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Mars: Evidence for geologically recent advance of the south polar cap

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Abstract. An impact crater near the south pole characterized by pristine-appearing secondary crater chains is partly covered with more than a kilometer of polar layered terrain deposits continuous with the main polar deposit. The observed relationships strongly suggest that the crater formed near the edge of the cap in Amazonian time, was buried by polar cap advance, and that some retreat occurred. These data appear to indicate that the south polar cap has been active in the geologically recent past.

1. Introduction and Background

The south polar region of Mars is dominated by deposits consisting of two units of Amazonian age. Residual ice (Api) is made up of high-albedo deposits remaining throughout Martian summer and interpreted to be water-ice cap deposits usually covered by a layer of CO_2. This unit overlies polar layered terrain (Apl) which is smooth, sparsely cratered, moderate-albedo material that is layered in places and is interpreted to be polar ice and dust deposits [*Tanaka and Scott*, 1987]. Broadly similar deposits also occur at the north pole [*Tanaka and Scott*, 1987; *Thomas et al.*, 1992; *Plaut et al.*, 1988] but show differences on a finer scale [*Thomas et al.*, 2000]. These polar deposits are distinguishable from seasonal deposits and the polar hood, which show distinctive annual variations in their distribution.

The age of the south polar layered terrain has been estimated to be very late Amazonian (about 10 Ma) on the basis of the number of superposed impact craters [*Herkenhoff and Plaut*, 2000]. This age, and the even younger age for the similar north polar deposits (about 100 ka [*Herkenhoff and Plaut*, 2000]), means that there is a significant hiatus between these deposits and the Hesperian-aged units that underlie them [*Tanaka and Scott*, 1987; *Fishbaugh and Head*, 2000a].

A major question is the nature, mode of emplacement, and evolution of the Mars polar deposits [e.g., *Thomas et al.*, 1992; *Clifford et al.*, 2000]. Are they passive steady state blankets that form from precipitation of atmospheric volatiles and dust and retreat by sublimation? Or are they more similar to terrestrial ice sheets, glaciers and glacial systems, characterized by accumulation, glacial flow, and ablation? Or could they be a combination of the two, depending on variable surface conditions in the history of Mars? Answering these questions is difficult due to the lack of knowledge of the deposit thickness and structure, ice composition and state, percentage of admixed impurities, thermal gradients, slopes, and past atmospheric conditions. The present consensus is that the geologic evidence that the polar layered deposits have undergone significant glacial flow remains ambiguous [*Clifford et al.*, 2000].

Is there any evidence for lateral changes and movement in the polar deposits, and if so, over what timescales? New Mars Orbiter Laser Altimeter (MOLA) data have shown the topographic characteristics of the polar deposits in considerable detail [e.g., *Zuber et al.*, 1998; *Smith et al.*, 1999; *Fishbaugh and Head*, 2000b] and revealed evidence for the retreat of a portion of the north polar cap in the Olympia Planitia area [*Fishbaugh and Head*, 2000b]. MOLA data also support interpretation of melting and retreat of volatile-rich ice sheet-like deposits in the more ancient Hesperian-aged units underlying the Api and Apl deposits at the south pole [e.g., *Head*, 2000; *Head and Pratt*, 2001].

Using MOLA data, we have been investigating the nature of the margins of the south polar cap, particularly in areas such as the Prometheus basin, where significant basal melting is suspected to have taken place in the past [*Anguita et al.*, 2000; *Fishbaugh et al.*, 2000]. Here we report on the nature of a 45 km diameter impact crater with pristine-appearing secondary crater chains and clusters; the crater is partly covered with more than a kilometer of polar layered terrain deposits continuous with the main polar deposit. The observed relationships strongly suggest that the crater formed near the edge of the cap in Amazonian time, was partly buried by polar cap advance, and that some retreat has occurred.

2. Description

Near the mouth of Chasma Australe on the floor of the Prometheus basin lies a 45 km diameter impact crater (Figure 1) which is partly embayed by deposits of the polar layered terrain (Apl) [*Tanaka and Scott*, 1987; *Kuzmin*, 1983]. These deposits cover the western rim and wall, extend onto and across its floor, and approach the edge of the eastern wall (Figures 1 and 2 and Plate 1a). The relationships of the crater and adjacent units are well illustrated in MOLA altimetric profiles (Figure 2) and MOC camera images (Figure 3). A series of three profiles across the crater extend from east to west (Figure 2). The first profile (Figure 2a) crosses outside the crater to its east and shows polar lobe 1 rising about 1300 m above the floor of Chasma Australe and then dropping down to the crater rim, rising as it intersects the edge of polar lobe 2, and then continuing down to the Prometheus basin floor. In the second profile (Figure 2b), which intersects just inside the crater rim, polar lobe 1 can be seen to extend to a depth of 800 m below the crater rim crest and abut the inner crater wall. The third profile (Figure 2c) extends through the crater close to its center,

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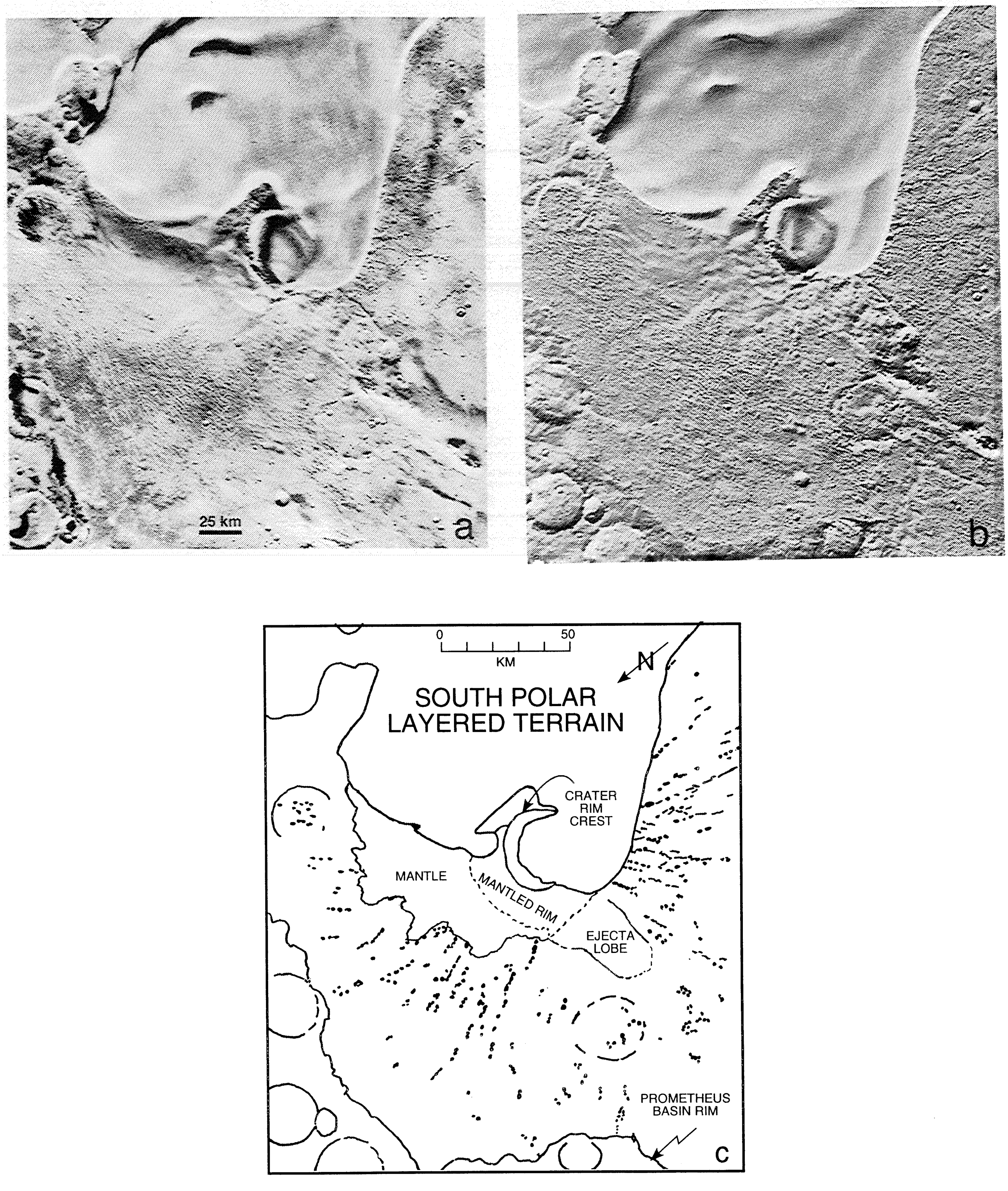


Figure 1. The northern edge of the south polar layered terrain (Apl; top) on the floor of the Prometheus basin. (a) Mosaic of Viking Orbiter frames 383848- 383852; (b) MOLA gradient (local slope) map of the same area. This map is compiled from the 300 m/pixel gridded topographic map by determining the altitude difference between adjacent pixels and scaling the range to a 256 DN gray scale. The data are portrayed as if the illumination is from the west. The map was prepared by Greg Neumann. (c) Geological sketch map. Shown are the (middle) Prometheus basin floor and (bottom) rim, the distal end of Chasma Australe (top right), the partially buried 45 km diameter crater (middle right), and its related secondary crater chains and clusters (surrounding the crater on the basin floor). Mantling material covers the inner portion of part of the secondary crater field (middle left). Dashed and arcuate forms on the basin floor are buried and degraded crater remnants.

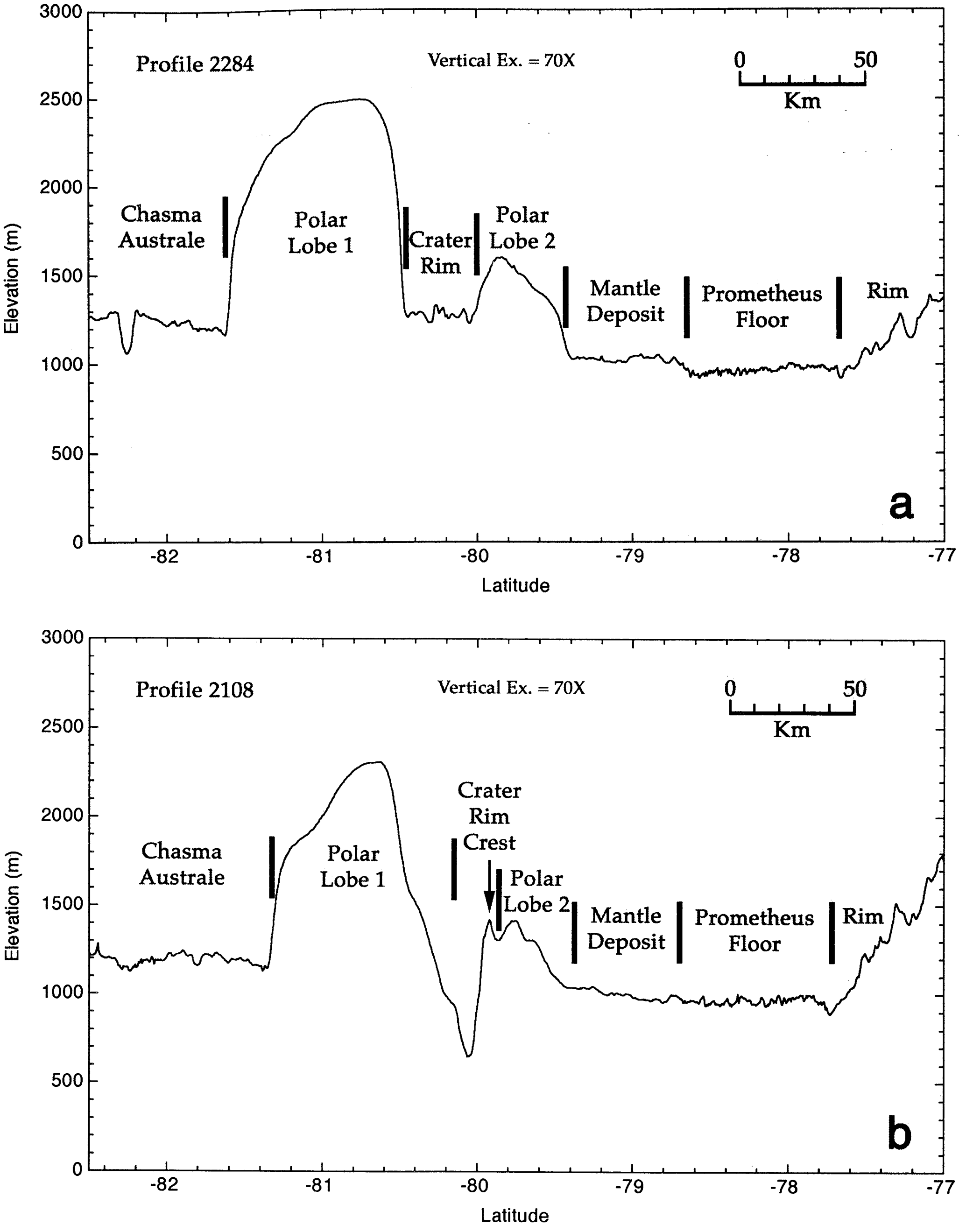
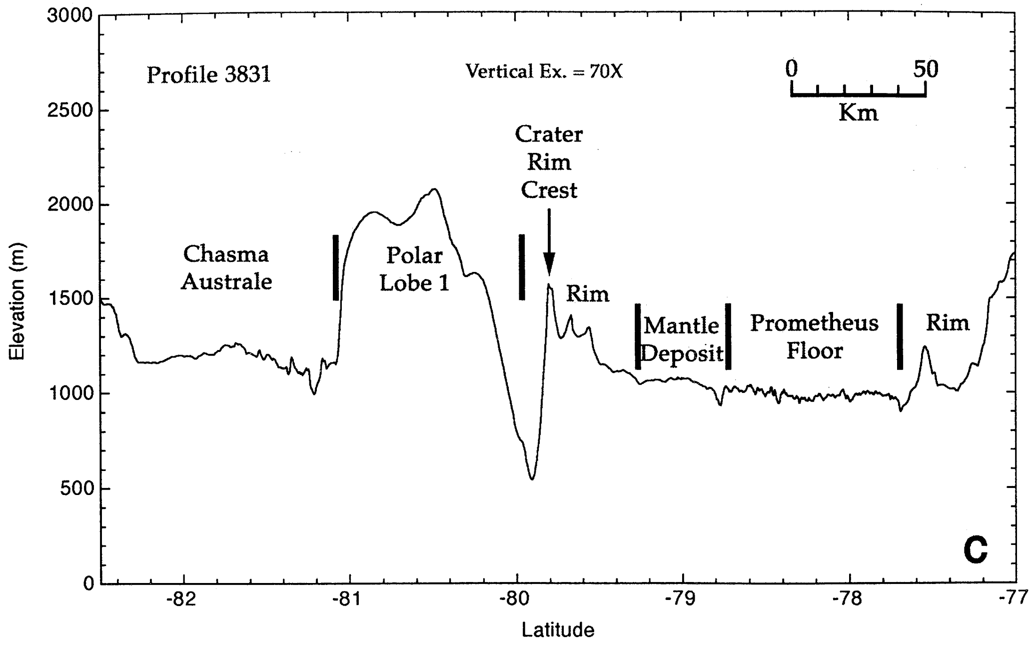


Figure 2. MOLA profiles across key units and structures and sketch location map. (a) Section of orbit 2284. (b) Section of orbit 2108. (c) Section of orbit 3831. (d) Location map (also shows location of section of profile 2040; see Figure 3).

clearly showing the northern crater rim crest and rim. Polar lobe 1 extends into the interior of the crater, covering its western side and floor and extending to the edge of the northern wall where the lobe edge lies at a depth of almost 1100 m below the crater rim crest. Polar lobe 2 is not intersected here, and the topography descends down from the rim to the Prometheus basin floor. On the west and southwest of the crater interior and rim, the layered terrain has a thickness in excess of 1 km (Figure 2). The crater occurs in Hdu, the Hesperian-aged Dorsa Argentea Formation [*Tanaka and Scott*, 1987]. MOLA data (Figure 2) show that the currently deepest part is about 1.2 km below the rim crest along the lower part of the eastern wall. The crater was clearly originally deeper but has been shallowed by embayment of polar deposits from the west. The crater has a distinct rim crest along its northern and eastern margins, standing over 500 m above the surrounding floor of the Prometheus basin. The crater is surrounded to the north and northeast by a broad rim lying about 250 m below the rim crest and rising about 250 m above the surrounding plains. This crater is anomalously deep relative to the array of other craters on the floor of the Prometheus basin (arcs and dashed lines in Figure 1c), some of which have been highly degraded and infilled [*Tanaka and Scott*, 1987]. Comparison to the new MOLA data for the fresh crater population of Mars [*Garvin et al.*, 2000a,



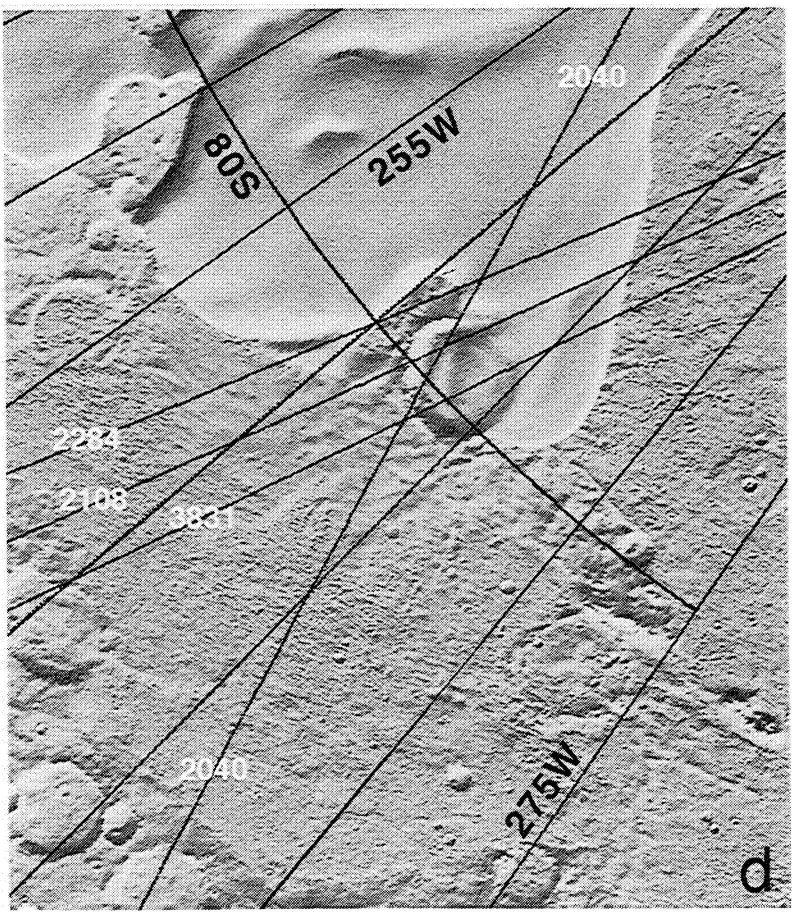


Figure 2. (continued)

2000b] shows that the values of rim height and depth for this crater are comparable to those of other fresh craters in this diameter range. These data thus show that the morphometry of the crater is comparable to fresh craters elsewhere on Mars, despite its embayment and partial superposition by unit Apl.

Mars Orbiter Camera (MOC) images reveal the structure and morphology of the lobe of polar deposits inside the crater (Figure 3). Where the MOLA profile crosses the top of the deposit, it is relatively even (although tilting toward the northeast) and made up of broad lineations striking generally northwestward, with abundant and pervasive fine-scale dunes oriented normal to the strike of the lineations (top of Figure 3b). At the edge of the relatively even area, the lineated dune unit gives way to a striated unit with intervening irregular smooth to hummocky patches (upper middle of Figures 3b and 3c). As the profile (Figure 3a) extends from the top, down the side of the deposits, to the crater floor, a series of layers are exposed over a vertical distance of about 500 m. At the base of this slope the floor is encountered and the layered unit abruptly terminates along an irregular contact. A linear to arcuate ridge is seen on the edge of the floor paralleling the lobate deposit margin. From here the topography ascends about 1100 meters up the inner crater wall to the rim crest.

The nature of the layers in the layered unit could provide evidence for possible flow. Examination of the layers shows evidence for convergence and what appear to be angular unconformities (e.g., top of the layered unit on the left) and some of the layers appear to be highly contorted (particularly those in the left-hand side of Figure 3). However, without more detailed knowledge of the topography, these apparent contortions cannot be distinguished from normal patterns in relatively flat-lying layers exposed by topographic irregularities. The exposure of these layers suggests that the lobe is presently undergoing some erosion. The ridge at the bottom of the crater near the base of the layered unit may be a terminal moraine associated with the emplacement of the lobe and its minor retreat.

Impact crater ejecta deposits on Mars consist predominantly of lobate features, with larger fresh craters also displaying secondary craters and crater chains; ballistic and diverse ejecta patterns tend to dominate at diameters >50 km [e.g., *Strom et al.*, 1992, Figure 5; *Mouginis-Mark*, 1979]. Crater degradation processes are much more abundant and varied on Mars (e.g., impact, eolian, fluvial, periglacial, etc.) than on the Moon (e.g., impact), and thus crater degradation generally operates more rapidly, particularly for finer scale features such as crater rays and secondary craters and chains.

The areas surrounding the 45 km diameter embayed crater show evidence of preserved ejecta deposits (Figure 1). On the distal part of the floor of Chasma Australe, adjacent to the lobe of Apl superposed on the crater rim, occurs a very well-developed set of linear and clustered pits (Figure 1). Mapping of these in detail reveals that they range in size from several hundred meters up to over 1 km and that they occur in clusters and chains. Some of the clusters have v-like apices pointing back to the 45 km diameter crater, and the chains are radial to subradial to the crater. Mapping of the area north of the crater also shows evidence for crater fields and clusters radial to the 45 km crater (Figure 1). Between these two occurrences of pits and crater chains lies an elongate lobate deposit extending from the direction of the crater for a distance of about 60 km. This feature has a marginal ridge, parallel linear textural elements, and is aligned radial to the crater, suggestive of lobate ejecta elements seen in fresh Martian craters [*Strom et al.*, 1992].

Examination of the full distribution of crater chains and clusters around this feature (Figure 1c) shows that there is a gap in their distribution to the north and northeast but that chains and clusters are again present beginning at a distance of 50-90 km from the rim crest in this direction. MOLA profiles across the region in this direction show that the area lies topographi-

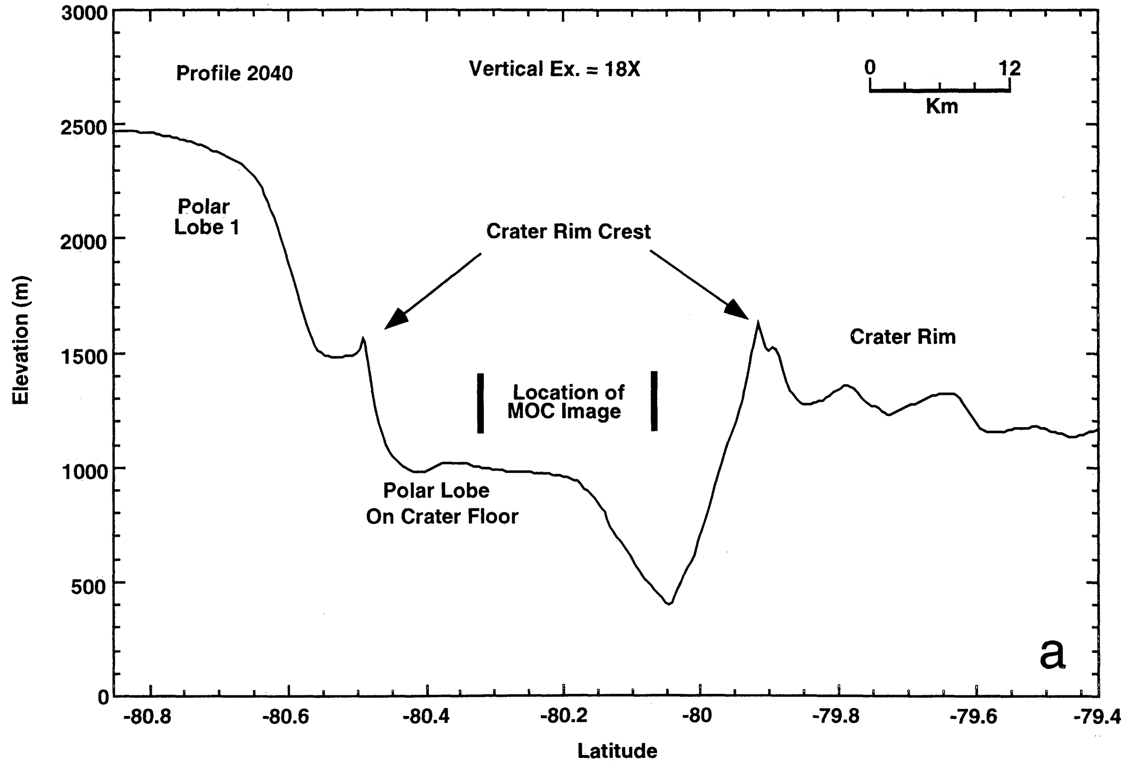


Figure 3. Mars Orbiter Camera (MOC) image of the interior lobe of polar material (polar lobe 1) inside the 45 km diameter crater. (a) MOLA profile showing the location of the image (MOLA orbit 2040). (b) Portion of MOC image M0402502 of the lobe, its margin, and the crater floor. Width of image is 2.83 km and resolution is 5.5 pixels. Illumination is from the lower right. (c) Sketch map showing the main features in the image.

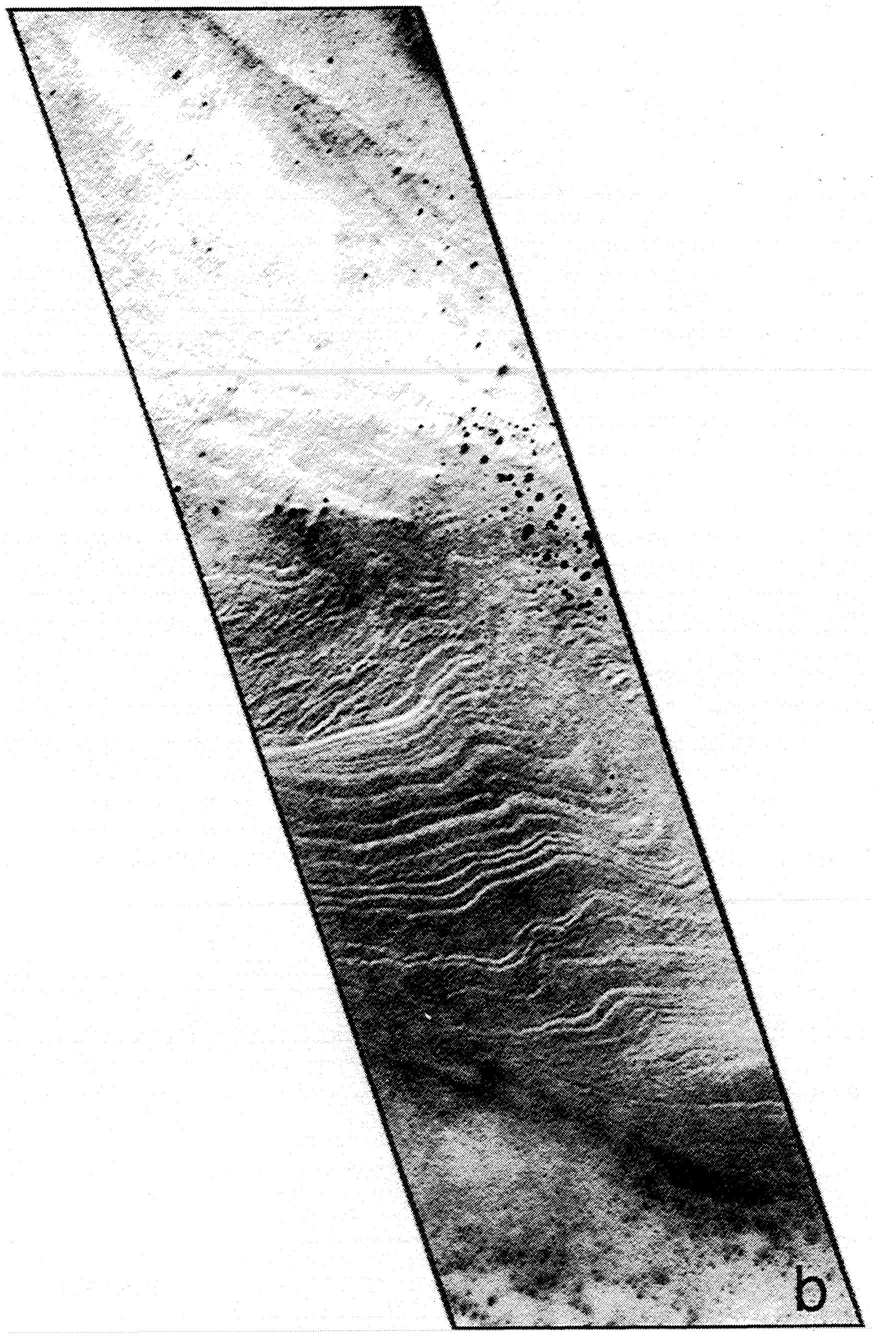


Figure 3. (continued)

cally well below the top of the layered deposits (1200-1400 m) but relatively higher than the crater floor by about 80-100 m (Figure 2).

3. Discussion and Interpretation

Pits and clusters of pits are observed in polar and circumpolar terrains and have been interpreted to be due to eolian deflation, melting, and sublimation processes [*Sharp*, 1973]. The morphology of such pits, however, is different than the crater clusters and chains described here [e.g., see *Sharp*, 1973; *Thomas et al.*, 2000]. The features mapped here show a distinctive size distribution in the range expected for secondary craters, show cluster apices and linear trends pointing back to the crater, and are arrayed to a radial distance in the range anticipated for secondary crater ejecta [e.g., *Strom et al.*, 1992]. It is thus concluded that these features were formed by ejecta emplaced at the time of formation of the 45 km diameter crater, now partly buried by polar deposits.

If this interpretation is correct, then this crater must have formed after the formation of the Hesperian-aged crater floor material, and prior to the emplacement of the polar layered deposits in the crater interior. The perspective provided by MOLA topography (Plate 1a) shows the secondary crater fields and chains radiating from the 45 km crater and emerging from beneath overlying polar deposits. The freshness of the secon-

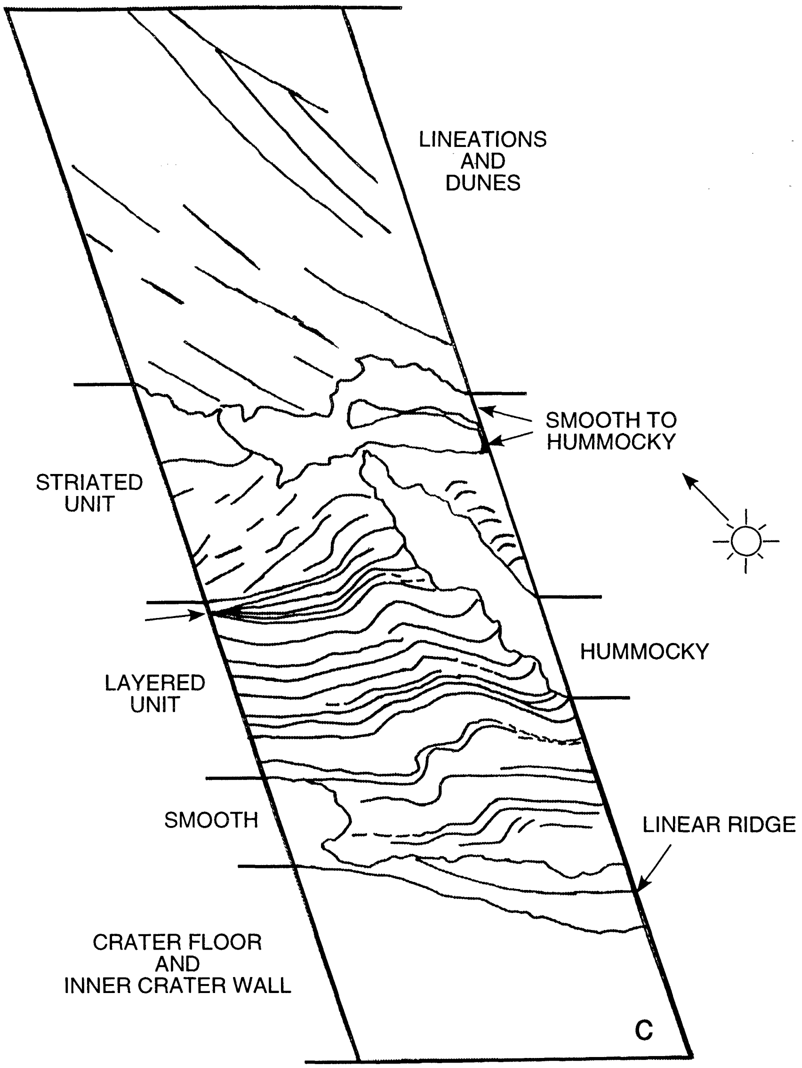


Figure 3. (continued)

dary crater clusters and chains implies that these features have undergone very little degradation at the scale of Viking Orbiter images. Two of the ways in which these observations might be explained include are described below.

3.1. Exhumation

In this scenario the crater would have formed sometime after the Hesperian-aged basin floor but was rapidly buried before erosion could modify the fine-textured ejecta deposits or degrade the rim and infill the floor. The crater was preserved in a pristine state for possibly many hundreds of millions of years and then recently exhumed [e.g., *Thomas*, 1982]. Evidence supporting this hypothesis includes the number of partly exhumed features seen in several other places on Mars [e.g., *Thomas*, 1982; *Schultz and Lutz*, 1988; *Grant and Schultz*, 1990; *Tanaka*, 2000]. The mantling material (presumably the polar layered terrain) would need to be areally extensive enough to have protected the entire secondary crater and chain deposit from degradation (i.e., most of the floor of the Prometheus basin; see Figure 1), and then to be exhumed to its present configuration, while preserving the fine-scale texture during this exhumation.

3.2. Very Recent Formation

A second option is that the crater formed very recently geologically (late in the Amazonian period) and was partly buried by polar deposit advance. In this scenario this activity occurred recently enough that there would have been insufficient time to modify and degrade the fine-textured ejecta features not covered by the advancing polar deposit. This would imply that the polar deposits advanced northward from their previous position superposing onto the crater after its recent formation.

Either of these two options means that the margin of the polar layered terrain has moved significantly northward (100-250 km) relative to its previous position. In the first option, polar deposits would have to cover the entire set of secondaries in order to preserve them (this would include most of the floor of the Prometheus basin in Figure 1), and then retreat to the present position. In the second option, the polar deposits advanced to cover the northeast rim and the crater floor.

Which option appears to be the most plausible? Secondary crater chains and clusters are widely areally distributed around the primary crater (Figure 1). Their similar level of preservation throughout their occurrence suggests that if they owe their preservation to mantling and subsequent exhumation, then the

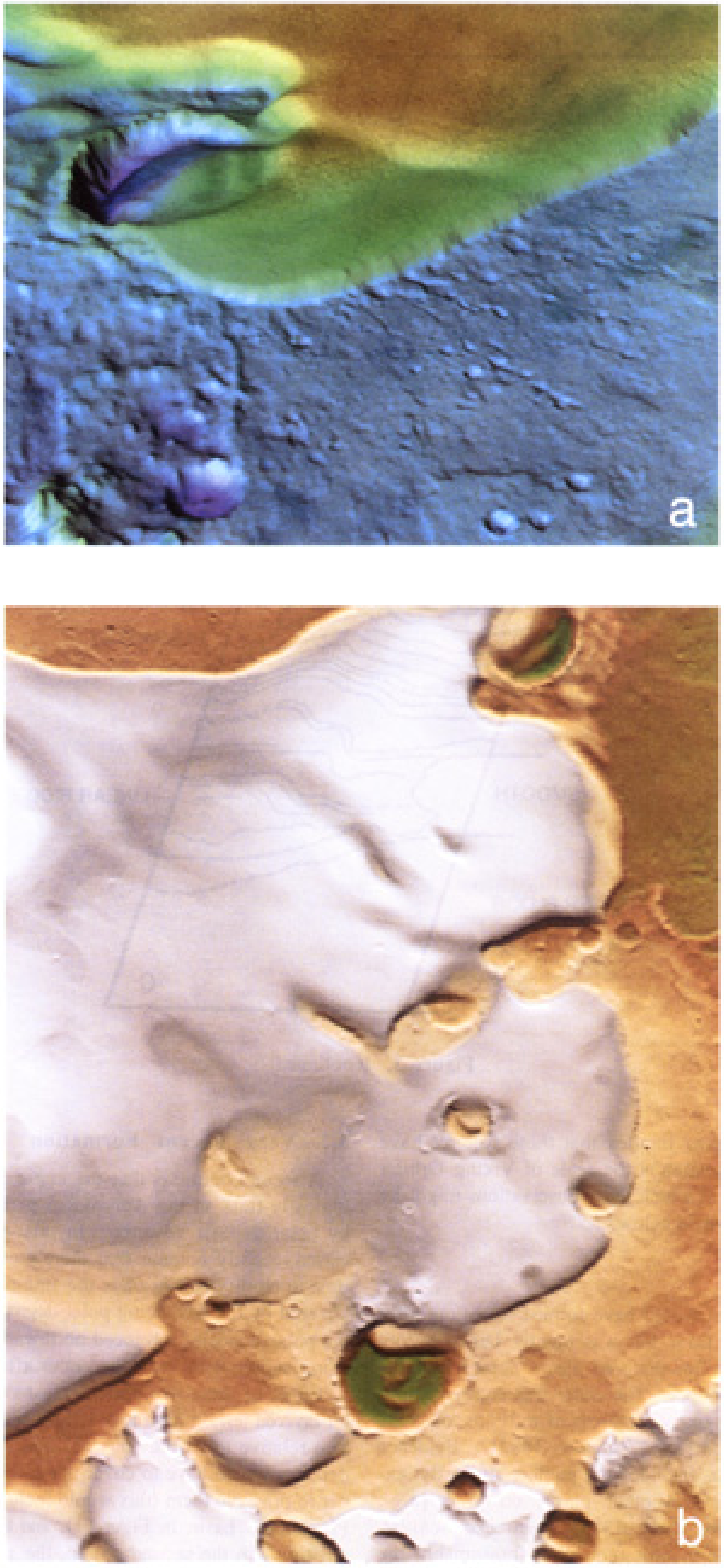


Plate 1. (a) MOLA digital elevation model (DEM) viewed from the north toward the crater, showing how the ejecta emerges from beneath the lobe of Apl (middle right). Yellow is high, purple (crater floor) is low, and blue is the background Dorsa Argentea Formation at intermediate elevations. Vertical exaggeration is about 9x. (b) Vertical view of a MOLA DEM with the 45 km diameter crater at the top, and the slightly larger deep crater at the bottom, about 300 km to the east. North is to the right. Layered terrain is white and high, Hd (Dorsa Argentea Formation) is brown and at intermediate elevations, and the two crater floors are deep (green).

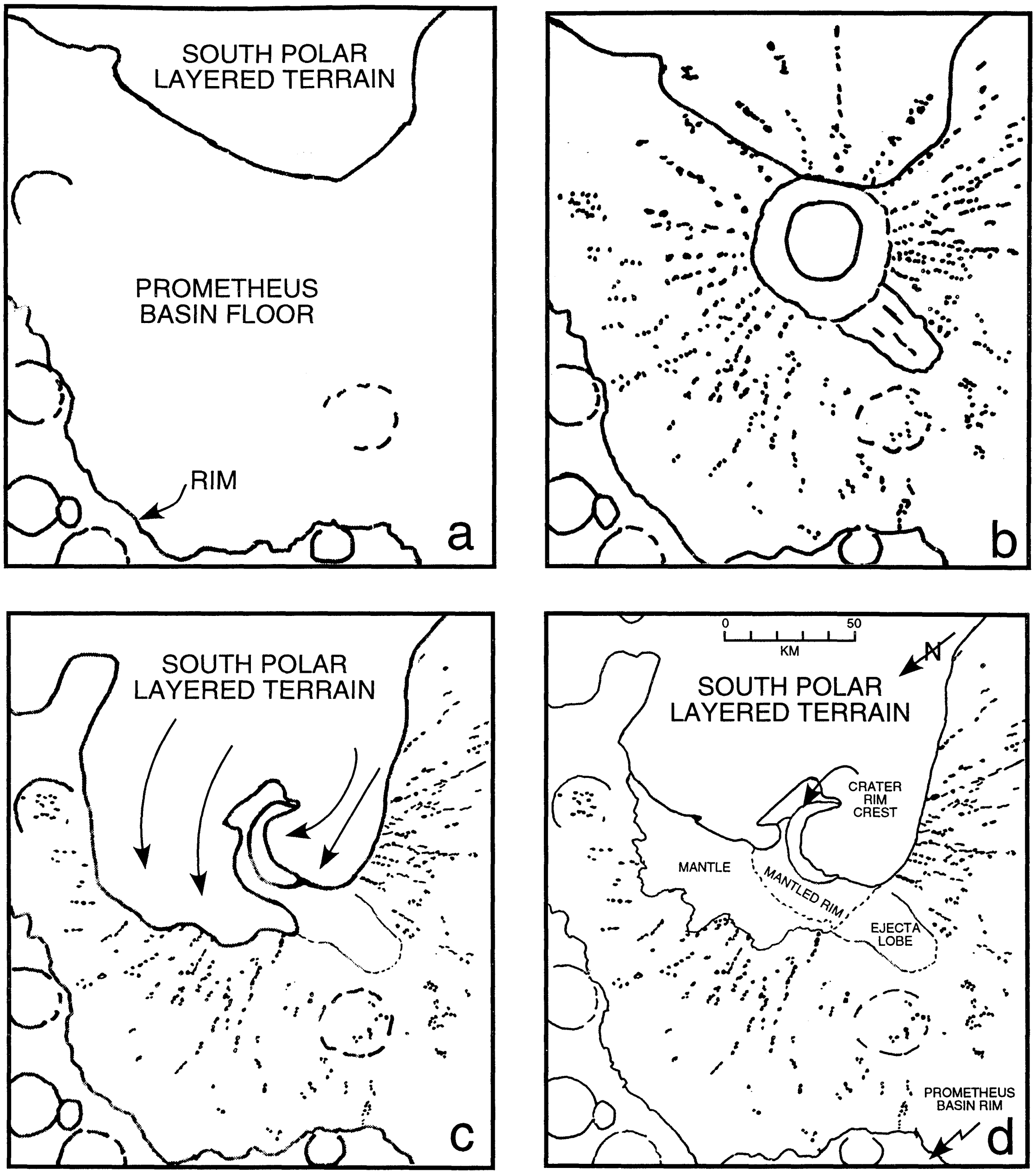


Figure 4. Interpreted sequence of events in the history of the Prometheus floor margin of the south polar layered terrain in the late Amazonian period. (a) South polar layered terrain extends into the Prometheus basin and onto the floor. (b) Large impact crater (45 km diameter) forms on the floor of the basin in front of the layered terrain. Ejecta is emplaced radially from the impact in the form of secondary crater chains and clusters, rim deposits, and an ejecta lobe. (c) Polar deposits move northward, extending a lobe of ice down into the interior and floor of the crater (middle right) and advancing further onto the crater floor (middle left). Secondaries on the polar deposits are destroyed by movement, while others are buried by advancing polar deposits. (d) Polar deposits retreat back to their present configuration, leaving a mantled deposit and the present configuration of features.

mantling would have to extend out at least to the edges of their occurrence (over 150 km north of the crater rim), to the northern edge of the Prometheus basin floor. Subsequent to this, meltback or sublimation of the volatile-rich deposits would occur, accompanied by the removal of the nonice component of the volatile-rich deposits, thought to represent as much as 50% of the deposit [*Herkenhoff*, 1998]. If the volatile-rich deposit was as thick along its margins as in the present (~1400 m) then its loss would have resulted in a sedimentary blanket averaging less than about 700 m thick, the exact thickness dependent upon the percentage of admixed dust. This deposit would then have to be removed to the exact level of the preexisting topography at which the secondary craters formed. Furthermore, the sediment removal and exhumation process would have to be so complete that it uniformly restores the pristine nature of the secondary crater chains and clusters over about a 40,000 km^2 area. Finally, this sediment would have to be removed from the Hesperian-aged floor of the Prometheus basin and deposited elsewhere, as there is little evidence for recent floor deposits of this magnitude.

Alternatively, geologically recent formation of the crater, followed by advance of the deposits by about 50-60 km to cover and modify the crater interior and northeastern inner ejecta facies, could also explain the observations. Some additional evidence for this type of advance is found in another slightly larger crater some 300 km to the east (Plate 1b, left, green) which also has a lobe of Apl extending into the crater floor. Although this crater does not have the same type of preserved secondaries, its depth suggests that it too was a relatively young post-Hd crater into which Apl advanced in a lobe-like manner. On the basis of these considerations, the latter explanation appears most plausible, even though relatively fresh morphological landforms can be preserved through burial and subsequent exhumation [e.g., *Thomas*, 1982].

The sequence of events in the second scenario is envisioned to have occurred as follows (Figure 4): (1) Initially, the edge of the polar deposits was located to the south of the crater prior to the time of its formation (Figure 4a). (2) Impact produced a fresh crater and ejecta composed of a large number of secondary chains and clusters and a local lobe of ejecta extended toward the northwest (Figure 4b). (3) Following this, polar deposits advanced approximately 50-60 km northward in two lobes (Figure 4c). The western lobe (polar lobe 1; Figure 2), about 45 km wide, extended northward and eastward into the crater interior. The eastern lobe (polar lobe 2; Figure 2), about 60-80 km wide, extended out onto the floor of the Prometheus basin for a distance of about 60 km. Any secondary craters and related ejecta on top of the polar lobes would have been obliterated by this movement. (4) Finally, the eastern lobe retreated somewhat southward, leaving a mantling deposit over the northeastern inner part of the secondary crater field and crater rim (Figure 4d), producing the presently observed configuration.

Is there support for such a scenario? Recently *Nye* [2000] developed a mechanical flow model for the polar caps of Mars and found support for the idea that the present Martian polar caps are composed of flowing water ice with some admixed sedimentary debris. He attributed the differences in age (younger in the north) largely to higher temperatures at the north polar cap causing more efficient flow. Did the deposits advance passively, through deposition of layers of volatile-rich material, or actively, through flow? Although conclusive evidence is lacking, evidence suggesting active flow includes (1) the presence of steep, sharp boundaries along the western margin of the western lobe, (2) the distinctively lobate nature of the fill of the crater, (3) the possible deformation of layers exposed in the lobe, and (4) the relatively sharp edges of the deposit suggesting flow rather than diffuse mantling. Could a specific set of conditions have produced or accelerated flow? Conditions that might have influenced flow [e.g., *Nye*, 2000] include increased atmospheric or basal temperatures, increased accumulation, and variations in the physical properties of the ice and percentage of admixed silicates. *Malin and Edgett* [2000] recently documented the presence of gullies within the walls of some impact craters, south polar pits, and two Martian valleys; they interpreted these to be formed by groundwater seepage and surface runoff. The morphology and stratigraphic relationships of these gullies strongly suggested to them the presence of liquid water at shallow depths beneath the surface in the very recent geological past. Geologically recent formation and release of water could be related to obliquity cycle maxima which might be accompanied by warming and increased polar ice accumulation. Another possibility for flow initiation could come from increased polar ice accumulation in the recent past. An additional possible contribution to mobilization may have been the emplacement of silicate ejecta on the edges of the volatile-rich cap (Figure 4b), causing localized increased heating and enhancing flow in the surface layers.

4. Conclusions

The relationships outlined in this analysis provide evidence for the advance and retreat of the margins of the polar cap deposits in the Prometheus basin late in the Amazonian period. In addition, a reasonable case can be made that the 45 km diameter impact crater formed on the floor of the Prometheus basin adjacent to the south polar layered terrain in the relatively recent geological past. In this interpretation, material advanced from the edge of the cap down over its western rim onto the floor of the newly formed crater, covering the rim and portions of the secondary crater field (Figure 4). These observations support the idea that there was actual movement and flowage in the cap itself and that this movement obliterated surface texture on top of the polar deposits (e.g., crater ejecta and secondary deposits). If correct, this interpretation may help to account for the very young age estimates for much of the polar layered terrain on the basis of superposed impact craters [e.g., *Plaut et al.*, 1988; *Thomas et al.*, 1992; *Herkenhoff and Plaut*, 2000]. In addition to accumulation, ice movement would both deform, and embay and cover, preexisting impact craters in the polar deposits, leading to a younger age estimate.

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