



High-latitude cold-based glacial deposits on Mars: Multiple superposed drop moraines in a crater interior at 70°N latitude

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(Received 03 November 2005; revision accepted 15 March 2006)

Abstract—An impact crater 26.8 km in diameter, located in the northern lowlands (70.32°N, 266.45°E) at the base of the flanking slopes of the shield volcano Alba Patera, is characterized by highly unusual deposits on its southeastern floor and interior walls and on its southeastern rim. These include multiple generations of distinctive arcuate ridges about 115–240 m in width and lobate deposits extending down the crater wall and across the crater floor, forming a broad, claw-like, ridged deposit around the central peak. Unusual deposits on the eastern and southeastern crater rim include frost, dunes, and a single distal arcuate ridge. Based on their morphology and geometric relationships, and terrestrial analogs from the Mars-like Antarctic Dry Valleys, the floor ridges are interpreted to represent drop moraines, remnants of the previous accumulation of snow and ice, and formation of cold-based glaciers on the crater rim. The configuration and superposition of the ridges indicate that the accumulated snow and ice formed glaciers that flowed down into the crater and across the crater floor, stabilized, covering an area of about 150 km², and produced multiple individual drop moraines due to fluctuation in the position of the stable glacier front. Superposition of a thin mantle and textures attributed to a recent ice-age period (~0.5–2 Myr ago) suggest that the glacial deposits date to at least 4–10 Myr before the present. At least five phases of advance and retreat are indicated by the stratigraphic relationships, and these may be related to obliquity excursions. These deposits are in contrast to other ice-related modification and degradation processes typical of craters in the northern lowlands, and may be related to the distinctive position of this crater in the past atmospheric circulation pattern, leading to sufficient preferential local accumulation of snow and ice to cause glacial flow.

INTRODUCTION AND BACKGROUND

It has long been known that Mars contains polar caps and that they are largely composed of water ice and dust. Less well understood are the presence and nature of glacial flow in polar regions (e.g., Thomas et al. 1992), the possibility of glacial processes operating outside the polar regions (e.g., Lucchitta 1981), and the mode of formation of circumpolar craters (e.g., Garvin and Frawley 1998; Garvin et al. 2000a, 2000b, 2002) that contain significant high-albedo mounds and deposits (e.g., Garvin et al. 2000b; Russell and Head 2005).

Recent studies have shown that deposits similar to those of debris-covered glaciers occur in mid-latitude impact craters (e.g., Marchant and Head 2003; Perron et al. 2003;

Kargel 2004), and that circumpolar craters (65–80° latitude) currently contain remnant ice deposits (Garvin et al. 2000b) some of which may be glacial in origin (e.g., Russell and Head 2005). Analysis of new data from spacecraft exploring Mars (Head and Marchant 2003; Shean et al. 2005) and a better understanding of glacial processes in terrestrial, hyperarid, cold polar deserts analogous to the Mars environment (Marchant and Head 2004) have led to the documentation of tropical mountain glaciers and their distinctive deposits (e.g., Head et al. 2003; Shean et al. 2005; Parsons and Head 2005; Milkovich et al. 2006), as well as mid-latitude deposits of apparent glacial origin (e.g., Head et al. 2006a, 2006b).

Most circumpolar craters that show evidence of icy fill (65–80° latitude) have distinctive concentrations of ice

around the central peak (e.g., Korelev), lobate deposits attached to polar layered terrain, or isolated mounds of material usually along the base of the pole-facing crater wall (e.g., Russell et al. 2004; Russell and Head 2005). Here we report on a crater in the same 65–80° latitude range, but with a distinctly different crater interior deposit. We describe the crater occurrence and characteristics, its distinctive deposits that we interpret to be remnant drop moraines, and the conditions and sequence of events implied in the origin and evolution of the deposits. We conclude that this unusual deposit represents the remnants of a cold-based glacier that formed as a result of snow and ice accumulation on the southeastern rim of the crater due to localized environmental conditions; the resulting cold-based glacier flowed down the crater wall, climbed the central peak structure and was passively diverted by it, and then underwent several phases of advance and retreat. These deposits appear to be very young in age.

DESCRIPTION OF THE CRATER AND DEPOSITS

The unusual deposits occur in association with a crater 26.8 km in diameter located in the northern lowlands (70.32°N, 266.45°E) at the base of the flanking slopes of the huge shield volcano Alba Patera, which forms the northern flank of the Tharsis Rise (Fig. 1). The crater formed at an elevation of about –4304 m and is about 1.6 km deep (Table 1). The impact occurred on the Late-Hesperian-aged to Early-Amazonian-aged Vastitas Borealis Formation (Tanaka and Scott 1987; Tanaka et al. 2004; Boyce et al. 2005) (Figs. 1b and 1c). The crater is characterized by a somewhat degraded lobate ejecta deposit (Fig. 1c), a distinctive central peak rising about 430 m from the crater floor (Figs. 2 and 3), and a relatively flat floor, with the northwestern portion of the floor being the deepest (Figs. 2 and 3). Topographic maps and profiles (Figs. 2 and 3) show that the southeast portion of the floor is shallower and lies about 250 m above the northwest floor. Altimetric profiles (Fig. 2) show that at the resolution of the Martian Orbiter Laser Altimeter (MOLA) gridded data set, the upper wall slopes are in the 8–14° range, and the lower wall slopes are in the 3–8° range. The profiles also suggest that crater walls are steeper on the southeast than the northwest (Fig. 3) (A–A').

Thermal Emission Imaging System (THEMIS) data reveal the presence of a complex set of linear and arcuate ridges, ranging from ~115 to 240 m in width (the average of 35 measurements is 175 m), extending from near the southeastern crater wall base out onto the crater floor (Figs. 4 and 5). Due to the small width of the ridges, MOLA data do not provide precise measurements of ridge heights, but multiple individual orbit profiles that cross the ridges (for example, those shown in Fig. 3) suggest that they range up to 20–30 m in height and about 100 m in width, and generally appear symmetrical.

Along the crater floor and basal wall, the ridges are oriented generally radially to the crater, extending as linear ridges hundreds of meters to several kilometers long (Figs. 4 and 5). On the crater floor, some of the ridges become arcuate and lobate in form and display complex intersecting and superposition patterns (Fig. 5). In the vicinity of the central peaks, the ridges display multiple tight lobate patterns, forming a bifurcating, claw-like structure around the base and southeastern flank of the central peak (Fig. 5). Some ridges, particularly the marginal ones, are very continuous and extend as much as ~15 km from the lower crater wall out onto the crater floor. Overall, the set of ridges form a distinctive sweeping pattern extending from near the southeastern crater wall base out onto the floor and central peak, where they form the claw-like structure on and around the central peak (Fig. 5). The ridges are more continuous toward the margins of the deposits and in the area surrounding the central peak, and evidence for the multiple phases and overlapping relationships are seen more readily on the floor and area surrounding the central peaks (Fig. 5). Perspective views (Fig. 4) emphasize that the set of ridges forms a contiguous deposit extending down the wall and out onto the floor, rising up onto the central peak summit and then bifurcating and forming two complex and multicomponent marginal lobes. The southern lobe extends ~2 km further than the northern one (Fig. 5), actually rising up onto the base of the western crater wall (Fig. 2). All concentric ridge structures are convex outward, away from the southeastern wall. Overlapping ridges (see arrows in Fig. 5b) indicate superposition relationships that imply at least five phases of successive lobe formation. Although Mars Orbiter Camera (MOC) images of the ridges on the floor are not currently available, the ridges themselves appear generally laterally continuous at local scales and symmetrical in cross-section in THEMIS data. Associated features on the crater floor include a dark patch (Fig. 5a), interpreted to be eolian dune deposits superposed on the lobate deposit on the southeastern slope of the central peak. No evidence of additional structures, such as fractures, gullies, or channels was observed. Superposition relationships show that the deposit largely overlies radial wall textures and deposits at the base of the walls (Figs. 4 and 5).

The THEMIS image centered on the crater interior (Fig. 2) does not provide coverage of the upper crater wall, but insight into the geology there is provided by a MOC image (Figs. 6 and 7) that partially overlaps the THEMIS image (Fig. 7a). Here the morphology can be subdivided into four zones (Figs. 7b and 7c). The lowermost zone 1 overlaps with several of the ridges in the THEMIS image and extends for several kilometers across the crater wall and about 150 m up the crater wall (Fig. 7d), where the ridges tend to die out and be replaced by zone 2, which is characterized by a more hummocky terrain that represents the middle parts of the crater interior wall. The boundary between these two zones, and indeed some of the deposits within zone 1, are lobate (see

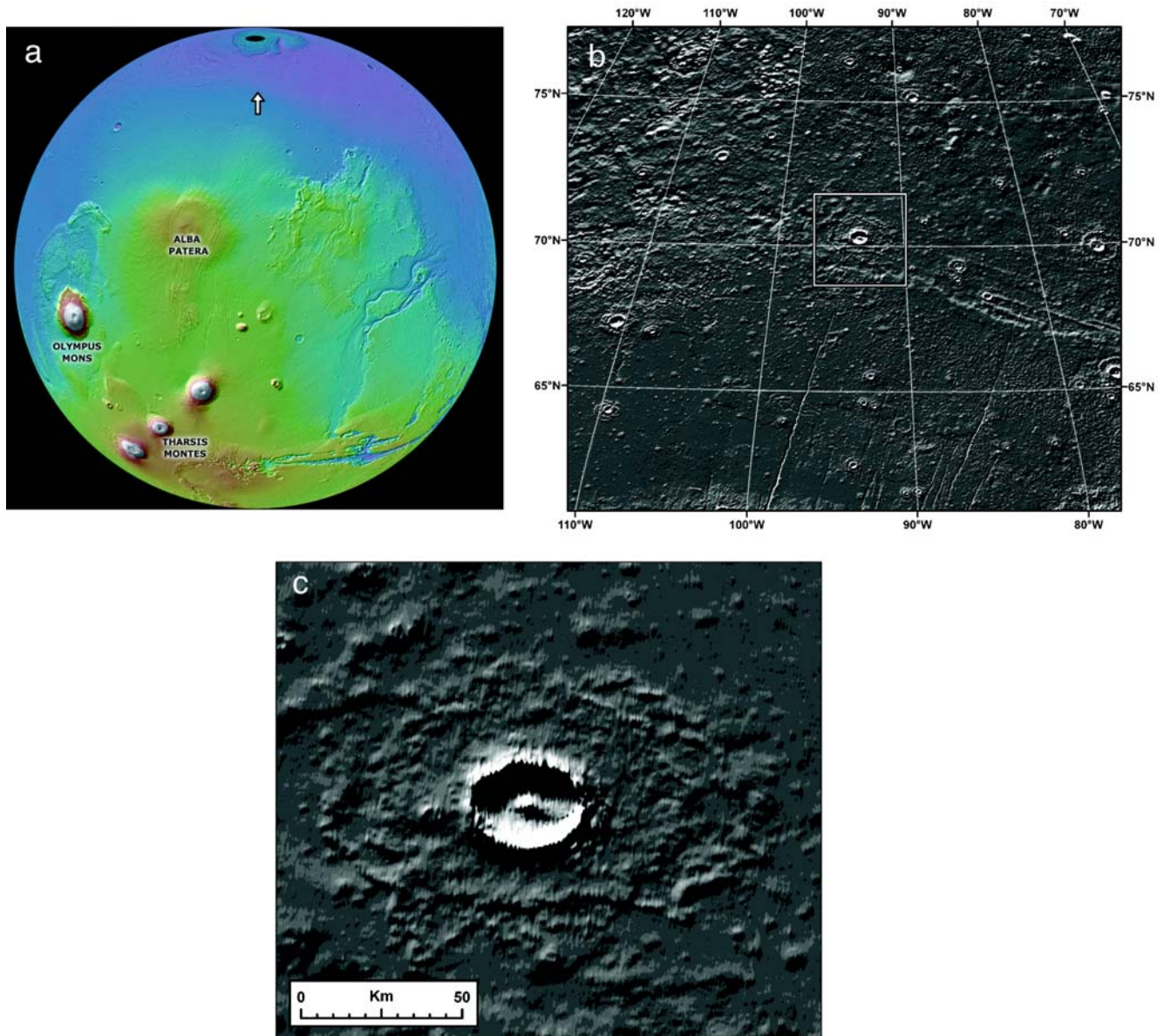


Fig. 1. A location map for the crater. a) A global view centered on 34°N, 265°E, showing the Tharsis Rise (lower left), Alba Patera (center left), and the northern lowlands (upper, purple). The arrow indicates the crater location at 70.32°N, 266.45°E. b) A MOLA gradient context image showing the detailed location and morphology of the crater at the base of the Alba Patera rise (smooth area with several graben in the bottom of the image) and the rougher northern lowlands. c) A MOLA gradient context image showing the detailed morphology of the crater. North is to the top in this and all other images.

the outward facing scarps in zone 1 indicated by tick marks in Fig. 7c). Zone 3 is near the rim crest and is characterized by a very distinctive texture of relatively dark domes 10–20 m in diameter, very similar to the bumpy basketball-textured terrain seen on the latitude dependent mantle (Kreslavsky and Head 2000, 2002; Mustard et al. 2001; Head et al. 2003). Although this terrain is very well developed in this zone, this same texture is seen throughout all four zones in this image. Zone 4 is on the crater rim and consists of a series of dune-like ridges that are oriented parallel to slightly tangential to the

crater rim crest. At the innermost ridge (about at the location of the rim crest), a white, frost-like patch is seen and several other patches of bright, frost-like deposits occur in the inter-ridge areas. This image was taken at L_s of 108°, at the beginning of northern summer.

An additional MOC image covers a portion of the southeastern rim of the crater (Figs. 6 and 8) and shows that the dune-like features extend for an additional several kilometers out onto the rim. Five zones can be mapped in this image (Figs. 8b and 8c). The boundary between zone 1 and 2

Table 1. Crater morphometric parameters: MOLA Crater c010204 (data from Garvin et al. 2002).

Latitude	70.32°N
Longitude	266.45°E
Elevation	−4303.6 m
Diameter	26.8 km
Depth	1624 m
Apparent diameter	23.1 km
Rim height	446 m
Ejecta diameter	73.6 km
Central peak diameter	9.7 km
Central peak height	434 m
Depth/diameter	0.0601
Area	591 km ²
Volume	593.3 km ³
Ejecta volume	264.5 km ³
Regional slope	0.1°
Central peak area	74.2 km ²
Central peak volume	12.6 km ³

represents the approximate crater rim crest. Zone 2 contains the dune-like ridges, which generally have a spacing of ~160–200 m, but are spaced up to 300–400 m and appear to represent reworked material on the crater rim. They occur on the steepest portion of the crater rim just exterior to the rim crest (see Figs. 6 and 7d). They could represent the result of viscous flow of ice-rich material perhaps related to the evolution of the ice-rich deposit (e.g., gelifluction or solifluction lobes). Alternatively, they could be eolian dunes related to circulation patterns influenced by the presence of the crater. The distribution of these dune-like features and the interpretation of them as formed by eolian reworking is strengthened by the bright, streak-like deposit seen extending about 60 km downrange from the crater rim in an ESE direction in the MOC narrow-angle (NA) image (Fig. 8a). Southeast of the dune-like features, the surface is broadly smoother (zone 3) and the topography of the underlying ejecta deposit and precrater substrate can be seen (zone 4). At the lower margin of the MOC coverage of this area, a single broadly arcuate ridge about 100 m in width is observed (defining the boundary between zones 3 and 5, marked “A” in Fig. 8c), which is similar in morphology and scale to the ridges seen within the crater (Figs. 5 and 8e). Also observed is a single, fresh-appearing impact crater about 400 m in diameter with a distinctive lobate ejecta deposit (Fig. 8d; marked “B” in Fig. 8c).

The western rim and crater interior differ considerably from the eastern rim and interior (Figs. 6 and 9) with no evidence for the large dune-like features, ridges, or bright frost patches seen on the southeastern rim, and no radial ridges or lobe-like deposits on the crater inner wall (compare Figs. 8 and 9). Most of the surface of the rim and wall is characterized by a thin, hummocky mantling material that appears to uniformly cover the area except for topographic prominences on the crater rim and wall.

The superposition relationships of the ridges and the internal stratigraphy of the deposit (Figs. 4, 5, and 10) show that the ridges form several sets of broad, continuous lobes of different sizes that are superposed on one another, often with no disruption of the underlying ridges, but in many cases apparently obscuring them due to deposition. Cross-cutting and overlapping relationships were determined and the sequence of lobe emplacement defined by these overlapping relationships is shown in Fig. 10. The first stage appears to be a broad lobe that extends from the wall out onto the crater floor to the base of the central peaks. The second stage extends further out onto the crater floor and bifurcates more around the base of the central peak. The third stage is the most areally extensive, extends down the wall and across the floor, and splits in a claw-like pattern around the central peak, with the southern part of the claw extending up onto the lower part of the far crater wall. The total distance from the crater rim crest to the distal part of this phase is about 20 km. The fourth stage crosses the floor and bifurcates at the central peak, climbing nearly to the peak summit, but does not extend as far across the crater floor as the third phase. The fifth and apparently last phase is limited in both width and extent, extends down the wall and out to the base of the central peak in a swath about 3.5 km wide.

INTERPRETATION

Linear and arcuate ridges can form from a variety of processes known to operate on the surface of Mars. Contractional deformation can form arcuate and sinuous wrinkle ridges a few kilometers wide with smaller superposed sinuous ridges (e.g., Golombek et al. 1991; Watters 1991). These occur in parallel bands (e.g., the Hesperian ridged plains) that extend for hundreds to thousands of kilometers in broad patterns. The shape and form of these differ substantially from the ridges described here (Figs. 2–5). Removal of overburden or younger deposits can exhumate subsurface structures that then form ridges due to their more competent nature, such as breccia dikes on crater floors (e.g., Head and Mustard 2005a, 2005b), and magmatic dikes (e.g., Head et al. 2006c). Instead of geologic and stratigraphic relationships suggesting exhumation, however, the features described here appear to be depositional on a relatively fresh crater floor.

Landslide deposits and impact crater exterior ejecta deposits are often characterized by marginal scarps (e.g., Lucchitta et al. 1992; Strom et al. 1992). The deposits described here, however, are inside rather than outside the crater, and there is no nearby crater that might have emplaced ejecta lobes in the crater interior (Fig. 1). Furthermore, the rim crest of the crater in the area where the ridges appear to originate does not appear to be scalloped in a manner that might suggest wall slumping and landslide deposits. Crater interiors are often modified by downslope mass wasting of

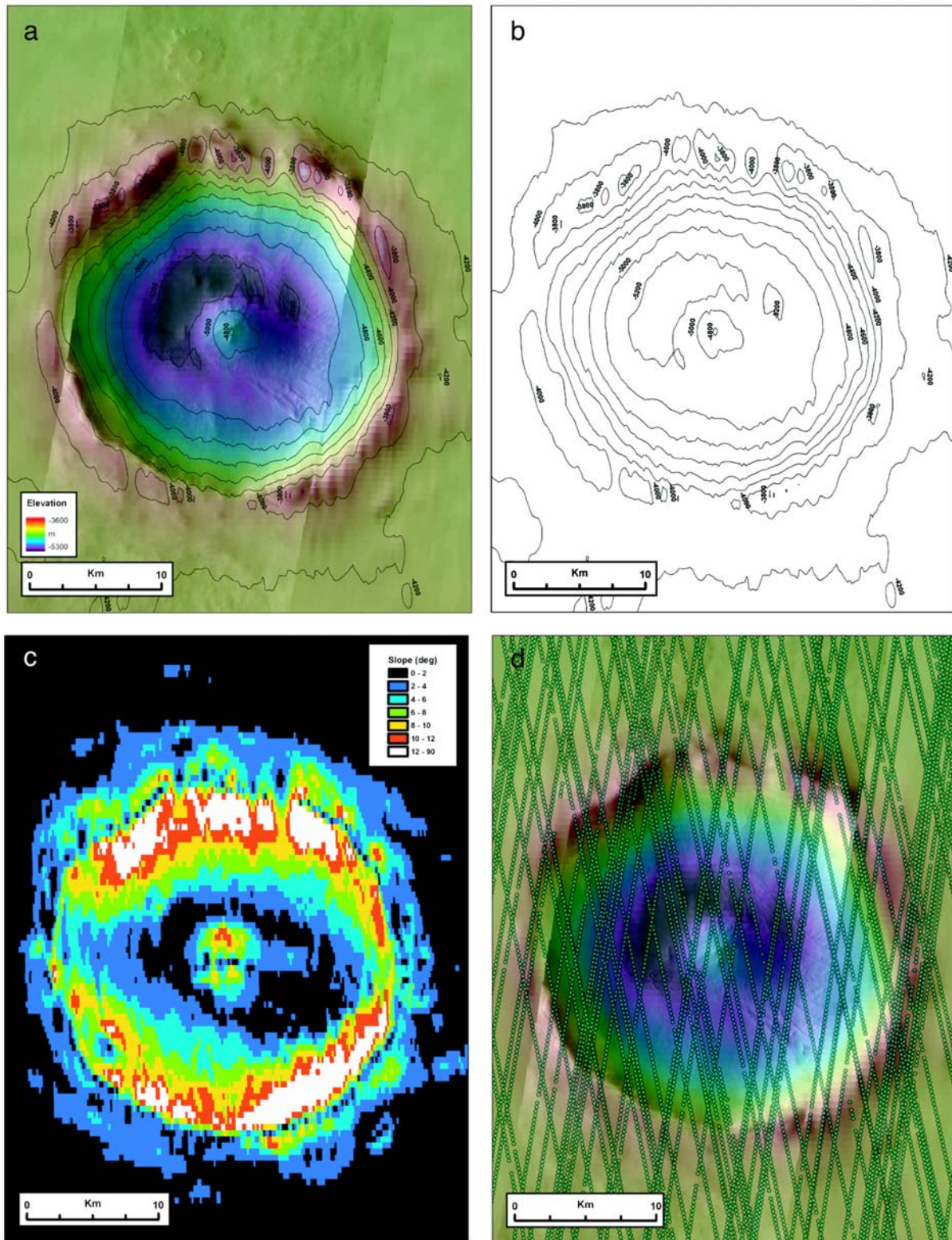


Fig. 2. Crater topography and slopes. a) MOLA gridded altimetry data superposed on THEMIS image V05259017, with 200 m contour lines superposed. b) A contour map compiled from MOLA gridded topography (128 pixels per degree), 200 m contour interval. c) A slope map compiled from MOLA gridded topography. The slope baseline is ~ 450 m. d) MOLA gridded altimetry data (128 pixels per degree) superposed on THEMIS image V05259017, showing the ground tracks and laser spot locations from the MOLA data used to derive the gridded data set and profiles.

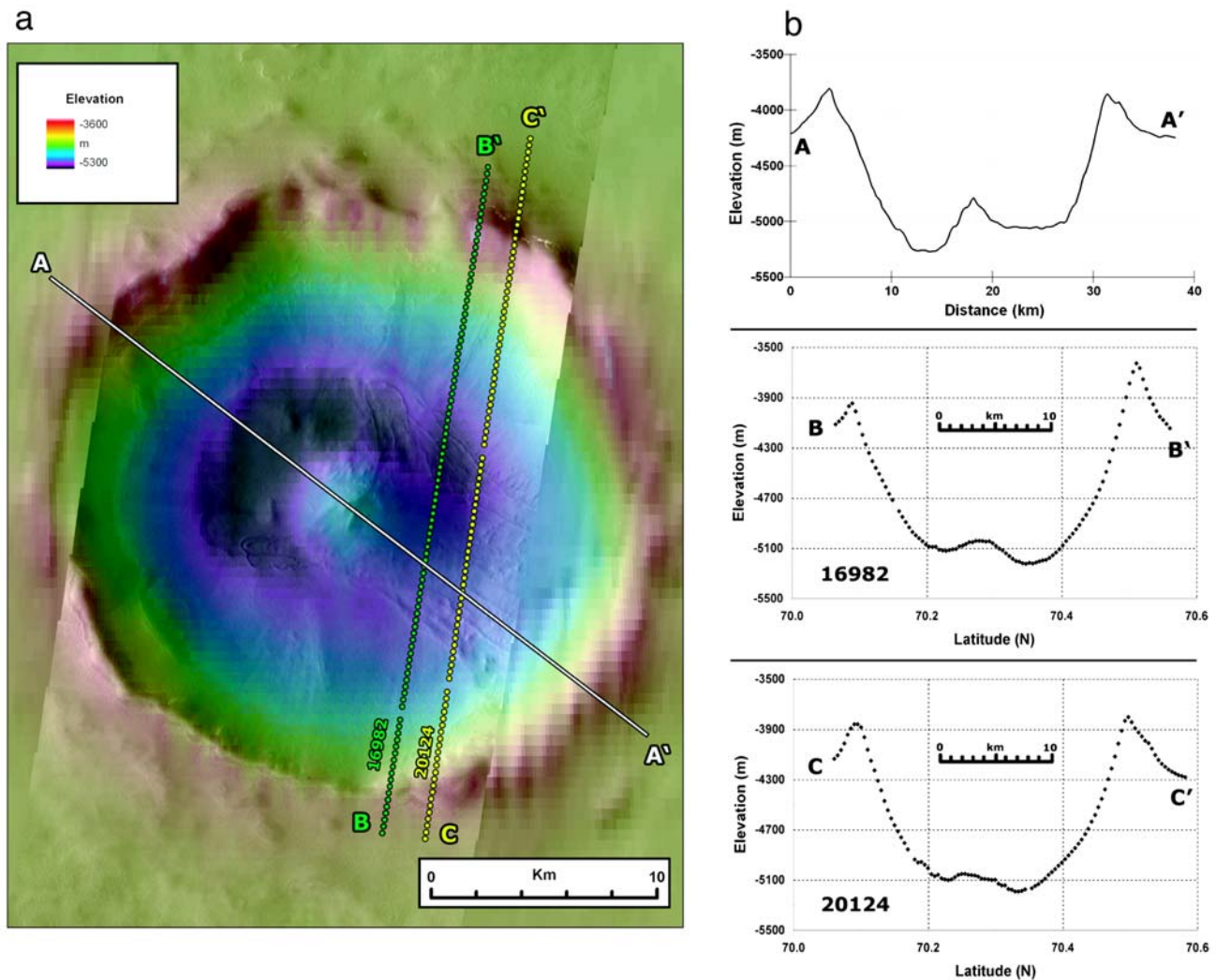


Fig. 3. Topographic profiles. a) A location map for profiles. b) A topographic profile along A-A' from gridded data set (128 pixels per degree). A topographic profile along B-B' from MOLA orbit 16982. A topographic profile along C-C' from MOLA orbit 20124.

material from the upper crater walls and the formation of talus lobes and aprons. Indeed, such talus lobes are seen on the crater wall inside this crater (Figs. 4a, 4b, 5a, and 7a); However, they differ in morphology and are superposed by the ridges (Fig. 5a). Although ridges are produced at the margins of some landslides, material deposits of the landslide proper commonly remain within the ridge, producing a ridged topographic stepdown at the edge of the deposit. Here, however, the ridges appear much more symmetrical and there is little evidence for the interior deposits common to landslides. Landslides also commonly respond to preexisting topography, with preferential thickening where the landslide approaches and interacts with positive topography. Here, however, the ridges show little, if any, variation in thickness, width, and morphology in relation to underlying topography, such as at the central mound on the crater floor (Fig. 5).

Sinuuous and arcuate ridges can also form as a result of sedimentary processes. For example, streams that produce

deposits that are coarser than surrounding deposits can sometimes be preferentially eroded to form ridges representing inverted stream deposits (e.g., Malin and Edgett 2003). However, the location of the ridges described here on crater interior walls, crater floors, and on the slopes of the central peak, and their broadly looping and arcuate nature, together with a lack of any evidence for associated fluvial structure (branching features, dendritic patterns, deltas, etc.) (e.g., Fassett and Head 2005), all argue against a fluvial and inverted stream origin. Another possible sedimentary process is subglacial stream formation, or eskers. Head and Pratt (2001) mapped a sequence of sinuous ridges interpreted to be esker deposits in the south circumpolar Dorsa Argentea Formation. Although the deposits mapped here display topographic characteristics common to eskers (e.g., sometimes extending up slope, such as at the base of the central peak, and showing superposition relationships), the patterns of the features

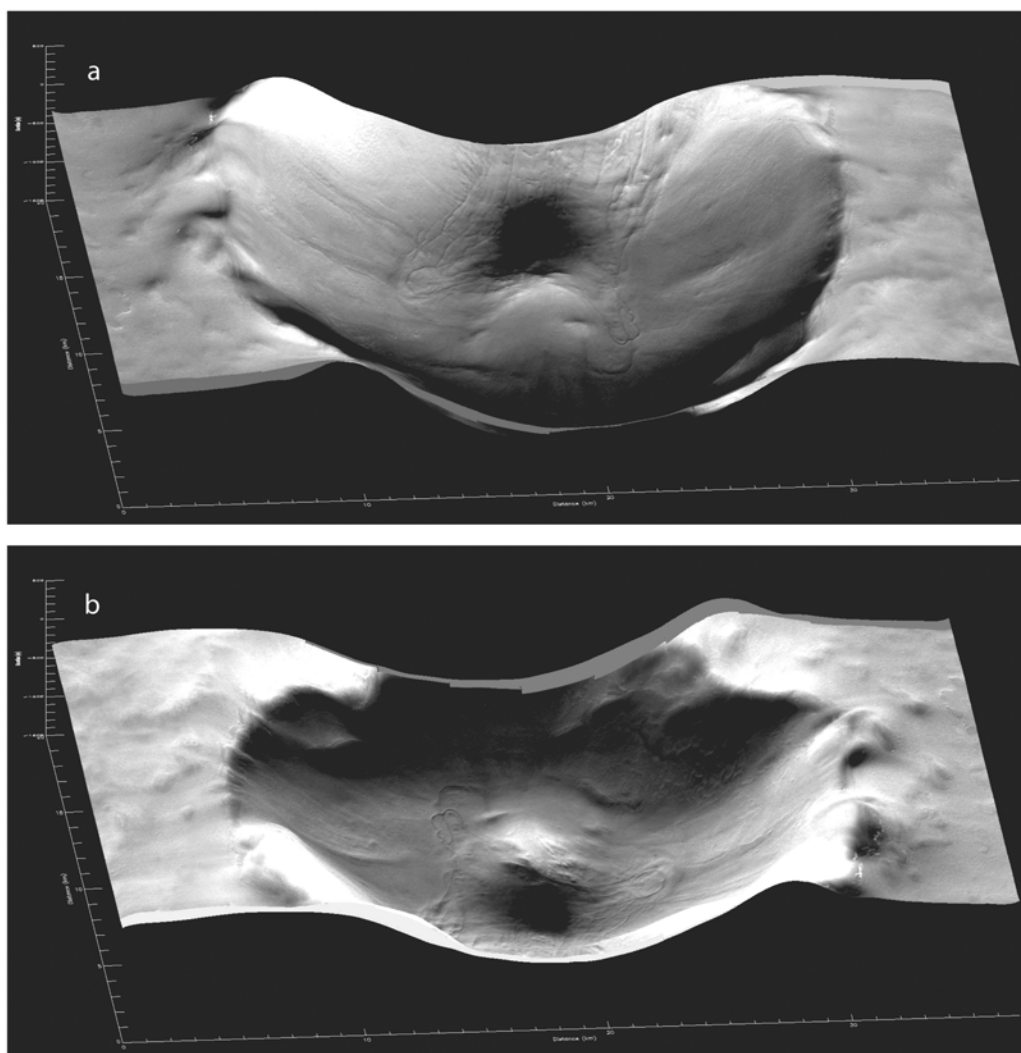


Fig. 4. Perspective views of crater interior (THEMIS V05259017 superposed on MOLA altimetry topographic base). a) Looking southeast. b) Looking northwest.

interpreted to be eskers are very different (e.g., dendritic, rather than arcuate and lobate) than the patterns mapped in the deposits in this crater.

The features on Mars most similar to the deposits seen in this crater are the patterns of ridges observed around the margins of the huge lobate fans on the northwest flanks of the Tharsis Montes (e.g., Williams 1978; Lucchitta 1981; Zimbelman and Edgett 1992; Scott and Zimbelmann 1995; Head and Marchant 2003; Shean et al. 2005; Parsons and Head 2005). These ridges, mapped as the ridged facies of the fan-shaped deposit, are typically 200–1100 m in width, 5–50 m in height, and can extend for tens to hundreds of kilometers (Fig. 11). Although historically interpreted in several different ways (e.g., as landslides, pyroclastic flows, glacial deposits, etc.), new data have confirmed earlier interpretations (e.g., Williams 1978; Lucchitta 1981) that they are of glacial origin (e.g., Head and Marchant 2003; Shean

et al. 2005). These latter studies have shown that many glacial deposits on Mars represent the process of cold-based glaciation (Head et al. 2005a, 2005b), which produces a distinctive set of features known as drop moraines. These features, well displayed in the Antarctic Dry Valleys (Fig. 12) (Marchant et al. 1993, 1994), form when two processes are in equilibrium: 1) sublimation from the glacier front, and 2) ice forward velocity. In this condition, there is no net movement of the glacier front, although the glacier itself, composed of ice and debris, continues to move forward to the margin of the glacier. Thus, as the ice and contained debris move forward to the margins of the glacier, the ice sublimates, and the debris falls out of the ice and drops to the front, forming accumulations known as “drop moraines.” When the equilibrium of the system is disturbed (for example, by increased sublimation rates along the ice front or increased ice forward velocity), retreat or advance of the ice front will

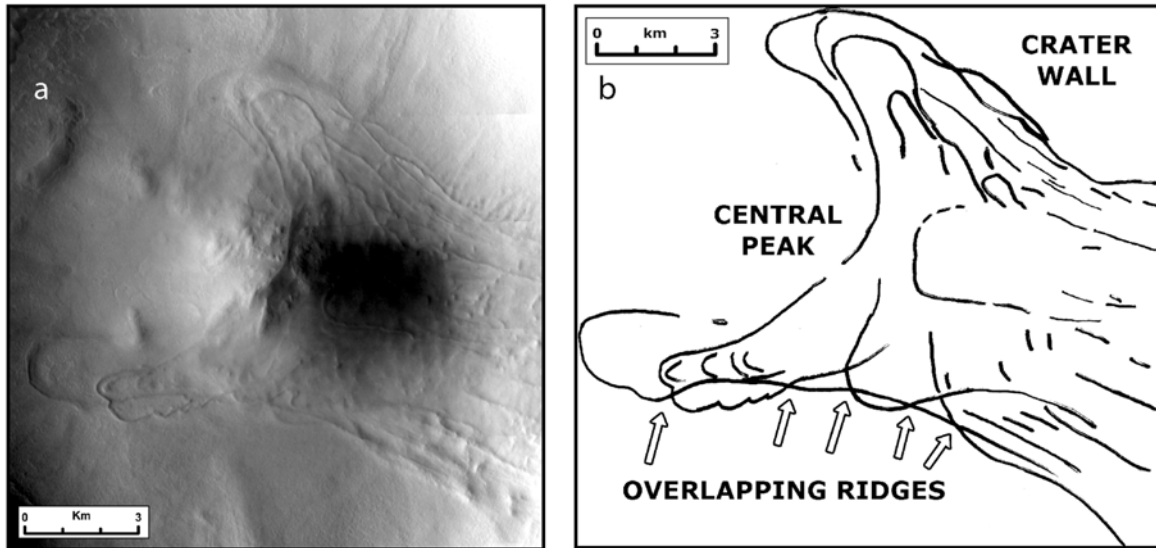


Fig. 5. The crater interior wall, floor structure, and morphology. a) A portion of THEMIS image V05259017. b) A sketch map of the ridges and their relationships. See Figs. 1 and 2 for context.

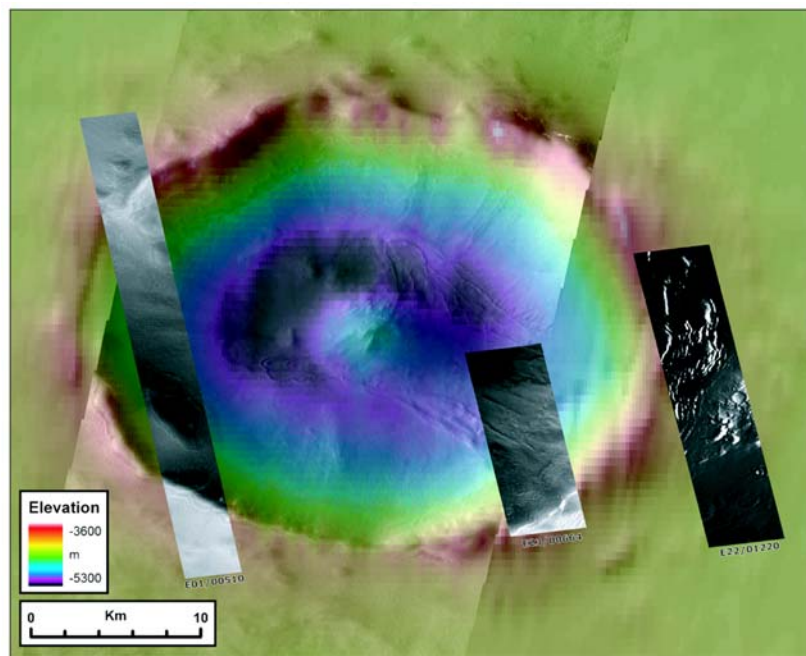


Fig. 6. Mars Orbiter Camera (MOC) coverage of the crater. MOLA topography overlain on THEMIS image V05259017 with MOC NA images E01-00510 (left), E23-00664 (middle), and E22-01220 (right).

occur, and a new drop moraine will form when equilibrium is again reached. In this manner, a series of drop moraines can form parallel concentric ridges marking the successive stands of the cold-based glacier margin. Multiple examples of such drop moraines are seen in the Antarctic Dry Valleys (e.g., Brook et al. 1993; Marchant et al. 1993, 1994) (Fig. 12) and dozens of such parallel ridges interpreted to be drop moraines (Fig. 11) are observed on the Arsia Mons tropical mountain glacier (e.g., Marchant and Head 2003).

The single ridge seen on the margin of the deposit on the southeastern crater rim (Fig. 8) is also interpreted as a drop moraine. This ridge probably marked the position of the ice rim accumulation on the relatively shallow outer rim slope, while the maximum ice accumulation on the rim crest fed the glacial lobes that extended down the much steeper crater interior and out onto the crater floor.

Additional examples of ridges have also been observed in crater interiors (Fig. 13) and have been interpreted to be

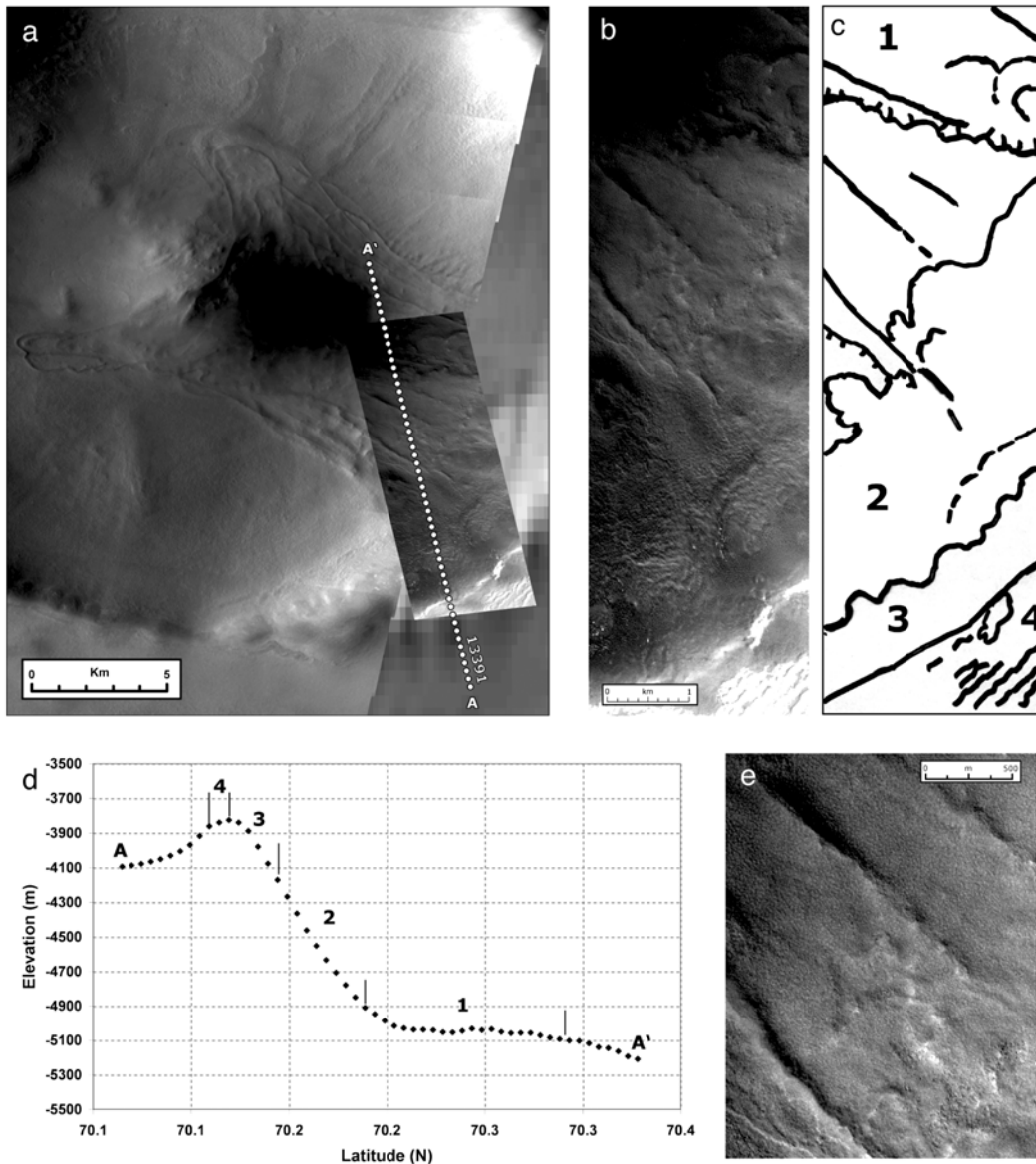


Fig. 7. The morphology and structure of the southeastern crater floor, wall, and rim. a) The location of MOC image E23-00664 and MOLA profile from orbit 13391. b) MOC image E23-00664; 3.4 m resolution, L_s 108.44°. c) A sketch map showing zones mapped in image (see text for description), ridges in zone 1 and 2 (straight lines), scarps in zone 1 (hatched on down slope), dune-like features on the rim (wiggly lines), and frost patch on rim (enclosed area to the left of 4). d) MOLA altimetric profile (orbit 13391) showing the location of the different zones (Figs. 7a and 7c) in relation to topography of the crater rim and interior. e) An enlargement of the ridges in zone 1.

due to the accumulation of snow and ice in alcoves in the crater wall, the formation of glaciers, their flow down the wall and out onto the crater floor, and their ultimate sublimation and volatile loss, leaving the deposits currently observed (Marchant and Head 2003; Marchant et al. 2003). These features differ from the ones described here in that they appear to originate from alcoves in the crater wall, rather than on the rim, and they represent a number of individual lobes originating from indentations (alcoves) in the upper part of the crater wall, rather than from a broader sheet-like deposit on the crater rim.

DISCUSSION

In summary, the ridges described here (Figs. 1–8) are most similar to ridges associated with cold-based glaciers on Earth (Marchant et al. 1993, 1994) and Mars (Marchant and Head 2003; Head and Marchant 2003; Shean et al. 2005). On the basis of the size and morphology of the ridges, the convex outward shape of their planform, their clear control by the topography of the wall and central peak, their discrete patterns, and their multiple superposition relationships, we interpret the ridges to be moraines associated with phases of

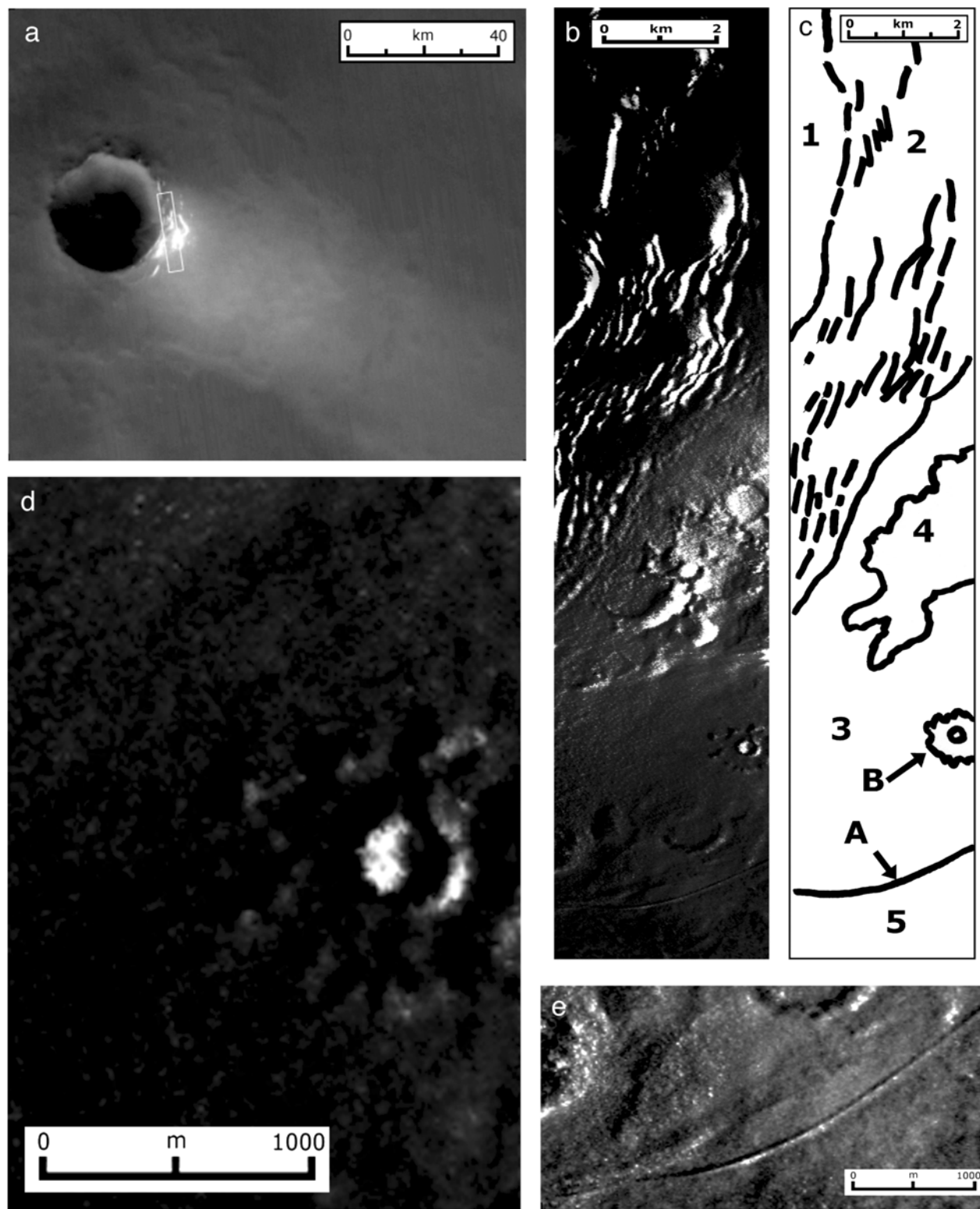


Fig. 8. The crater southeast rim, frost patches, and bright streak. a) MOC WA image E22-01221 showing the location of MOC NA image E-22-01220. Also seen is an extensive bright frost patch and a bright streak 40–50 km from the crater rim crest. L_s is 98.72°. b) MOC NA image E-22-01220; resolution is 13.5 m. c) A sketch map showing the location of the major features and structures in b). d) A small impact crater on the crater rim; note the unusual ejecta deposit. A portion of MOC NA E-22-01220. e) An arcuate ridge located in the lower portion of MOC NA E-22-01220.

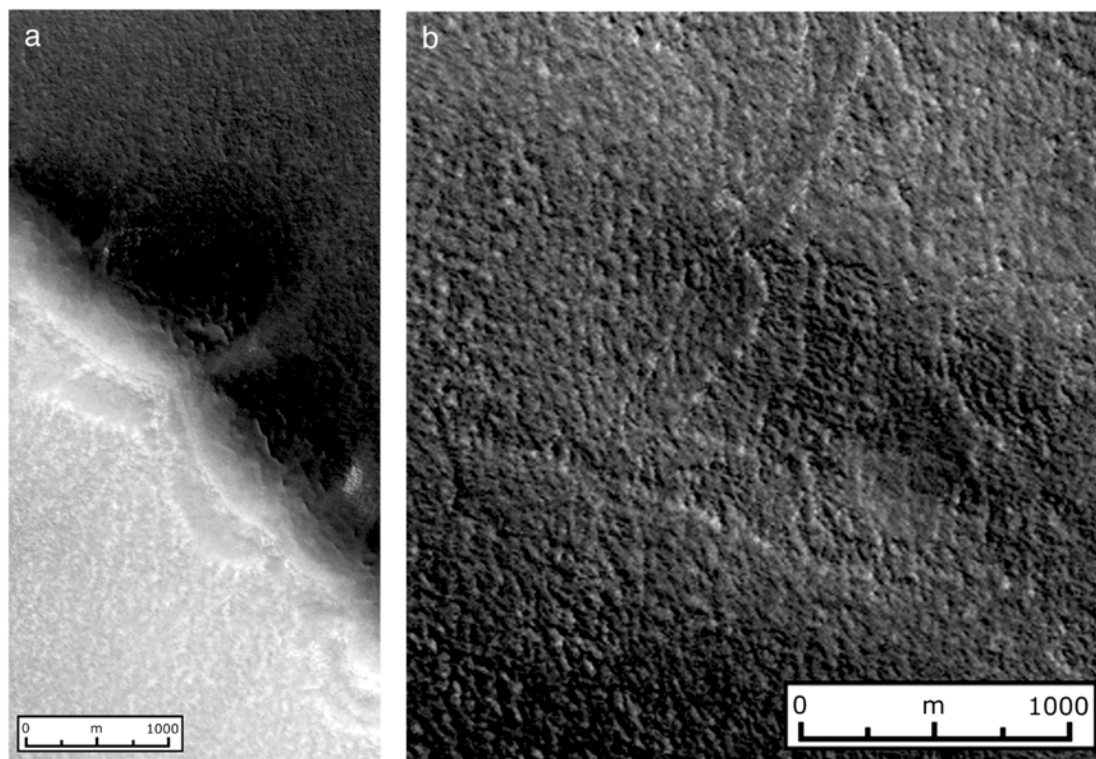


Fig. 9. The crater's western rim and interior wall. Portions of MOC NA image E01-00510 (8 m resolution; L_s 114.37°) showing tens of meter-scale hummocky texture on the crater's rim and interior. a) The southwest rim crest, rim, and crater's inner wall, showing a hummocky pattern, except on the steepest slopes. b) A hummocky pattern on the crater's interior wall (middle of MOC image E01-00510). See Fig. 6 for context.

advance of glacier lobes from the southeastern margins of the crater wall and rim.

In this interpretation, snow, ice, and dust accumulated on the southeastern rim and wall, flowed down the wall and out onto the crater floor, incorporating debris and riding up on the central peaks, and then bifurcating and extending partially out onto the northwest crater floor. Changing climate conditions caused the retreat of the ice, leaving moraines and deposits of glacial till. Distinctive superposition relationships suggest that advance and retreat occurred several times, and sharp preservation of underlying moraines below later moraines suggests cold-based glacial conditions (Marchant et al. 2003, 2004; Cuffey et al. 2000; Head and Marchant 2003).

When did this deposit form? On the basis of its morphology and morphometry, the crater on which these features formed has been morphologically degraded in relation to the very few pristine impact craters in the northern lowlands (Kreslavsky and Head 2005). It does, however, postdate the Late Hesperian Vastitas Borealis Formation (e.g., Tanaka and Scott 1987; Head et al. 2003; Tanaka et al. 2004), and is thus Amazonian in age. The slightly degraded nature of its ejecta deposit and the steepness of the slopes in the crater walls (Kreslavsky and Head 2005) suggest that it is probably mid-Amazonian to late-Amazonian in age. The deposits themselves have no visible fresh superposed craters on their

surfaces in either the THEMIS data (resolution ~ 20 m) or the MOC images (resolution ~ 3.4 – 13.5 m), with the possible exception of a single impact on the southeast crater rim (Fig. 8d). There are three possible age relations of this crater to the deposit: 1) because of its location in the marginal regions of the poorly defined deposits on the rim, it could be outside the deposit and either predate or postdate its formation; 2) if it is inside the deposit, as suggested by its position relative to the single marginal ridge, then it would apparently postdate it; 3) alternatively, the crater could predate the deposit and have been overridden by the ice forming the deposit, but left largely unaltered by the nature of the cold-based glacial process, which can override topography with little to any evidence of erosion (e.g., Cuffey et al. 2000). In any case, the deposit either has no detectable craters or one.

Uniformly superposed on the deposit is the 10–20 m scale bumpy texture of the basketball terrain (Figs. 7–9), a terrain that has been interpreted to have resulted from the deposition of a broad, latitude-dependent ice and dust mantle emplaced during orbital parameter excursions in the last several million years (e.g., Kreslavsky et al. 2000, 2002; Mustard et al. 2001; Head et al. 2003). The low-albedo patch on the eastern side of the central peak (Fig. 5a) appears to postdate the ridges but lack of high-resolution MOC images

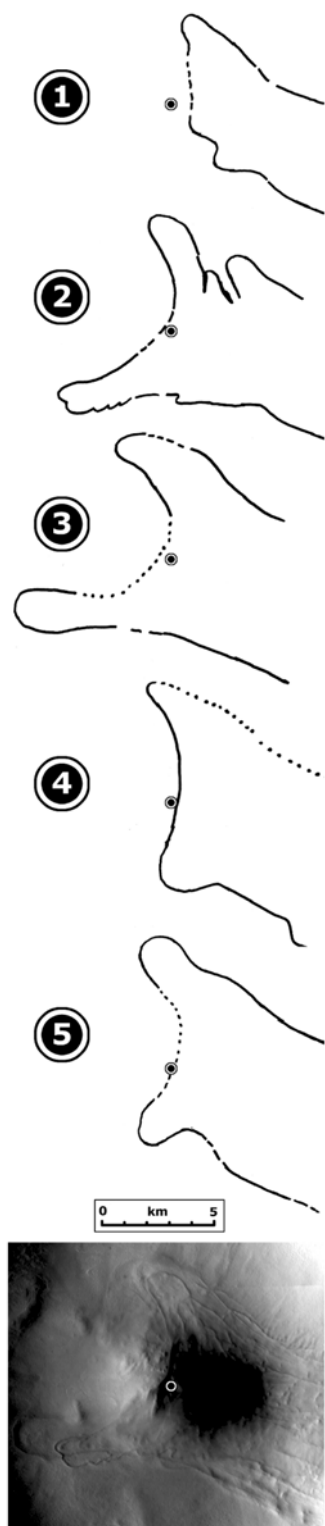


Fig. 10. The sequence of lobe formation implied by the stratigraphic relationships between superposed crossing ridges (Fig. 5). Five main ridge sequences are shown in order from the first (oldest) (1) to the last (youngest) (5). The circled solid dot in each sketch represents the approximate position of the central peak summit. Dashed lines are approximate; dotted are inferred or covered.

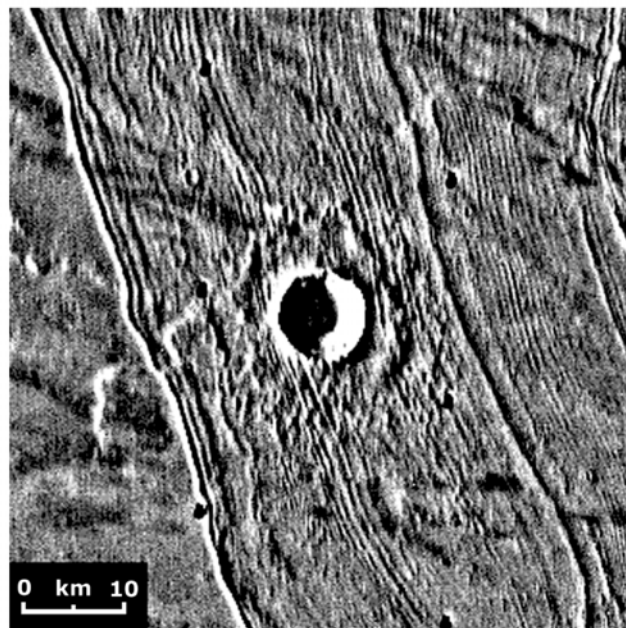


Fig. 11. Linear ridges interpreted to be drop moraines in the exterior ridged facies of the fan-shaped deposit on the northwest flank of Arsia Mons. Dozens of linear ridges are delicately emplaced on top of the underlying impact crater and its deposits, and are interpreted to have been emplaced during cold-based glaciation there, as the huge piedmont glacier receded and stabilized numerous times (e.g., Head and Marchant 2003). Viking Orbiter image.

precludes determination of detailed age determinations. If these stratigraphic relationships are correctly interpreted, then the deposits predate the latitude-dependent mantle (and are thus greater than ~ 0.5 – 2 Myr old) but postdate the crater (which is earlier Amazonian in age).

What might have been the key conditions necessary for the formation of these deposits? And could this help in understanding their age? Obviously the deposits are not forming today, as they appear to be relicts of the former greater extent of a local cold-based glacial deposit. What appears to be required are conditions that permit the accumulation of sufficient ice and dust on the southeastern crater rim to permit glacial flow down onto the crater wall and floor, resulting in multiple phases of advance and retreat. This period would be followed by changing conditions, the loss of the ice, formation of the latitude-dependent mantle, and ultimate evolution to current conditions.

The current configuration provides some important clues to the conditions required for this deposit to form. First, the broad, bright streak extending southeast from the crater rim (Fig. 8a), the dune-like features near the rim, and the frost patches that remain on the rim into early northern summer (Fig. 8) all suggest a major relationship between atmospheric circulation and preferential volatile deposition on the southeast rim. The global climate model of Forget et al. (1999) that well represents the present climate of Mars, shows that atmospheric circulation in this region is consistent with

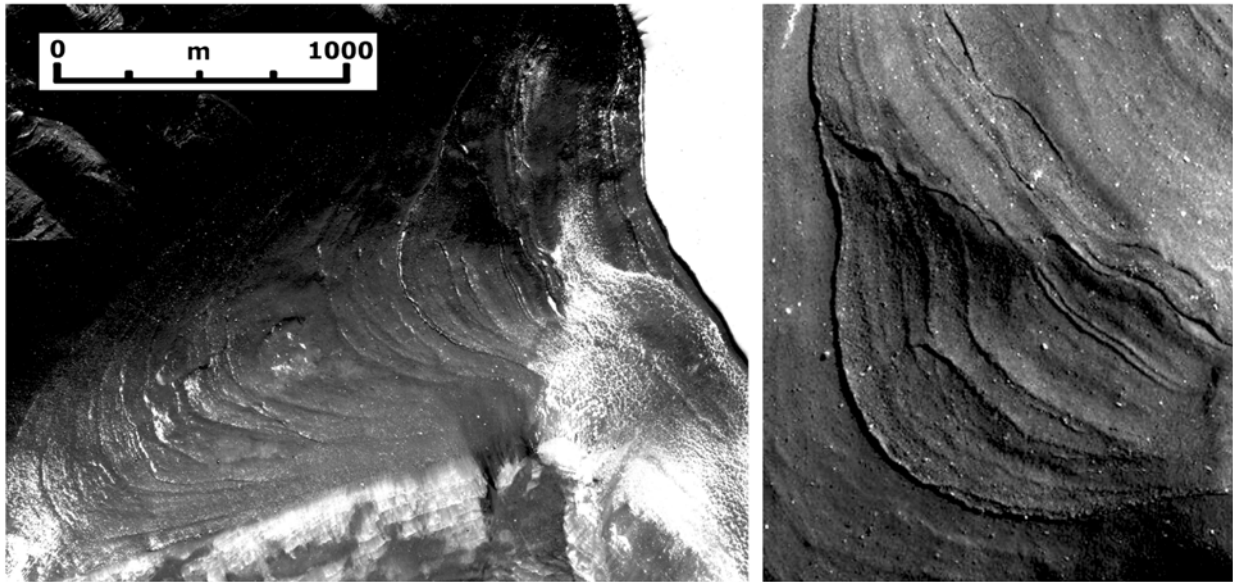


Fig. 12. Drop moraines in Arena Valley of the Antarctic Dry Valleys. a) An aerial photograph of Arena Valley showing Taylor Glacier (white, upper right corner) and the sequence of multiple drop moraines formed as the cold-based glacier advanced and retreated over the last ~2 Myr (Brook et al. 1993; Marchant et al. 1993, 1994) (TMA3079/303). b) An IKONOS image of a portion of the drop moraines in Arena Valley, showing the ridges superposed on each other and draping underlying topography. The width of image is about 500 m.

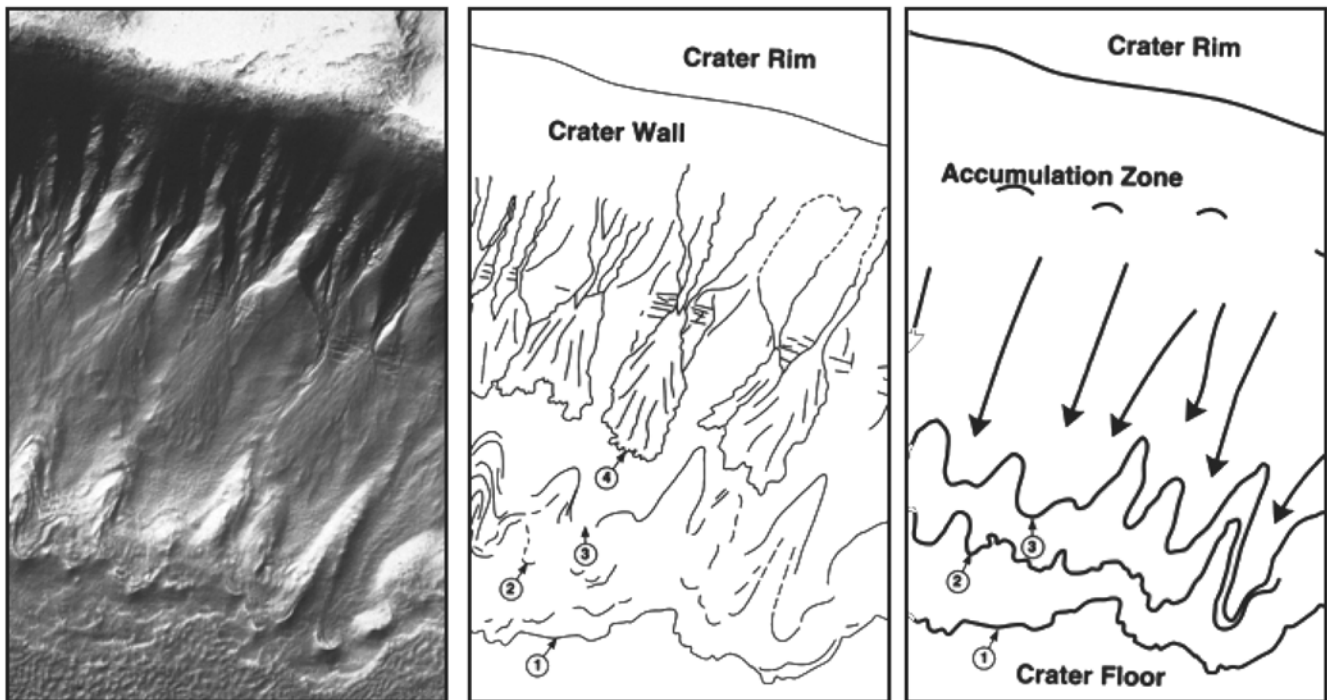


Fig. 13. Lobate features on crater wall interiors provide evidence of the former presence of debris-covered glaciers forming due to snow accumulation in alcoves on the crater walls, flowing downslope, and extending out onto the crater floors (MOC image). Left, a MOC image of the crater interior showing the deposits and sketch map (middle) illustrating the position of the crater rim, wall, and upper wall alcoves showing sequential formation of viscous lobes followed by dry debris aprons. Broad lobes (right) (1) extend out onto the crater floor, and individual ridges and depressions (2 and 3) mark the former extent of glacial-like ice-rich lobes forming from ice and snow accumulation in the wall alcoves and flow down onto the crater floor. Changing conditions caused the emplacement of moraines (1–3) and the ultimate recession and loss of snow and glacial ice. Currently, dry conditions cause the formation of dry talus aprons (middle, 4) from mass wasting of the steep alcove walls. This sequence differs considerably from drop moraines emplaced from glaciers forming on the crater rim, as seen in the crater analyzed here (Figs. 5 and 10).

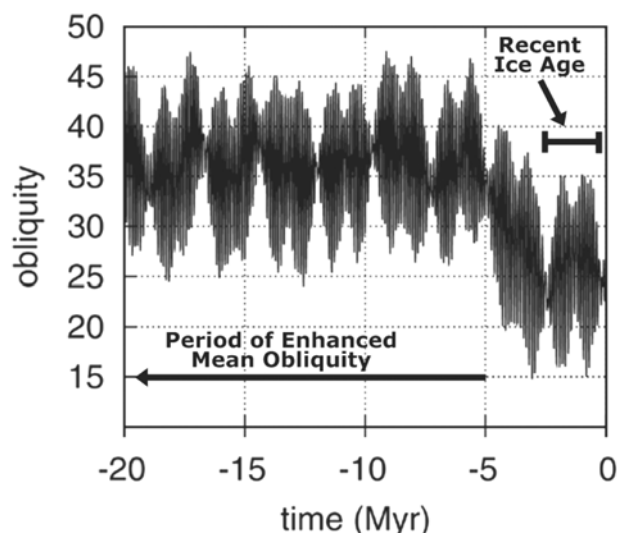


Fig. 14. Obliquity cycles during the recent history of Mars (after Laskar et al. 2004). The interpreted position of the recent ice age during which the latitude-dependent layer was emplaced is shown (see Head et al. 2004). Ridges in crater interior predate the latitude-dependent layer emplacement, probably dating from the previous periods of higher obliquity, perhaps even prior to 20 Myr.

these patterns. According to this model, the region at 250–270°E is exceptional in the 70°N latitudinal zone because of the strongest near-surface westerlies throughout the whole year, excluding late spring and early summer, but including midsummer ($L_s = 120\text{--}150^\circ$), when the atmospheric water vapor abundance is still very high, according to TES atmospheric water vapor maps (Smith 2002).

How might sufficiently abundant water vapor be mobilized to create glacial conditions? Several plausible options exist. For example, periods of enhanced obliquity (Laskar et al. 2004) would warm the poles, resulting in the mobilization of increased amounts of water vapor from the north pole and its transport southward (e.g., Richardson and Wilson 2002; Mischna et al. 2003; Forget et al. 2006). As the water-rich air approached the topography of the crater, upward flow would occur locally, adiabatically cooling the water-rich air mass, causing condensation and precipitation of snow. Increased water vapor supply caused by higher obliquity permitted the accumulation and preservation of snow and ice until accumulation conditions were reached that permitted glacial flow. These conditions need to persist for a sufficiently long period to cause the multiple stages of ice advance and retreat observed in the record. A candidate period for the formation of these deposits is thus prior to the recent period of mildly enhanced obliquity during which time the recent ice age and formation of the “basketball terrain” is thought to have occurred (–0.5 to –2 Myr ago) (Head et al. 2003, 2006), and most likely in the period of more enhanced obliquity (more than ~4 Myr ago) (Fig. 14).

A second plausible option involves the poleward

transport of water sublimating from unstable ice-rich equatorial deposits during periods of low obliquity (e.g., Levrard et al. 2004). In this scenario, during periods of high obliquity, ice is preferentially distributed in equatorial regions (e.g., Forget et al. 2006); the return to low obliquity creates conditions causing the sublimation of ice in the equatorial regions (e.g., the tropical mountain glaciers) (Head and Marchant 2003; Shean et al. 2005), and transport of ice poleward and its redeposition at high latitudes (Levrard et al. 2004).

Finally, we speculate that some Late-Amazonian-aged outflow events might deliver significant amounts of water to the northern lowlands; a plausible candidate is water ponded in Amazonis Planitia as a result of the Cerberus Rupes-Marte Valles outflow (Plescia 1993; Burr et al. 2002; Berman and Hartmann 2002; Fuller and Head 2002; Head et al. 2003). This water outflow, ponded and frozen in the region where surface ice is not stable, could be a significant localized source of additional water vapor immediately following its initial emplacement in the Late Amazonian age.

CONCLUSIONS

On the basis of this evidence and reconstruction, we outline the geological history of this deposit. We interpret the geological relations to mean that under relatively recent conditions not yet uniquely determined, water vapor was preferentially deposited as frost and snow on the southeastern rim of the crater to sufficient depths such that glacial flow ensued. Martian temperature-pressure conditions ensured that glacial flow would be cold-based and deposition preferentially on the rim meant that a significant amount of the entrained sediment was atmospheric dust that commonly occurred as nuclei for snow condensation. Variations in ice accumulation and ablation conditions associated with the variable insolation history of this period resulted in the advance and retreat of the ice in what appear to be five distinct phases (Fig. 10) that might be related to peak insolation periods due to obliquity (Fig. 14) or other causes (e.g., Levrard et al. 2004). Subsequent to this period, conditions became insufficient for the accumulation of enough snow and ice to cause glacial flow.

There is a well-known north-south, pole-facing-equator-facing asymmetry on the interior slopes of impact craters on Mars in the mid-to-high latitudes, which has been attributed to long-term insolation-related erosion at high obliquity (e.g., Kreslavsky and Head 2003, 2006) involving local glaciation and active layer formation (Kreslavsky et al. 2005). The conditions that characterize the crater described here, however, are somewhat unique, implying crater ice rim accumulation and flow (Fig. 5) rather than wall-alcove accumulation and erosion (Fig. 13). This uniqueness may be due to the special circumstances of the location of this crater in terms of latitude and slopes. This is suggested by the recent

discovery of a crater with similar interior ridged deposits in the same vicinity (67.5°N, 249.8°E). Alternatively, new data may reveal other similar deposits at other latitudes; a search for such examples is currently underway.

Acknowledgments—We thank the National Aeronautics and Space Administration for financial support for this study from the Mars Data Analysis Program (to J. W. H.). We thank Francois Forget and Jeff Kargel for constructive and helpful reviews, James Dickson for helpful discussions and data preparation, and Anne Côté and Peter Neivert for help in the preparation of the manuscript.

Editorial Handling—Dr. Nadine Barlow

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