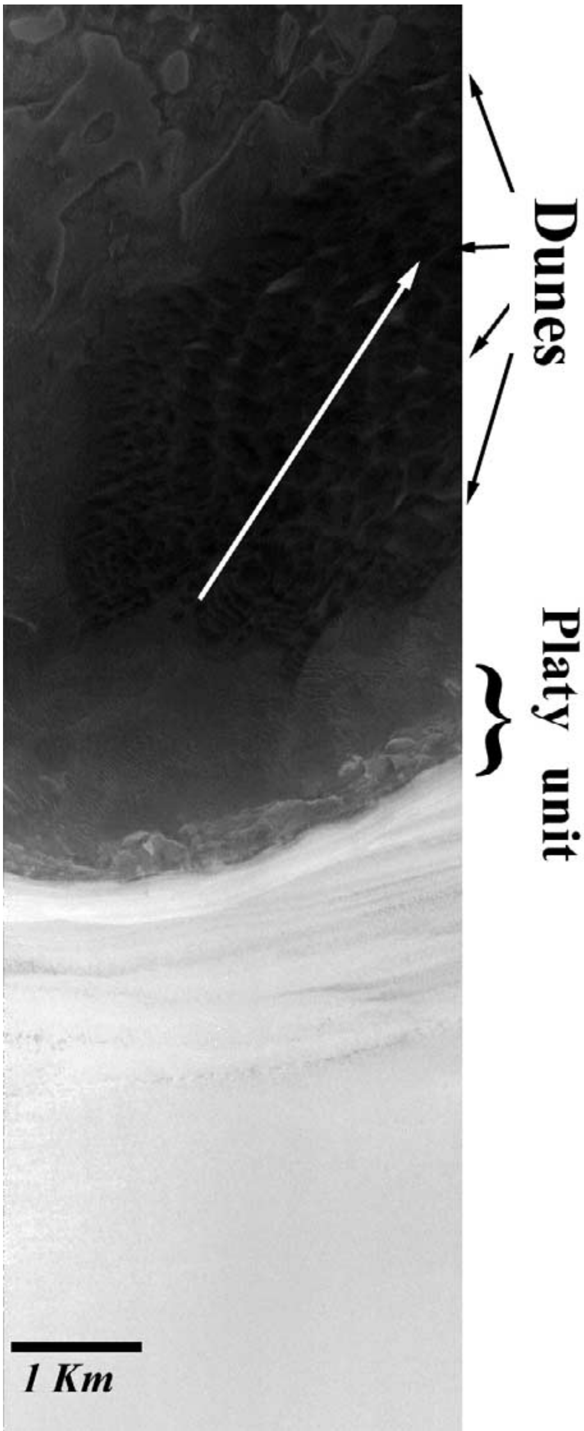

Figure 9. Section of MOC narrow-angle image M03/05954 (83.8°N, 124°W, Sun from upper right) showing another contact example and dunes climbing over ridge. The outline of this image is shown as 3 in Figure 1d. The direction of dune travel (which can be confirmed by observing the orientation of the slip faces of the dunes), which is transporting sand up a ridge, is indicated by the white arrow. The ridge is more clearly visible on the shaded relief image in Figure 1d (i).

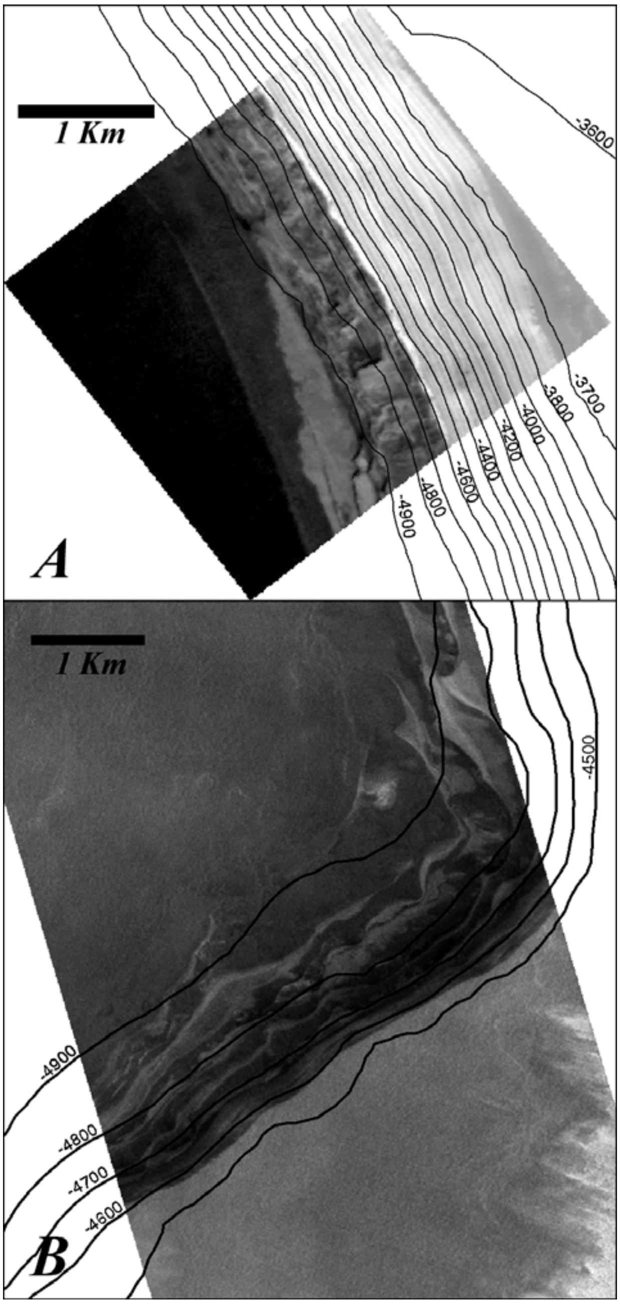

Figure 10. (a) MOC narrow-angle image M01/01410 (84.9°N, 357°W, Sun from bottom in this orientation) with overlain MOLA elevation contours showing the contact between fine and platy layered units at the eastern head scarp of Chasma Boreale. Contact elevation in this locality can be seen to be roughly −4600 m. (b) MOC narrow-angle image M03/03107 (84.8°N, 16°W, Sun from bottom in this orientation) also overlain with MOLA elevation contours showing an exposure of the platy unit continuing down to −4900 m at the western head scarp of Chasma Boreale. Here it appears that the finely layered unit has been completely removed as the scarp top is at −4600 m.

unit (Figure 10b); however, it appears that the upper finely layered unit has been completely stripped off in this location. The eastern head scarp is cut off from the rest of the chasm by the western head scarp, a sharp cliff with slopes well above the angle of repose, so it is reasonable to assume that the dune material in the portion of the chasam between the eastern and western head scarps must have been derived in situ and have not migrated in from the outside.

[25] Troughs further poleward are higher in the stratigraphic sequence of layers, and so the lower platy unit is not exposed. These toughs do not have any associated dunes, and so the finely layered unit has been ruled out as a significant source of dark sand-sized material.

5. Discussion and Conclusions

[26] Observations of a distinct change in layering style that is evident over at least half the northern polar cap at a nearly constant elevation have been presented. Exposures of the lower platy unit are associated with the presence of nearby dune fields. This leads to the conclusion that the dune material is being derived from the erosion of the lower platy unit.

[27] The elevation of the lowest observed outcrop of the platy unit is −4900 m, although it may extend deeper. This is only ~200 m above the lowest terrain surrounding the polar cap. The basement topography under the cap is largely dependent on whether the cap is compensated or not [*Johnson et al.*, 2000]. However, it is likely that the basement cannot be more than a few hundred meters below the lowest observed occurrence of the platy unit. The highest observed occurrence of this unit in the same region (head of Chasma Boreale) is at −4600 m elevation, implying that the platy unit is at least a few hundred meters thick in this locality.

[28] We are of the opinion that this unit is rich in, and perhaps entirely composed of, frozen sand. Owing to the difficulties in codepositing an ice-dust mixture with large amounts of sand [*Herkenhoff and Murray*, 1990], it seems likely that this unit was deposited in a very different environment than that needed to deposit the upper unit or that of present-day Mars. The Olympia Planitia dunefield, which sits atop the Olympia lobe, ranges in elevation from roughly −4200 to −4700 meters. This is the same elevation range over which exposures of the sand-rich deposit are seen. We suggest that the Olympia lobe is composed of the same sand-rich, platy unit which extends under the north polar layered deposits. The Olympia Planitia dunefield and the rest of the circumpolar erg could then be composed of material eroded from this platy unit. This would vastly increase the minimum size of the platy unit initially estimated in section 3.

[29] A possible geologic history is outlined in Figure 11, which represents a cross section through the polar deposits from 75°N, 0°W (left) through the pole to 75°N, 180°W (right). A large sand or sand-rich deposit is postulated to have formed before the existence of the present-day north polar cap. It may be that sand-sized particles migrated to this locality through aeolian action from elsewhere on the planet, and the broad topographic low centered roughly on the north pole seemingly served as an effective sink for this material. From mapping the contact elevations in Chasma Boreale and the arcuate scarps at the cap edge, the center (thickest part) of the deposit is interpreted to be offset from the rotational pole along the 180°W meridian. This interpretation is dependent on having reasonably flat basement topography. A shift in environmental or climatic conditions caused the present ice cap to begin forming. This may be related to some climatic change triggered by a chaotic obliquity swing [*Touma and Wisdom*, 1993] or perhaps even to the end of large-scale volcanism on the planet. The accepted mechanism of deposition of ice with varying concentrations of dust could create the finely layered ice cap. This icy cap may have been much larger in the past and only more recently retreated to its current extent [*Fishbaugh and Head*, 2000]. This climatic shift need not have been sudden; a relatively shallow covering of ice could stabilize any dunes, thus allowing the rest of the cap some time before starting to form. Finally, at some point in the past, Chasma Boreale and the spiral troughs formed, cutting through the cap into the platy deposit underneath (where the cap is thin enough). A highly porous sand deposit could have stored the large amounts of groundwater needed for the catastrophic outburst theorized to have formed Chasma Boreale. Groundwater in the platy unit would not be molten under present conditions, and so this mechanism would require some form of heat injection such as that theorized by *Benito et al.* [1997] or much higher planetary heat flow in the past. In this scenario, since the icy portion of the cap formed symmetrically about the rotational pole, the upper finely layered unit drapes completely over the lower unit in the vicinity of 0°W (left side of Figure 11). For this reason no exposures of the platy unit are expected to be observed at the edge of the cap in this region.

[30] Accumulation of the platy unit may have occurred over a considerable period of time with many episodes of dune migration involved. Modest obliquity changes could have mildly affected polar climate and insured that each episode of dune deposition could contain differing quantities of ice, leading to stratigraphic variations in erosional resistance. Incorporation of bright dust in such units can be ruled out, however, as saltating particles would kick dust back into suspension [*Herkenhoff and Murray*, 1990]. The irregular outcrops of the platy unit are consistent with laterally variable resistance to erosion, perhaps due to variable dune thickness. A large enduring change in mean obliquity, as modeled by *Touma and Wisdom* [1993], could have ended this depositional period and begun that of the overlying ice-dust mixture of the northern polar layered deposits.

[31] If Figure 11 is an accurate representation of the current situation, the volume of material contained within the platy unit can be approximated. Taking it to be a section of a sphere with a radius of 540 km and height of 600 m, the volume occupied is 0.27 million cubic kilometers. For comparison the volume of the total north polar cap is 1.2–1.7 million cubic kilometers [*Zuber et al.*, 1998], and the volume of sand in the present-day erg has been estimated at 1158 cubic kilometers [*Lancaster and Greeley*, 1990]. Even assuming a large percentage of pore space (which is presumably filled with ice), e.g., 50%, the volume

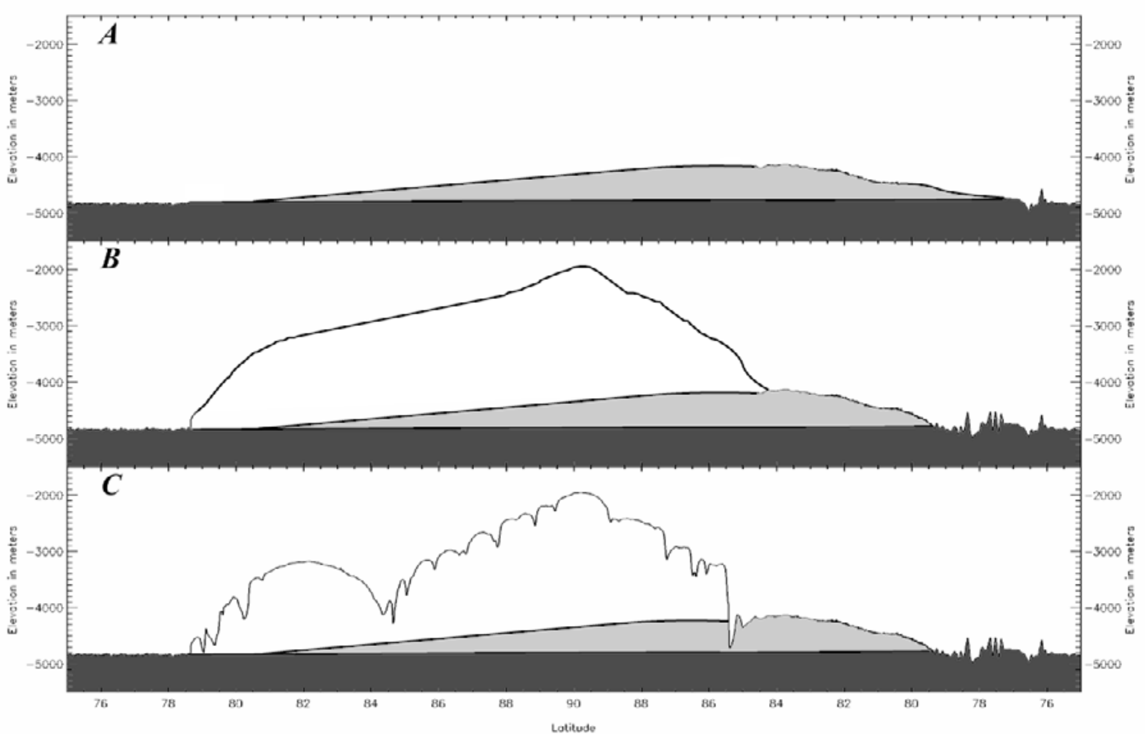

Figure 11. Possible geologic sequence of events, vertical exaggeration of 100. (a) The northern hemisphere acts like a large depression centered on the pole. A large erg collects there from sand derived elsewhere on the planet. (b) A dramatic change in climate results in the formation of an icecap. Deposition of ice centered on the pole with varying concentrations of dust, perhaps modulated by obliquity cycles, produces the finely layered unit. The exposed section of the paleo-erg is eroded back, perhaps releasing the sand found in the present-day circumpolar erg. (c) Formation of Chasma Boreale and the spiral troughs which incise the cap, some of which cut into the lower sand unit. Present-day MOLA profile 11734.

of rock eroded to produce this material is on the order of 10^5 km^3.

[32] At the cap edge in the vicinity of 180°W (right side of Figure 11) the Olympia Planitia dunefield could have once extended farther equatorward. However, since it lacks the protective cover of the ice cap, it would have been subject to erosion and would have possibly liberated large quantities of sand. This sand could be that which forms the remainder of the circumpolar erg. It is difficult to estimate a timescale over which this process would occur since it is an open question as to how much of the year these dunes are free to saltate [*Ward and Doyle*, 1983]. Previous wind regime studies [*Thomas and Gierasch*, 1995] concluded that the current circumpolar erg is confined to a narrow latitude band by winds created in part by its own low albedo. Thus this dark, sand-sized material would not be expected to have been redistributed over a large fraction of the planet.

[33] The major implication of this newly recognized deposit is climatic in nature. The fact that the icy part of the northern polar cap was absent at some point indicates a much warmer polar environment than at present. The northern cap is also the largest known reservoir of water on the planet. Where this water was in the past if not locked up in the polar cap is a puzzling mystery. It is possible that the water was concentrated at lower latitudes filling craters and is responsible for the apparent sedimentary exposures reported by *Malin and Edgett* [2000]. A secondary implication is that no exotic polar dust aggregates are needed to explain how sand can possibly be weathering out of the current layered deposits. The low thermal inertia results [*Herkenhoff and Vasavada*, 1999; *Paige et al.*, 1994] still prove to be an unresolved issue though.

[34] High-resolution Thermal Emission Imaging System (THEMIS) data from the upcoming Odyssey mission will likely be able to definitively say whether the layered unit in question has the same infrared spectral signature as the circumpolar erg. These data may also resolve the difference in temperature between the ''hot'' and ''cold'' sides of the dunes, leading to a more accurate value of thermal inertia. The near-complete 20 m per pixel multiband coverage expected from the THEMIS visible camera will be used to search for exposures of this contact in areas where MOC has not imaged and look for characteristic color ratios unique to each unit.

[35] **Acknowledgments.** We are especially grateful to the MOLA and MOC teams for providing their high-quality data in such a prompt manner. We would like to especially thank Anton Ivanov (master of all things MOLA) for his help in acquiring MOLA data in an accessible form and Lori Fenton for her help in understanding dunes and all the cool stuff they can do. We would also like to thank Arden Albee, Andrew Ingersoll, Mark Richardson and Ashwin Vasavada for their comments (and encouragement).

Finally we thank Ken Herkenhoff for his comments as a reviewer; the paper is very much improved as a result.

References

Albee, A. L., F. D. Palluconi, and R. E. Arvidson, Mars Global Surveyor mission: Overview and status, *Science*, *279*, 1671–1672, 1998.

Albee, A. L., F. D. Palluconi, R. E. Arvidson, and T. Thorpe, Overview of the Mars Global Surveyor mission, *J. Geophys. Res.*, *106*, 23,291–23,316, 2001.

Baker, V. R., and D. J. Milton, Erosion by catastrophic flood on Mars and Earth, *Icarus*, *23*, 27–41, 1974.

Benito, G., F. Mediavilla, M. Fernandez, A. Marquez, J. Martinez, and F. Anguita, Chasma Boreale, Mars: A sapping and outflow channel with a tectono-thermal origin, *Icarus*, *129*, 528–538, 1997.

Blasius, K. R., J. A. Cutts, and A. D. Howard, Topography and stratigraphy of the Martian polar layered deposits, *Icarus*, *50*, 140–160, 1982.

Breed, C. S., M. J. Grolier, and J. F. McCauley, Morphology and distribution of common ''sand'' dunes on Mars: Comparison with Earth, *J. Geophys. Res.*, *84*, 8183–8204, 1979.

Clifford, S. M., Chasma Boreale (85°N, 0°W): Remnant of a Martian jökulhlaup?, *Bull. Am. Astron. Soc.*, *12*, 678, 1980.

Clifford, S. M., Polar basal melting on Mars, *J. Geophys. Res.*, *92*, 9135–9152, 1987.

Cutts, J. A., Wind erosion in the Martian polar regions, *J. Geophys. Res.*, *78*, 4211–4221, 1973a.

Cutts, J. A., Nature and origin of layered deposits on the Martin polar regions, *J. Geophys. Res.*, *78*, 4231–4249, 1973b.

Cutts, J. A., K. R. Blasius, and W. J. Roberts, Evolution of Martian polar landscapes: Interplay of long-term variations in perennial ice cover and dust storm intensity, *J. Geophys. Res.*, *84*, 2975–2994, 1979.

Dial, A. L., Jr., Geologic Map of the Mare Boreum area of Mars, *U.S. Geol. Surv. Misc. Invest. Ser.*, *Map I-1640*, 1984.

Edgett, K. S., and M. C. Malin, The Martian north polar cap: Sedimentary aspects, paper presented at 2nd International Conference on Mars Polar Science and Exploration, Geol. Soc. of Can., Reykjavik, Iceland, 2000.

Fenton, L. K., and K. E. Herkenhoff, Topography and stratigraphy of the northern Martian polar layered deposits using photoclinometry, stereogrammetry, and MOLA altimetry, *Icarus*, *147*, 433–443, 2000.

Fishbaugh, K. E., and J. W. Head, North polar region of Mars: Topography of circumpolar deposits from Mars Orbiter Laser Altimeter (MOLA) data and evidence for asymmetric retreat of the polar cap, *J. Geophys. Res.*, *105*, 22,455–22,486, 2000.

Fisher, D. A., If Martian ice caps flow: Ablation mechanisms and appearance, *Icarus*, *105*, 501–511, 1993.

Greeley, R., Silt-clay aggregates on Mars, *J. Geophys. Res.*, *84*, 6248–6254, 1979.

Greeley, R., N. Lancaster, S. Lee, and P. C. Thomas, Martian aeolian processes, sediments, and features, in *Mars*, pp. 730–766, Univ. of Ariz. Press, Tucson, 1992.

Herkenhoff, K. E., Geology, composition, age and stratigraphy of the polar layered deposits on Mars, in *1st International Conference on Mars Polar Science and Exploration*, *LPI Contrib. 953*, pp. 18–19, Lunar and Planet. Inst., Houston, Tex., 1998.

Herkenhoff, K. E., and R. L. Kirk, Topography and stratigraphy of the polar layered deposits on Mars, paper presented at 2nd International Conference on Mars Polar Science and Exploration, Geol. Soc. of Can., Reykjavik, Iceland, 2000.

Herkenhoff, K. E., and B. C. Murray, Color and albedo of the south polar layered deposits on Mars, *J. Geophys. Res.*, *95*, 1343–1358, 1990.

Herkenhoff, K. E., and A. R. Vasavada, Dark material in the polar layered deposits and dunes on Mars, *J. Geophys. Res.*, *104*, 16,487–16,500, 1999.

Howard, A. D., The role of eolian processes in forming surface features of the Martian polar layered deposits, *Icarus*, *144*, 267–288, 2000.

Howard, A. D., J. A. Cutts, and K. R. Blasius, Stratigraphic relationships within Martian polar cap deposits, *Icarus*, *50*, 161–215, 1982.

Ivanov, A. B., and D. O. Muhleman, The role of sublimation for the formation of the northern ice cap: Results from the Mars Orbiter Laser Altimeter, *Icarus*, *144*, 436–448, 2000.

Johnson, C. L., S. C. Solomon, J. W. Head, R. J. Philips, D. E. Smith, and M. T. Zuber, Lithospheric loading by the northern polar cap on Mars, *Icarus*, *144*, 313–328, 2000.

Kolb, E. J., and K. L. Tanaka, Geologic history of the polar regions of Mars based on Mars Global Surveyor data, II, Amazonian Period, *Icarus*, *154*, 22–39, 2001.

Lancaster, N., and R. Greeley, Sediment volume in the north polar sand seas of Mars, *J. Geophys. Res.*, *95*, 10,921–10,927, 1990.

Malin, M. C., and K. S. Edgett, Sedimentary rocks of early Mars, *Science*, *290*, 1927–1937, 2000.

Malin, M. C., and K. S. Edgett, Mars Global Surveyor Mars Orbiter Camera: Interplanetary cruise through primary mission, *J. Geophys. Res.*, *106*, 23,429–23,570, 2001.

Malin, M. C., G. E. Danielson, A. P. Ingersoll, H. Masursky, J. Veverka, M. A. Ravine, and T. A. Soulanille, Mars Observer Camera, *J. Geophys. Res.*, *97*, 7699–7718, 1992.

Murray, B. C., L. A. Soderblom, J. A. Cutts, R. P. Sharp, D. J. Milton, and R. B. Leighton, Geological framework of the south polar region of Mars, *Icarus*, *17*, 328–345, 1972.

Murray, B. C., M. Koutnik, S. Byrne, L. A. Soderblom, K. E. Herkenhoff, and K. L. Tanaka, Preliminary geological assessment of the northern edge of Ultimi Lobe, Mars south polar layered deposits, *Icarus*, *154*, 80–97, 2001.

Neumann, G. A., D. D. Rowlands, F. G. Lemoine, D. E. Smith, and M. T. Zuber, The crossover analysis of Mars Orbiter Laser Altimeter data, *J. Geophys. Res.*, *106*, 23,753–23,768, 2001.

Nye, J. F., A flow model for the polar caps of Mars, *J. Glaciol.*, *46*, 438–444, 2000.

Paige, D. A., J. E. Bachman, and K. D. Keegan, Thermal and albedo mapping of the polar regions of Mars using Viking thermal mapper observations, 1, North polar region, *J. Geophys. Res.*, *99*, 25,959–25,991, 1994.

Saunders, R. S., and D. T. Blewett, Mars north polar dunes: Possible formation from low density sedimentary aggregates, *Astron. Vestn.*, *21*, 181–188, 1987.

Saunders, R. S., T. J. Parker, J. B. Stephens, E. G. Laue, and F. P. Fanale, Transformation of polar ice sublimate residue into Martian circumpolar sand, *NASA Tech. Memo., NASA TM*, *87563*, 300–301, 1985.

Saunders, R. S., F. P. Fanale, T. J. Parker, J. B. Stephens, and S. Sutton, Properties of filamentary sublimation residues from dispersions of clay in ice, *Icarus*, *66*, 94–104, 1986.

Squyres, S. W., The evolution of dust deposits in the Martian north polar region, *Icarus*, *40*, 244–261, 1979.

Smith, D. E., et al., Topography of the northern hemisphere of Mars from the Mars Orbiter Laser Altimeter, *Science*, *279*, 1686–1692, 1998.

Tanaka, K. L., and E. J. Kolb, Geologic history of the polar regions of Mars based on Mars Global Surveyor data, I, Noachian and Hesperian Periods, *Icarus*, *154*, 3–21, 2001.

Tanaka, K. L., and D. Scott, Geologic map of the polar regions of Mars, *U.S. Geol. Surv. Misc. Invest. Ser.*, *Map I-1802-C*, 1987.

Thomas, P. C., Present wind activity on Mars—Relation to large latitudinally zoned sediment deposits, *J. Geophys. Res.*, *87*, 9999–10,008, 1982.

Thomas, P. C., and P. J. Gierasch, Polar margin dunes and winds on Mars, *J. Geophys. Res.*, *100*, 5397–5406, 1995.

Thomas, P. C., and C. Weitz, Sand dune materials and polar layered deposits on Mars, *Icarus*, *81*, 185–215, 1989.

Thomas, P. C., S. W. Squyres, K. E. Herkenhoff, B. C. Murray, and A. D. Howard, Polar deposits on Mars, in *Mars*, pp. 767–795, Univ. of Ariz. Press, Tucson, 1992.

Toon, O. B., J. B. Pollack, W. Ward, J. A. Burns, and K. Bilski, The astronomical theory of climate change on Mars, *Icarus*, *44*, 552–607, 1980.

Touma, J., and J. Wisdom, The chaotic obliquity of Mars, *Science*, *259*, 1294–1297, 1993.

Tsoar, H., R. Greeley, and A. R. Peterfreund, Mars: The north polar sand sea and related wind patterns, *J. Geophys. Res.*, *84*, 8167–8180, 1979.

Ward, A. W., and K. B. Doyle, Speculation on Martian north polar wind circulation and resultant orientations of polar sand dunes, *Icarus*, *55*, 420–431, 1983.

Ward, W. R., and D. J. Rudy, Resonant obliquity of Mars, *Icarus*, *94*, 160–164, 1991.

Wessel, P., and W. H. F. Smith, New, improved version of Generic Mapping Tools released, *Eos Trans. AGU*, *79*(47), 579, 1998.

Zuber, M. T., D. E. Smith, S. C. Solomon, D. O. Muhleman, J. W. Head, J. B. Garvin, J. B. Abshire, and J. L. Bufton, The Mars Observer Laser Altimeter investigation, *J. Geophys. Res.*, *97*, 7781–7797, 1992.

Zuber, M. T., et al., Observations of the north polar region of Mars from the Mars Orbiter Laser Altimeter, *Science*, *282*, 2053–2060, 1998.

S. Byrne and B. C. Murray, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91106, USA. (shane@gps.caltech.edu)

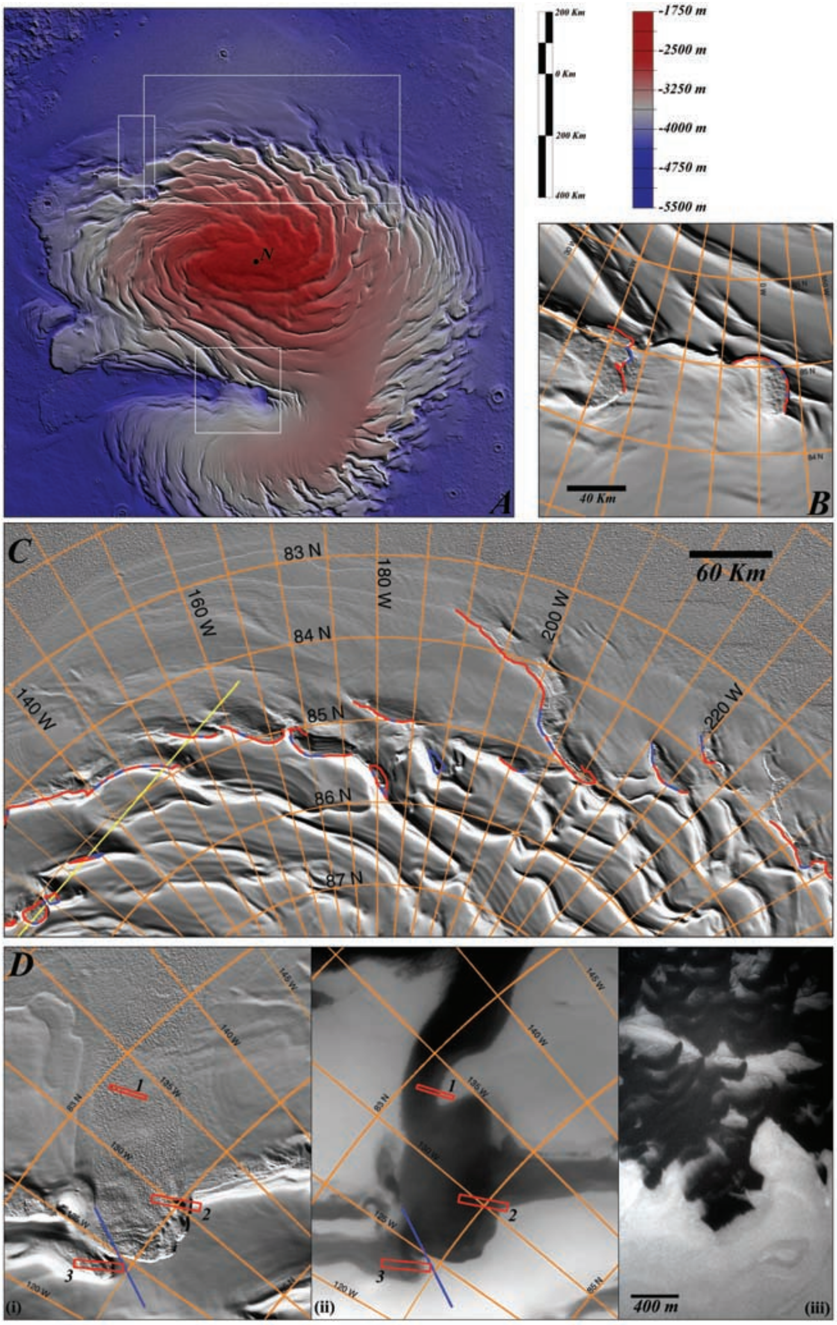

Figure 1. (a) Digital elevation model (DEM) constructed from ~28 million altimetry measurements made by Mars Orbiter Laser Altimeter (MOLA). Vertical and horizontal scales are in the upper right. The DEM extends to fully include the 80th parallel and is artificially illuminated from the upper right. White boxes indicate the positions of other subframes in Figure 1. (b) Derived shaded relief image of the region containing the head of Chasma Boreale is shown. Colored lines indicate where the contact between the finely and platy units can be mapped from the shaded relief map (red) and confirmed with Mars Orbiter Camera (MOC) narrow-angle frames (blue). (c) Derived shaded relief image showing area of residual cap edge centered on 180°W. Red and blue lines have the same meaning as in Figure 1b. The yellow line in the lower left indicates the position of the topographic profile shown in Figure 3. (d) Area of cap edge at 130°W shown in (i) shaded relief and (ii) MOC wide-angle M01/01617. This shows the correspondence of rough texture in shaded relief to dark albedo regions in the visible images, commonly associated with sand dunes. The blue line indicated in (i) and (ii) represents the position of the MOLA profile shown in Figure 7. MOC narrow-angle outlines 1, 2, and 3 represent positions of Figure 1d (iii), Figure 8, and Figure 9, respectively. (iii) Section of MOC narrow-angle image M03/01003 (illumination from the upper right) showing the contact between dark/light, textured/smooth areas, confirming the transition from a dune to nondune area. The outline of this image is shown as 1 in Figure 1d (i) and Figure 1d (ii).