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Comparison of the North and South Polar Caps of Mars: New Observations from MOLA Data and Discussion of Some Outstanding Questions

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New high-resolution data from the Mars Orbiter Laser Altimeter (MOLA) have provided detailed topographic maps for the north and south polar regions. These new data allow one to compare the overall topography and geologic histories of the two polar regions and to highlight some specific outstanding questions in Mars polar studies, following earlier comparisons using *Viking* and *Mars Global Surveyor* data. The new data show that the centers of symmetry of the polar cap deposits in map view (which include both the layered terrain and residual ice) are offset from the current rotational pole in antipodal directions. Offset in the north appears to be due to retreat of the polar materials from predominantly one direction (180° W). Lines of evidence for movement and melting in different forms (e.g., lobes in young craters, kettle-like depressions, candidate residual mantles overlying polar layered terrain, and possible eskers) have been seen at both poles. The exact timing and causes of movement and melting is yet unknown. Differences in underlying topography (large, low, flat depression in the north; broad, cratered high and edge of a large impact basin in the south) may influence the accumulation, flow, and movement of polar material and the storage and movement of meltwater. The small number of superposed craters has been interpreted to indicate a Late Amazonian age for both caps, with the southern cap being somewhat older (7–15 × 10^6 years) than the northern cap ($<100 \times 10^3$ years). The Late Amazonian-aged caps are surrounded and underlain by Hesperian-aged material, indicating an apparent hiatus almost 3-byr in duration. This apparent hiatus in the geologic record from the Late Hesperian to Late Amazonian at both poles may be accounted for in one of three ways. (1) Polar caps are recent events in the history of Mars: This scenario requires that conditions in the Late Amazonian changed to produce environments favorable for cap formation late in the history of Mars, or that polar wander brought the caps to their present position very recently. (2) The polar caps are oscillating: In this scenario, caps are periodically deposited and then retreat and disappear, possibly due to extremes in the obliquity cycle. In this model, the present caps are the latest example of cap deposition and represent the type of deposit that has come and gone numerous times in the Amazonian. (3) The present caps are old, but have been renewed: In this scenario, the present caps have been in their current position for much of the Amazonian, but some process (e.g., melting, flow) is periodically destroying preexisting craters to produce cap surfaces that appear very young in terms of crater retention ages. Documenting the nature of the emplacement history of the present polar deposits and distinguishing among these disparate scenarios for their history are among major challenges facing Mars polar studies in the coming years.

Key Words: **Mars; ices; geological processes; Mars climate.**

1. INTRODUCTION AND BACKGROUND

Mapping of the polar regions of Mars by Tanaka and Scott (1987) and by Dial (1984) revealed Late Amazonian caps surrounded by Hesperian-aged material in both polar regions (Figs. 1, 2). The polar caps themselves are composed of polar residual ice (Api) and layered terrain (Apl). The polar residual ice is mainly H_2O in the north (Kieffer *et al.* 1976), while in the south, a surface layer of residual CO_2 ice (Kieffer 1979, Paige *et al.* 1990) shows distinctive collapse and erosional features (Thomas *et al.* 2000). The north polar residual water ice has a more gradational relationship with the underlying layered deposits (Thomas *et al.* 2000). The layered terrain consists of layers of ice and dust with layer thicknesses possibly being influenced by obliquity cycles (Thomas *et al.* 1992, Herkenhoff 1998). In the north, the residual ice (Api) covers nearly all of the layered terrain (Apl). In the south, however, the residual ice covers a much smaller portion of the layered terrain (compare Figs. 2a, 2b). The center of this southern residual ice cover is offset a few degrees from the rotational pole. The Mars Orbiter Laser Altimeter (MOLA) experiment on board the *Mars Global Surveyor* spacecraft has acquired detailed altimetry data for the polar regions, which have been compiled into topographic maps (Fig. 3).

The north polar cap is characterized by spiraling troughs (Howard *et al.* 1982; Fisher 1993, 2000). The south polar cap is characterized by spiraling scarps in Api and curvilinear scarps and troughs in Apl (Schenk and Moore 2000). In both caps, these troughs and scarps (Figs. 2 and 3) expose Apl in their walls and are thought to be ablational features. They spiral more symmetrically within the north polar cap than within the south polar cap

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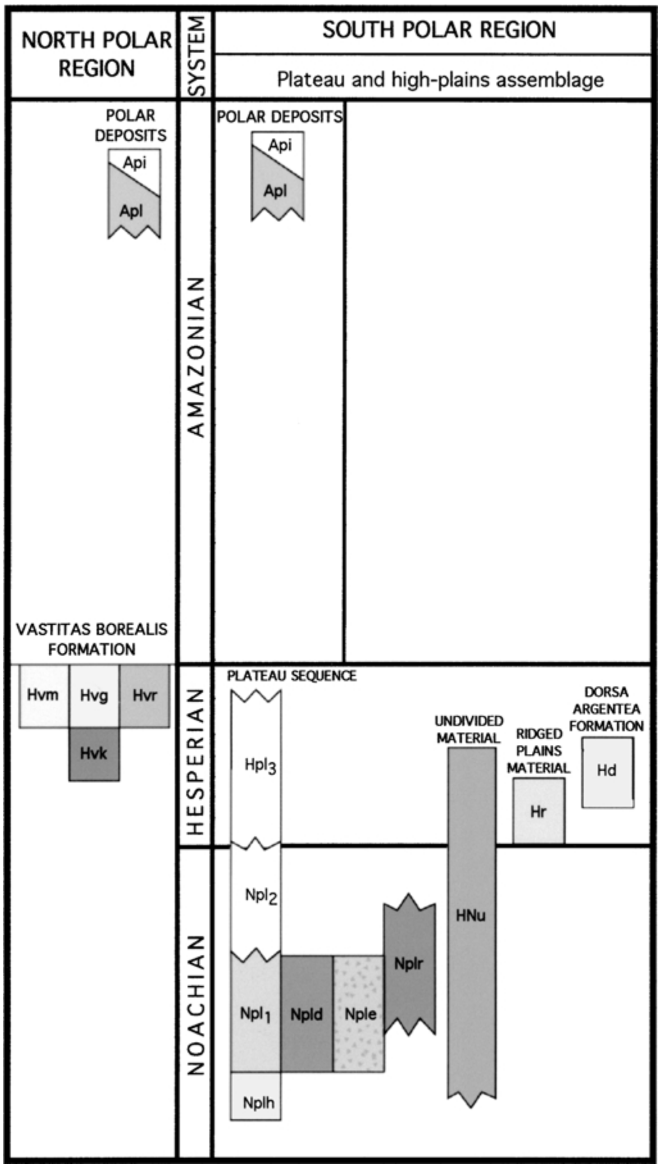

FIG. 1. Stratigraphic column for the north and south polar regions. See geological maps in Fig. 2 and text for more description. Modified from Tanaka and Scott (1987).

(Fig. 3). In both topography and *Viking* images, the south polar scarps within Api spiral more symmetrically than the troughs and scarps within Apl and are therefore more like the troughs in the north polar region.

Distinguished from the troughs in both shape and size are the chasmata (defined by the International Astronomical Union as elongate, steep-sided depressions), the most notable of which are Chasma Boreale in the north and Chasma Australe in the south (see Figs. 2, 3, and 6). The chasmata have been proposed to be formed by katabatic winds modifying a previously existing cap (Howard 1980, 2000; Zuber *et al.* 1998), or by outflow of meltwater during heating and partial melting of the polar cap (Clifford 1987, Benito *et al.* 1997, Anguita *et al.* 2000, Fishbaugh and Head 2001b, Fishbaugh *et al.* 2000).

The caps are considered to be very young. The northern and southern caps are stratigraphically Late Amazonian in age (Tanaka and Scott 1987) (Figs. 1, 2). On the basis of crater counts from high-resolution *Viking* images covering ~80% of the layered deposits, Plaut *et al.* (1988) estimated the southern cap to be a few 100×10^6 years. This age was later revised to $7–15 \times 10^6$ years (Late Amazonian) based upon a recently revised martian cratering flux (Herkenhoff and Plaut 2000). On the basis of crater counts (Cutts *et al.* 1976), the estimates of the age of the north polar deposits range from $<100 \times 10^3$ years (Herkenhoff 1998, Clifford *et al.* 2000) to $<10 \times 10^6$ years (Thomas *et al.* 1992). Thus, the southern cap appears to be characterized by a somewhat older surface age than the northern cap, yet both have a Late Amazonian surface age (e.g., Hartmann and Neukum 2001).

On the basis of the presence of kettle-like features and topographic extensions of the layered terrain apparently mantled by sediment (Olympia Planitia), Fishbaugh and Head (2000) have proposed that the north polar cap has undergone at least one episode of retreat (Fig. 4). Head and Pratt (2001), citing the presence of esker-like features, drainage channels, and collapse pits, have interpreted the Hesperian-aged Dorsa Argentea Formation, which underlies the present Amazonian-aged polar deposits, to represent volatile-rich south polar deposits that underwent melting and retreat (Fig. 5).

The circumpolar units in the north (Fig. 2a) (Tanaka and Scott 1987, Lucchitta *et al.* 1986, Fishbaugh and Head 2000) consist for the most part of the Hesperian Vastitas Borealis Formation (Hv), Amazonian mantle material (Am), and the largest dune sea on Mars (Greeley *et al.* 1992). The Vastitas Borealis Formation underlies the Amazonian polar deposits and has four major members. The mottled member (Hvm) has several possible origins: lava flows, or alluvial or eolian deposits. The grooved (Hvg), ridged (Hvr), and knobby (Hvk) members are thought to be degraded lava flows or sediments, distinguished from each other by specific landforms. Volcanoes and remnants of Hesperian/Noachian highland material have been proposed as possible origins of the knobs of Hvk (Tanaka and Scott 1987). Fishbaugh and Head (2000) have shown that Hvk and Hvm stratigraphically overlie the Noachian cratered terrain and provided a background for later Amazonian sedimentation.

The grooves of Hvg form large polygonal patterns whose origin has been interpreted in many ways (e.g., lava cooling, periglacial activity, tectonic activity, desiccation, or ocompaction). A review of origins by Hiesinger and Head (2000) using new MOLA data suggests that tectonic deformation is the dominant formation mechanism for the larger polygons. The ridges of Hvr have been interpreted to be formed by stripping of easily eroded material around resistant dikes or filling of Hvg grooves with lava (Tanaka and Scott 1987). Fishbaugh and Head (2000), building on previous studies by Tanaka and Scott (1987), have shown that the Hvr and Hvg members are gradational with each other, are exposed in several places in the north polar region, and underlie part or all of the polar cap. Recent analysis of the northern lowlands using detrended altimetry data has revealed evidence for the extensive development of wrinkle ridges on the floor of the northern lowlands and has led Head *et al*. (2001) to propose that the Vastitas Borealis Formation is underlain by a volcanic unit (Hesperian ridged plains, Hr) that flooded and smoothed the northern lowlands in the Early Hesperian. Further analysis of the topographic characteristics of the Vastitas Borealis Formation (Kresalvsky and Head 1999, 2000; Head *et al*. 2001) shows that it is a sedimentary unit that apparently overlies the Hesperian ridged plains (Hr) and has a minimum thickness of about 100 m.

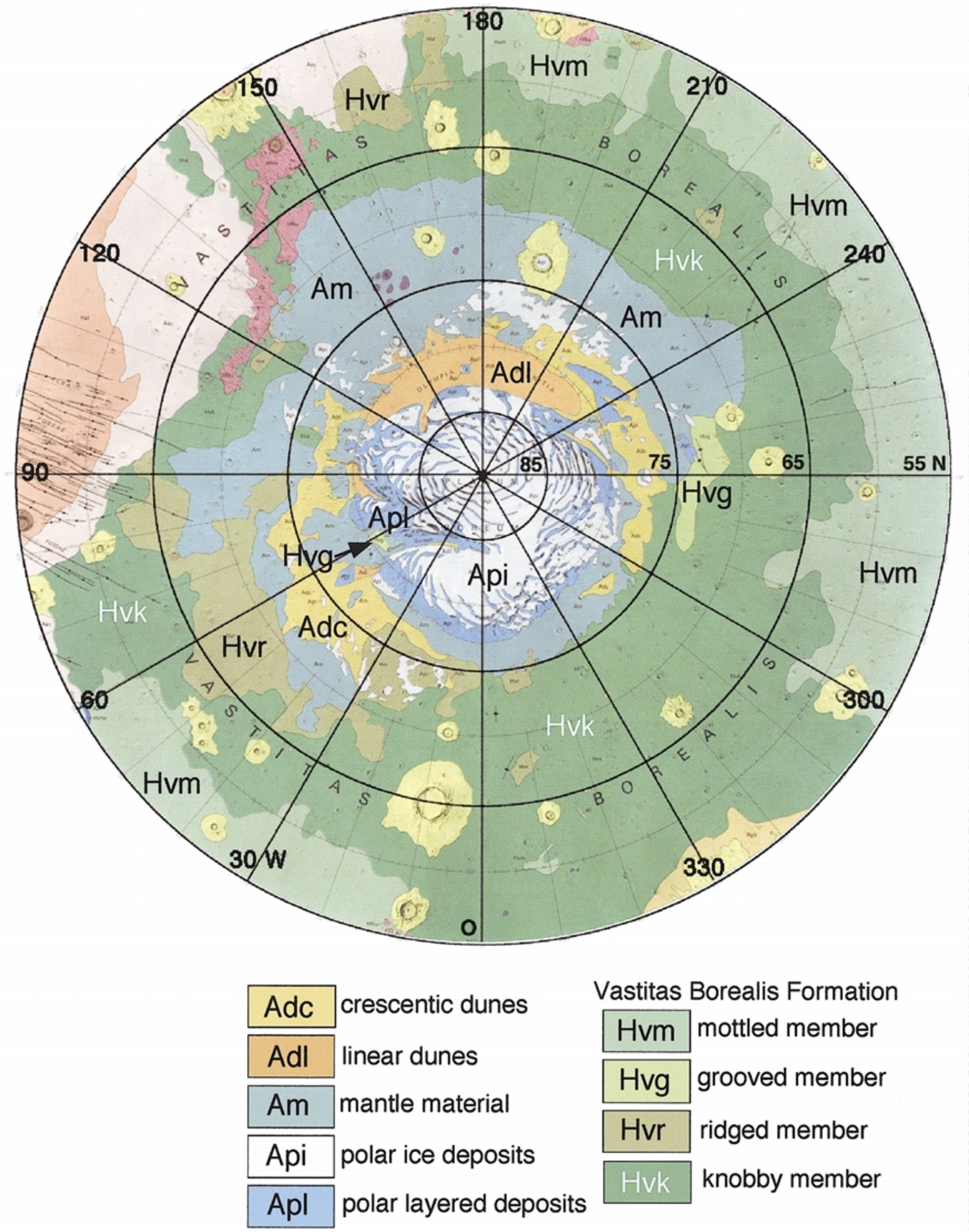

FIG. 2. Geologic maps of (a) the north and (b) the south polar regions of Mars from Tanaka and Scott (1987).

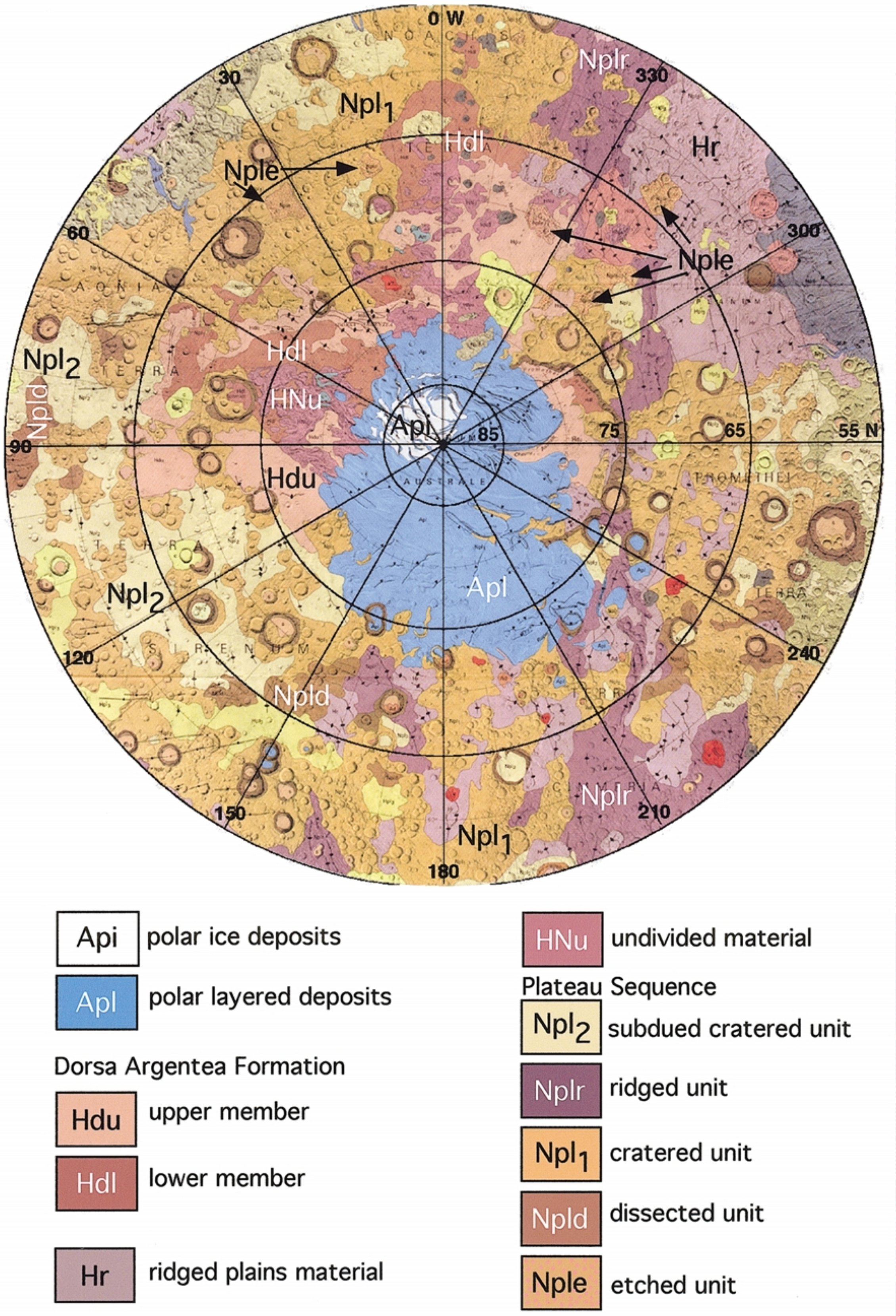

FIG. 2—*Continued*

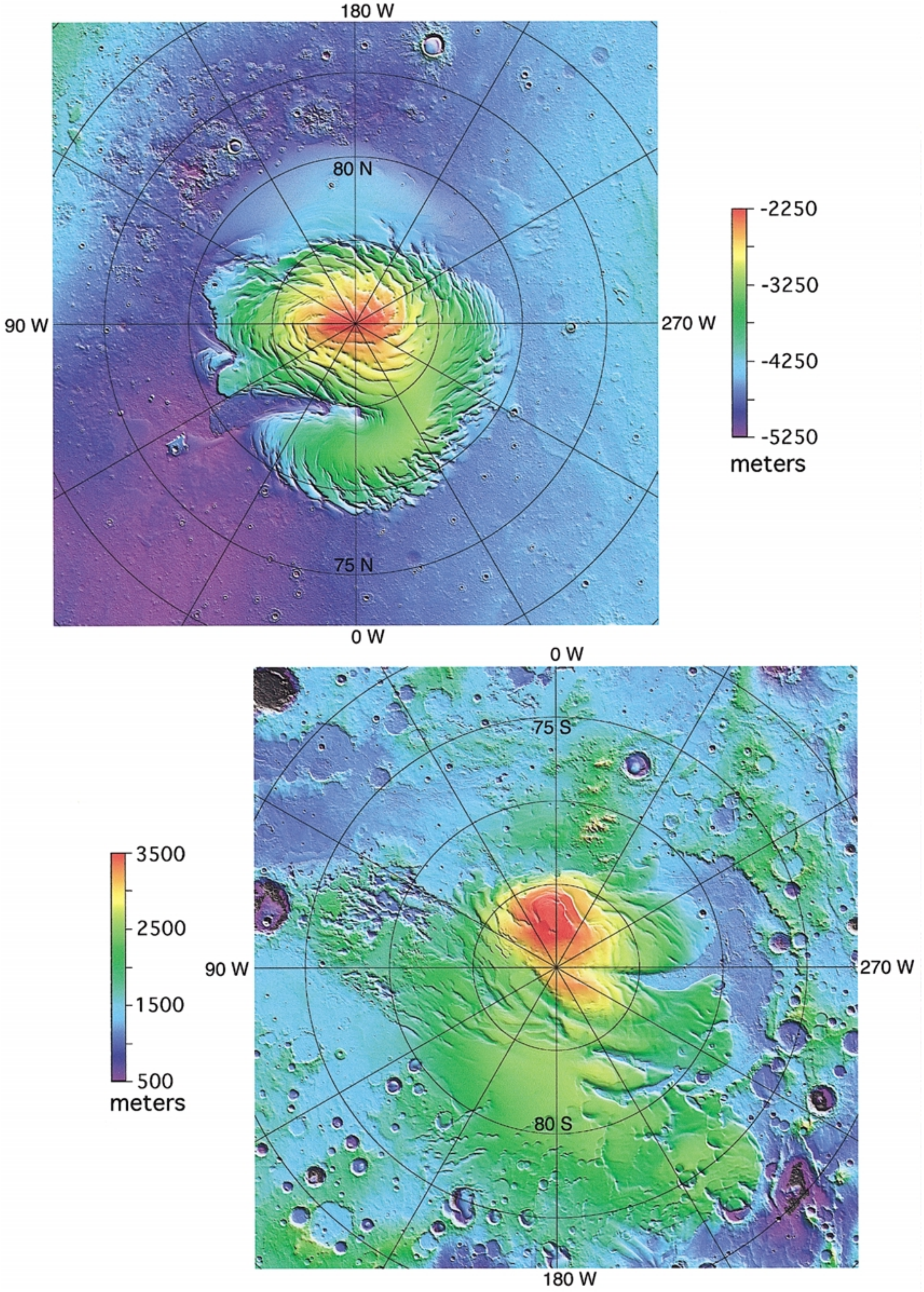

FIG. 3. Shaded relief, topographic map of the north (top) and the south (bottom) polar regions of Mars. Prometheus Basin (see text) is the circular basin extending from beneath the south polar cap in the 270°W direction. Both maps were created from gridded MOLA data extending from 72°N and S with a 300-m/pixel resolution.

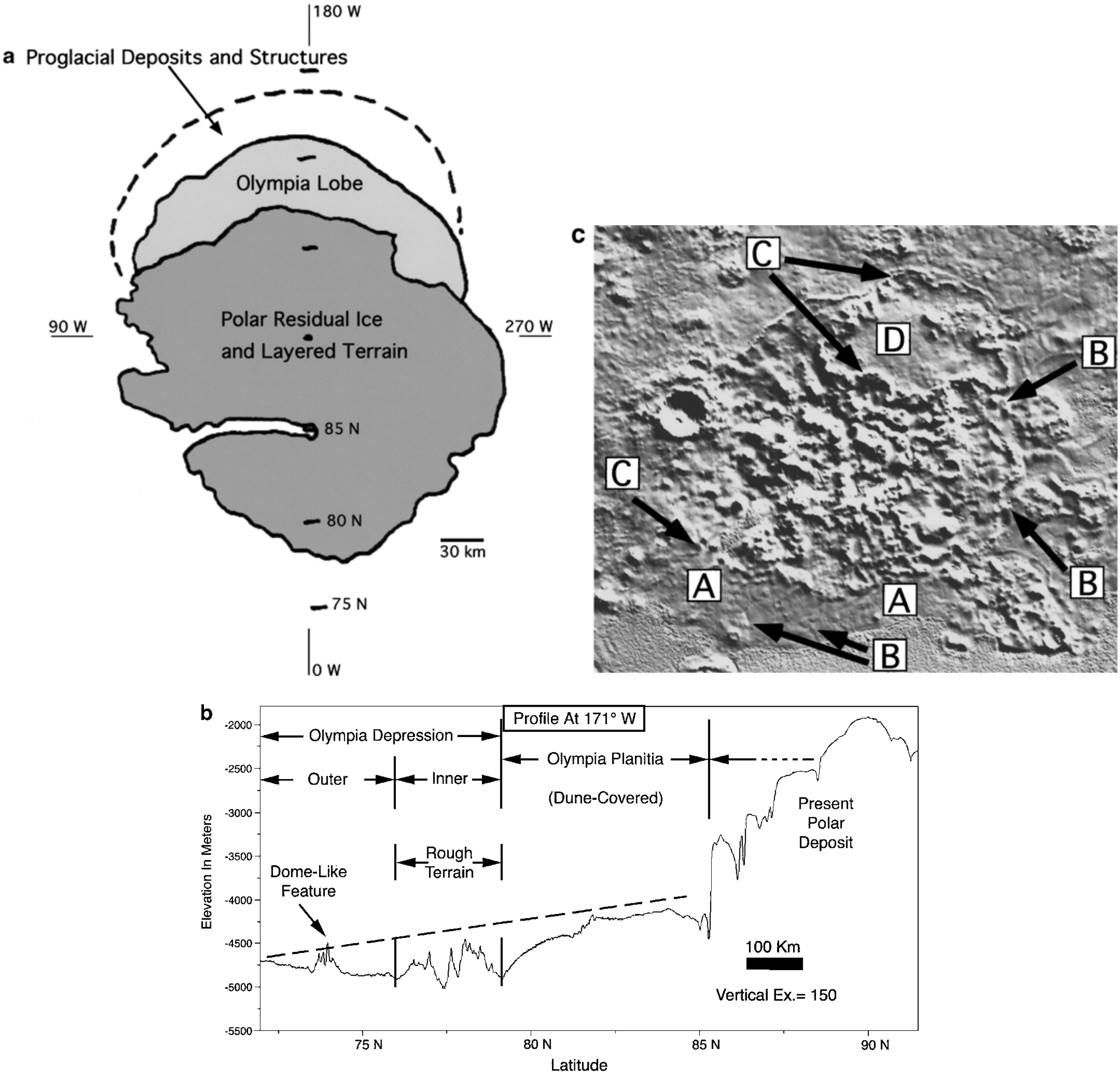

FIG. 4. North polar region and evidence for retreat of the polar deposits. (a) Diagram showing configuration of the once more extensive north polar cap. The dark gray region shows the current polar materials (Api, Apl), including Chasma Boreale, the reentrant extending into the cap at 85°N. The light gray region is the Olympia Lobe, an extension of the polar materials that has partially retreated and is now covered by dunes. The proglacial deposits south of the Olympia Lobe include kame and kettle-like structures and remnants of polar material (Api, Apl). Together, these deposits and structures constitute a possible former extent of the cap, more symmetrical about the current rotational pole than the current polar cap. (b) Annotated MOLA altimetric profile extending from the present polar deposit southward at 171°W longitude, showing the dune-covered Olympia Planitia, and the topography of the adjacent Olympia depression, interpreted to be the site of proglacial deposits and structures. (c) Terrain typical of the distal region of the polar deposits at 180°W longitude interpreted to be kame and kettle topography (Fishbaugh and Head 2000, 2001a). The features interpreted to be kames and kettles are found only in the eastern half of the depression south of Olympia Planitia. They are isolated from each other and irregular in shape. They have been partially mapped as outlying ice material by Tanaka and Scott (1987), and images show them to be partially covered by high-albedo material (Fishbaugh and Head 2000, 2001a). Letters designate important characteristics: (A) Smooth topography that surrounds the feature, (b) associated valleys, (C) ridges that encircle much of the feature, and (D) several smooth, low-lying areas associated with the features. Note the hummocky material in the center.

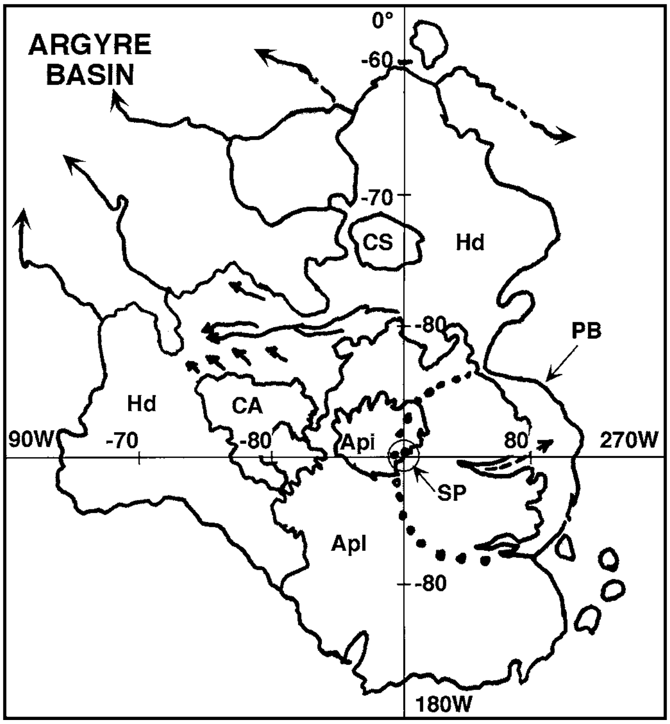

FIG. 5. Sketch map of the south polar region showing possible Hesperian polar deposits that have since undergone retreat (Hd: Dorsa Argentea formation) (Head and Pratt 2001). The dark arrows within Hd represent esker-like features, with the arrows pointing in the downslope direction. The cavi (CA: Cavi Angusti, CS: Cavi Sisyphi) represent possible volatile-rich material that has melted and drained vertically, resulting in collapse pits. The arrows extending from Hd toward the Argyre basin (downslope direction) represent channels that may have drained meltwater from the retreat of Hesperian polar-like materials. Api and Apl represent the Amazonian-age polar ice and layered terrain, respectively. The dotted line in the vicinity of the pole is the continuation of the rim of the Prometheus Basin under the polar cap.

Eolian deposition and erosion of the polar deposits and of the Vastitas Borealis Formation has left a mantle (Am; Fig. 2a) locally hundreds of meters thick (Tanaka and Scott 1987) that has collected in topographic lows surrounding the north polar cap (Fishbaugh and Head 2000) (Fig. 3). The largest sand sea on Mars (Olympia Planitia) lies just to the south of the polar cap (in the 180° direction) and was once thought to have been collecting in a flat plain (Greeley *et al.* 1992). However, Fishbaugh and Head (2000) used MOLA data to show that Olympia Planitia actually has a convex topography (compare Figs. 2a and 3), contiguous with the polar cap, strongly suggesting that it represents an extension of polar material (the Olympia Lobe) now covered by dunes (Ad) (Fig. 4).

The southern circumpolar units (Fig. 2b) are more varied and span the Noachian to the Late Amazonian. The major Noachian units are part of the Plateau Sequence (Npl) and are interpreted to consist of heavily cratered lava flows, impact breccia, eolian deposits, and pyroclastic material (Tanaka and Scott 1987). Channels, proposed to have been carved by runoff or ground ice sapping, are found in Npld. The ridges that characterize Nplr have been suggested to have been formed by volcanism, folding, or faulting (Tanaka and Scott 1987). Nple has been subjected to eolian erosion and ground ice removal (Tanaka and Scott 1987). The main Hesperian units are members of the Dorsa Argentea Formation (Hd) which is characterized by ridges interpreted as lava flow features or eskers and by cavi, thought to be formed by ground ice removal (Tanaka and Scott 1987). The southern circumpolar units thus span a longer period of the history of Mars and are lacking the Amazonian mantle material (Am) and large dune seas of the north, although small dune fields are seen on the floors of some craters surrounding the south pole (Tanaka and Scott 1987).

Recent studies with local and regional MOLA topographic data support the interpretation of the Dorsa Argentea Formation (Hd and related units; Fig. 5) as an extensive Hesperian-aged volatile-rich south polar deposit (Head and Pratt 2001). These deposits underlie the present Amazonian-aged cap and cover a surface area that could be as large as 5.24×10^6 km^2, about 3.6% of the surface of Mars, and over three times the area of the present Amazonian-age south polar deposits. The deposit characteristics indicate that it contained significant quantities of water ice in amounts comparable to present day polar deposits. Several lines of evidence for melting indicate that the deposits underwent meltback and liquid water drainage into surrounding lows. Narrow sinuous ridges lie in a broad linear depression extending from a high at the polar cap continuously downslope to near the distal portion of Hd. The new topographic data support the interpretation of these ridges as eskers, representing meltwater distribution networks at the base of the receding deposit. Extensive development of large pits and depressions (cavi) have previously been interpreted as eolian etching or basal melting of ice-rich deposits. Analysis of MOLA topography supports the interpretation that they represent melting of ice-rich deposits and shows that they have links to the esker systems. Inspection of the margins of the Dorsa Argentea Formation reveals several large channels that begin there and drain downslope for distances between 900 and 1600 km onto the floor of the Argyre basin, some 3.5–4.0 km below their origin.

Estimates of the present deposit thicknesses together with amounts of the deposit removed by meltback (Head and Pratt 2001) suggest that the original volume could have been as much as 1×10^7 km^3, equivalent to a global layer of water $\sim$35 m deep if the deposit consisted of $\sim$50% volatiles. A significant portion of the volatiles remain in the deposit, representing a net removal from the atmosphere and from the active hydrologic system, and forming a record of aqueous conditions and possible biological environments dating from early Mars history.

The exact nature and timing of possible melting and retreat events as well as the exact ages of the polar caps are crucial to our understanding of the complex interaction between the polar materials and the circumpolar units throughout the geologic history of Mars. Altimetric data from the MOLA can be used to help elucidate the morphological and straitigraphical relationships between the polar caps themselves and the circumpolar units (compare Fig. 2 and Fig. 3). A thorough review by Clifford *et al*. (2000) has detailed the major advances and current state of knowledge in Mars polar studies as of the *1st International Mars Polar Science and Exploration Conference* in 1998. Since the publication of that review, altimetric data from MOLA (Zuber *et al*. 1998, Smith *et al*. 1999, Fishbaugh and Head 2000) have revealed further detailed topographic characteristics of the polar caps and the circumpolar deposits (Fig. 3). These new data and investigations have allowed specific comparisons of the two polar regions and have provided new insight into their geologic histories, extending the comparisons and insights presented by Clifford *et al*. (2000). In this paper, we discuss evidence for formerly larger polar caps, further address evidence for possible melting and outflow in both polar regions, address the role of circumpolar and subpolar topography in cap evolution at both poles, discuss the importance of the antipodal offset of the polar cap centers of symmetry in map view, and assess polar stratigraphy and polar cap ages, linking these to the geologic histories of the two regions. A further purpose of this paper is to outline several outstanding questions in Mars polar studies that have resulted from this research.

2. OBSERVATIONS AND DISCUSSION

2.1. Evidence for Formerly Larger Polar Caps

MOLA has revealed that Olympia Planitia, formerly thought to be a flat plain collecting dunes (Greeley *et al*. 1992), actually shows a convex topography, contiguous with the polar cap (Figs. 2a, 3, and 4). Fishbaugh and Head (2000) have termed this the Olympia Lobe and consider it to be an extension of the polar cap material that is now blanketed by dunes consisting of lag deposits left by cap retreat. They have also noted unusual topography, south of and concentric to the Olympia Lobe, that resembles terrestrial kame and kettle topography (Fishbaugh and Head 2000, 2001a) (Fig. 4b). Kames are formed when supraglacial, englacial, and subglacial debris is deposited as mounds (kames) as the glacier retreats (Benn and Evans 1998, Clayton 1964). Kettles form when blocks of glacial ice, separated from the glacier as it retreats, are buried and later melted, creating collapse pits (kettles) (Benn and Evans 1998). Isolated patches of polar material also lie among this kame-and-kettle topography. Together, the Olympia Lobe and irregular topography to the south are taken as evidence of a once larger northern polar cap (Fishbaugh and Head 2000). The once larger extent of the cap (Fig. 4) is more symmetrical about the current rotational pole than are the current deposits.

In the south polar region (Figs. 2b, 3), as discussed in more detail above, the Hesperian-aged Dorsa Argentea Formation and related units (Fig. 5) have been interpreted to represent older, water ice-rich polar deposits below the Amazonian Api/Apl (Head and Pratt 2001). Evidence for this is the presence of esker-like ridges (Head and Hallet 2001), extensive development of cavi, and chasmata and other features. These features and the presence of channels draining the deposits into the surrounding Argyre Basin (Fig. 5) have been cited as evidence that the deposits underwent extensive melting and retreat of several hundreds of kilometers (Head and Pratt 2001; see also Kargel and Strom 1992, Clifford *et al*. 2000, Head 2000).

MOLA data have also been used to assess evidence for possible movement of the Amazonian-aged south polar cap. Specifically, a lobe of layered terrain is seen to extend from the margins of the deposit down into the interior and floor of a 50-km-diameter impact crater (Fig. 6). The detailed preservation of fine-textured secondary crater chains from the adjacent crater suggests that the crater is geologically very young and that the layered terrain may have flowed into the crater relatively recently (Head 2001). An alternative interpretation is that the crater and its secondaries were covered by layered terrain, preserved, and then recently exhumed (Head 2001). An additional suggestion of movement of the south polar layered terrain is seen in the form of ice stream-like features extending from the central cap to distal regions (e.g., Head 2000). Here, lineated depressions several tens of kilometers wide extend from the high point in the south polar cap to more distal regions (e.g., Head 2000; his Fig. 3) and show striking similarities to Antarctic ice streams (e.g., Bentley 1987). If this interpretation is correct, it would imply that there were times in the past history of the south polar layered terrain in which the unit was more mobile. An alternative interpretation is that these depressions are due to erosion and sublimation by katabatic winds (e.g., Howard 2000).

In summary, evidence exists for possible advance and retreat of polar deposits at both poles, but the detailed nature and exact timing of such movement remains unknown. Among the many outstanding questions and issues relative to movement of the polar caps are: How many episodes of retreat and advance have occurred and on what time scales do they happen? What was the cause of the apparent retreat of the Amazonian north polar cap and of the Hesperian south polar materials? Was the cause the same for each example? Why has the apparent retreat of the northern cap been asymmetrical (i.e., from 180°W, rather than uniformly around the entire cap)? In deposits that have undergone meltback, what was the ultimate fate of any water and sediments derived from the melting of the polar material? Why are some of the familiar terrestrial glacial recession features (e.g., moraines, drumlins) not observed in abundance at either pole? Is their absence related to the dynamics of retreat, to the nature of the sediment within the martian layered terrain and its effect on flow, or to the nature of flow (warm-based versus cold-based)?

2.2. Melting and Outflow

One possible agent of polar cap retreat in both regions is loss of polar material through melting. The largest examples of features interpreted by some authors to have been formed by outflow of meltwater are Chasma Boreale in the north (Clifford 1987, Benito *et al*. 1997, Fishbaugh and Head 2001b) and Chasma Australe in the south (Anguita *et al*. 2000, Fishbaugh *et al*. 2000) (Figs. 2, 3, and 6). Chasma Boreale is seen to be a large

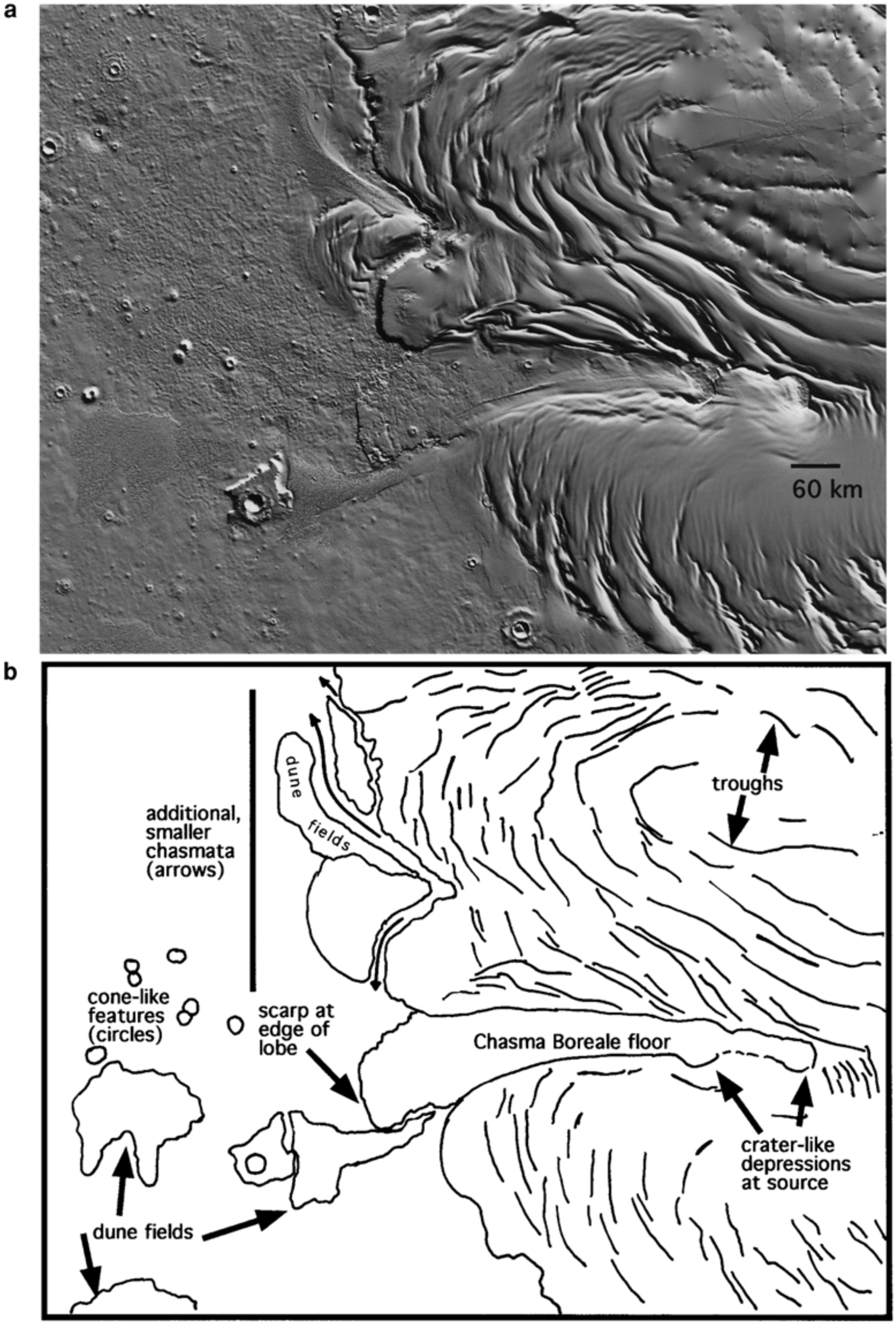

FIG. 6. (a) MOLA altimetry gradient map of the Chasma Boreale region illustrating major features. (b) Sketch map showing major features seen in (a) and their interpretation. Note the distinction between the troughs of the polar terrain and Chasma Boreale. The texture in the crater-like depressions at the proximal end of Chasma Boreale is similar to that on the floor of the north polar basin. The scarp at the edge of the lobe on the floor of Chasma Boreale extends out into the surrounding terrain. Other, smaller chasmata are shown by arrows at the edge of the cap. Several small cone-like features are observed distal to the mouth of Chasma Boreale. These are interpreted to be volcanic edifices (Garvin *et al*. 2000, Sakimoto *et al*. 2001) and could be a source of heat in a melting event.

reentrant in the north polar cap, extending from the margins of layered terrain well into the main body of the cap. Compared to the spiraling troughs that characterize most of the cap (Fig. 3), Chasma Boreale is distinct in scale, detailed topography, and orientation. MOLA altimetry data reveal that the depressions at the head of the chasma are at the same elevation and have the same floor texture as the terrain surrounding the cap, and that the chasma on average, slopes downhill from these depressions toward the floor of the basin. The floor of the chasma shows abundant evidence of eolian dunes and has certainly been reworked by eolian processes, but some of the larger structures could also be consistent with streamlined features and drainage due to outflow. The lobate deposit at the mouth of the chasma extends out into the surrounding lowlands and is about 300 m high, apparently overlying a polygonal unit (Hvg) that may be part of the underlying Vastitas Borealis Formation. On the basis of these observations, Fishbaugh and Head (2001b) find support for an origin involving outflow of meltwater, as originally proposed by Clifford (1987) and Benito *et al.* (1997), with later modification by katabatic winds and sublimation. They envision melting to have occurred within and beneath the cap, leading to buildup and migration of meltwater downslope toward the cap margin. Meltwater eventually broke out at the surface, leading to flooding of the adjacent lowlands and to the erosion and lowering of the polar ice surface to form the chasma. The outflow of water deposited a lobe of sediment at the chasma mouth as the flow broadened in width and slowed at the edge of the lowlands. Further into the surrounding lowlands, the water ponded and deposited a layer no more than a few meters thick. Several smaller chasmata similar to Chasma Boreale and Chasma Australe are also observed (Fig. 6) and are interpreted to have been formed in a similar manner (Fishbaugh and Head 2001b). Although katabatic winds have certainly played a major role in the modification of these features (e.g., Howard, 2000), the details of their structure revealed by MOLA, their relation to topography, and the several additional smaller examples argue favorably for a significant role for melting and outflow. New quantitative models for both outflow and eolian processes would aid in distinguishing the relative roles of the two processes.

The southern polar and circumpolar deposits are also associated with additional varieties of possible melting features such as esker-like ridges and cavi (pits possibly formed by melting and collapse) (Kargel and Strom 1992; Clifford *et al.* 2000; Head 2000, 2001; Head and Pratt 2001; Head and Hallet 2001). The greater variety of southern candidate melting features could be due to differences in topography, age, and/or substrate (Head 2000, Fishbaugh *et al.* 2000). Analysis of the regional topography (Fig. 3) shows that any polar material meltwater would likely ultimately drain toward the center of the north polar basin. On the other hand, meltwater would tend to drain away from the southern cap, or possibly pond in one or more of the ancient crater depressions (such as the Prometheus Basin) underlying the deposits (Fig. 2b). The nature of the cap substrate could certainly influence the distribution of meltwater. The porous megaregolith beneath the southern cap may play a different role than the very smooth Vastitas Borealis Formation in the north (Kreslavsky and Head 1999, 2000). For example, meltwater may pool within local craters in the south versus within a broad basin in the north. If Hesperian ridged plains, thought to consist of basaltic lava flows, underlie the Vastitas Borealis Formation in the North Polar Basin (Head *et al.* 2001), they may influence vertical drainage.

The way in which meltwater is stored and distributed may affect what type of meltwater features are formed. In the north polar cap, which resides within the broad northern lowlands basin (Fig. 3), the only major meltwater features that have developed are chasmata. Although kame and kettle-like features are observed (Fishbaugh and Head 2001a), there is little evidence for abundant cavi and esker-like features as seen in the south polar region. In the south, chasmata appear within the Prometheus Basin (Fig. 3) and nowhere else within the cap. This coincidence in location may be due to the fact that large amounts of meltwater can collect within such basins and be released to form the chasmata. On the other hand, where cavi exist in the south (in the 0° and 80°W directions), the more porous regolith substrate outside of the Prometheus Basin may be conducive to downward percolation of meltwater (e.g., Clifford 1993) rather than storage and lateral release.

What factors might favor or be responsible for melting? Among the possible scenarios are the following: (1) local subcap volcanic eruptions (Clifford 1987, Garvin *et al.* 2000, Sakimoto *et al.* 2001), (2) a higher geothermal heat flux in the past (Clifford *et al.* 2000), (3) much thicker caps (Clifford 1987), (4) climate change due to outgassing of volatiles and/or variations in solar luminosity, (5) increased obliquity, (6) polar wander, (7) cap compositional differences, and/or (8) frictional heating due to basal sliding (Clifford *et al.* 2000).

Zuber *et al.* (2000) have determined the effective elastic lithosphere thickness using gravity and topography data and find that the southern highlands are characterized by an effective elastic lithosphere thinner than that of the northern lowlands near Utopia Basin. Johnson *et al.* (2000) found that if the circumpolar Amazonian mantle material (Am) is filling a depression of flexural origin due to loading by the cap, the lithosphere may be 60–120 km thick beneath the north polar cap. These observations suggest that the geothermal heat flux at each cap would likely be different. This could have an effect on the relative importance of melting at each cap. Further analysis of the flexural response to lithospheric loading by changes in the cap thickness and volume may be very helpful as more information becomes available about the structure of the lithosphere with time, and the geometry of former polar deposit loads.

The current melting isotherm for water ice lies at least 3 km below the surface at the north pole, as calculated by Clifford and Parker (2001). Addition of the northern cap volume now missing from the Olympia Lobe (approximately 25% of the current cap volume) (Fishbaugh and Head 2000) is still insufficient to induce lithostatic pressure-related melting at the cap base (e.g., Clifford

1987, Clifford *et al.* 2000). Thus, the caps at their present positions would have to have been much thicker than they are now (and much thicker than their proposed former extents) to allow the melting isotherm to rise to the base of the polar materials.

One model for the formation of the deposits that underlie the north polar cap (the Vastitas Borealis Formation) is that they were emplaced by outflow channel flooding, which formed standing bodies of water that eventually sublimated and evaporated, leaving a sedimentary veneer (e.g., Parker *et al.* 1989, 1993). If this model is correct, then evaporites may occur at the base of the polar deposits. Such materials could serve to lower the melting point of the polar materials. The south polar cap may contain CO_2 clathrate (Clifford *et al.* 2000, Nye *et al.* 2000), which could also lower the melting point of the polar materials.

In summary, although progress is being made, there are many outstanding issues and questions. What is the relative role of outflow and katabatic winds in the formation of the chasmata? What range of conditions and processes account for the difference in morphology and mode of occurrence of the esker-like ridges, cavi, and chasmata? What is the range of causes of melting, and did it differ with time and at each pole? What was the timing of possible melting, and was it contemporaneous at both poles? If significant melting is implied by the range of features described, what is the fate of the meltwater and the sediment derived from melted layered terrain?

2.3. Circumpolar and Subpolar Topography and Their Effects on Polar Cap Evolution

The Amazonian-aged south polar cap is much more irregular in planform than is the more circular northern cap (Fig. 2). It is possible that the great differences in underlying topography (both in roughness and slope) (Fig. 3) between the two regions may have enhanced and distributed cap flow differently, in addition to influencing the storage and movement of meltwater at the base of the caps. MOLA data have revealed a fundamental difference between the subcap and surrounding topography in the north and south polar regions (Fig. 3). These data show that the north polar cap lies near the bottom of the North Polar Basin (Zuber *et al.* 1998, Head *et al.* 1999, Fishbaugh and Head 2000), while the southern cap lies at an elevation higher than the surrounding terrain, which slopes away from the cap center.

These differences can manifest themselves in cap evolution in various ways, especially if the caps are currently able to flow or have flowed in the past. Several authors (e.g., Hvidberg and Maries 2000, Larsen 2000, Larsen and Dahl-Jensen 2000, Hvidberg 2001) have suggested that flow is or has been possible in the recent past. Maximum ice flow velocities in the north polar cap may have been on the order of millimeters per year during past high obliquity cycles (Greve *et al.* 2000). Fisher (2000) and Pathare and Paige (2000) have estimated current flow velocities of centimeters to meters per year for the northern cap. According to these authors, the actual velocity depends in part upon the obliquity value, since warmer temperatures at higher obliquities may enhance flow. In addition, the dust content of the layered terrain is important. Although the direct effect of the inclusion of dust is to inhibit flow, its presence in the layered deposits also increases density, lowers thermal conductivity, and precludes dynamic crystallization. These factors result in greater driving stresses, higher subsurface temperatures, and smaller ice grain sizes, all of which enhance flow by grain boundary sliding (Pathare and Paige 2000). Pathare and Paige (2000) suggest that a year-long covering of CO_2 frost in the south would prevent the flow of the H_2O ice below that cover, except possibly at very high obliquity. According to their calculations, enhanced flow due to high obliquity would have occurred most recently in the south about 9×10^6 years ago. Thus, flow of the southern cap in the past may be partially dependent upon whether it has always retained a permanent CO_2 frost cover. Neither of these two velocities are detectable by any current means, and Durham (2000) points out that strain rates in the martian polar caps are too low to measure in the laboratory. Ivanov and Muhleman (2000) suggest that sublimation is as important as flow in creating the profile and trough shape of the northern cap.

The regional topographic differences between the poles (a basin in the north and a broad high in the south) would probably not greatly affect flow of the caps, because large-scale flow of an ice sheet depends mainly on the surface slope of the ice, not the slope of the bedrock (Paterson 1981). However, substrate topography on a local scale may influence small-scale cap flow. According to Paterson (1981), the detailed form of the Antarctic ice sheet surface on a lateral scale of less than 20 times the ice thickness is affected by irregularities in the bedrock, which create longitudinal stress gradients. On Mars, craters may provide flow obstacles in certain positions beneath the southern cap or depressions into which ice might more readily flow (e.g., Head 2000, 2001) (Fig. 7). Ice streaming may also be initiated at a step in topography where a stream of ice flows downslope more rapidly than the ice surrounding it (Bentley 1987). Evidence of possible ice streaming has been found within the south polar cap (Head 2000), and may be linked to topographic changes in the underlying Prometheus Basin. The southern cap is superposed on the ∼875-km-diameter Prometheus Basin (Schenk and Moore 1999, 2000), and its presence may well be an important factor in its evolution. Local irregularities in flow, assuming that both caps have flowed at some time in the past, may account for the more irregular planform shape of the southern cap. If the spiral pattern of troughs is related to flow of material from the cap center toward the margin, as Fisher (1993, 2000) has suggested for the northern troughs, then the difference in cap shape could account for the more defined spiraling pattern of the northern polar cap troughs than that of the southern scarps/troughs. As an alternative, the southern scarps and troughs may be older, their symmetry having long since been destroyed by ablation and/or flow of polar materials.

The underlying topography does not appear to have had much influence on the cross-sectional shapes of the polar caps. The

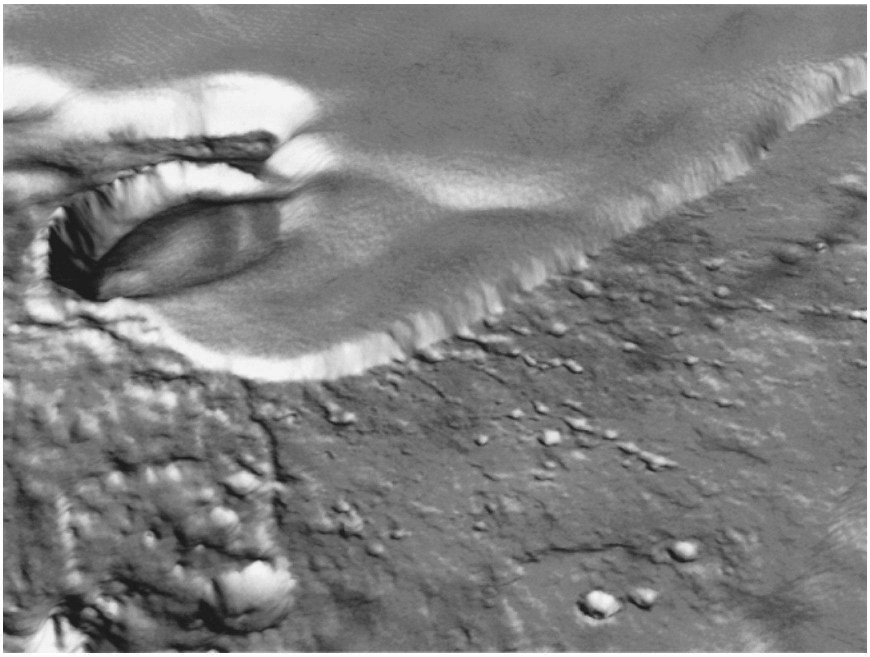

FIG. 7. Oblique view of the northern edge of the south polar layered terrain (Apl; top) on the floor of the Prometheus basin. MOLA digital elevation model (DEM) viewed from the north toward the crater. The partially buried 45-km-diameter crater (middle left), and its related secondary crater chains and clusters (surrounding the crater on the basin floor), appears to be embayed by a lobe of material from the layered terrain (Api) that extends from the continuous deposit of Apl down into the crater. Note how the ejecta (linear secondary crater chains, middle right) emerges from beneath the lobe of Apl, as if advancing flow covered the secondaries and ejecta between the rim of the crater and those observed. Vertical exaggeration is about 9x.

caps, including residual ice and layered terrain, have similar cross-sectional shapes (Smith *et al.* 1998), but the south polar cap has a larger volume, $\sim$2–3 × 10^6 km^3 (Smith *et al.* 1998), than the north cap, $\sim$1.2–1.7 × 10^6 km^3 (Zuber *et al.* 1998).

In summary, among the outstanding questions and issues related to regional and subcap topography and their effects on the evolution of the polar caps are the following: What morphological features can be confidently attributed to flow, and when and under what conditions did they occur? How and to what extent has the surrounding and subcap topography influenced polar ice flow and movement? Are the differing planform shapes of the caps related to the underlying topography and/or to flow of polar material over this topography? Is the polar trough/scarp pattern, which is more symmetrically spiraling in the north, influenced by the planform shapes of the caps? To what extent has the subcap topography governed storage and movement of polar meltwater?

2.4. *Antipodal Offset of the Polar Caps*

The centers of symmetry of the planform shape of the Amazonian-aged polar deposits (Api, Apl) do not coincide with the present polar rotational axis (compare Figs. 2a, 2b). The center of the north polar deposits is offset toward the 0°W longitude (Fig. 2a), while the center of the south polar deposits is offset toward the 180°W longitude (Fig. 2b). Thus, the centers of symmetry of the planform shapes are asymmetrical about the current rotational pole in that they are offset a few degrees from the pole in antipodal directions from each other (Fig. 8).

The topographic centers of both Amazonian-aged caps (Zuber *et al.* 1998), as defined by their highest elevations, do not show relationships similar to those seen in map view (Fig. 3). The highest region of the north polar cap approximates the position of the present rotational pole. The highest region of the south polar cap is offset from the present rotational axis by about 3°–4° in the 0°W longitude direction.

Offset of the Amazonian polar cap planform center of symmetry from the rotational pole in the north has been interpreted to be due to retreat of the cap from predominantly the 180°W direction (Fishbaugh and Head 2000). In this scenario, the cap was previously more symmetrical about the rotational pole, but asymmetrical meltback resulted in the current planform asymmetry (Fig. 4). Could retreat of the south polar Amazonian deposits from the 0°W longitude direction (Fig. 2b) account for the offset there? Although a distinctive scarp exists in this direction (Fig. 3) at about 84°N latitude, most of the adjacent deposits appear to be related to the Amazonian polar deposits or to the Hesperian-aged Dorsa Argentea Formation (Fig. 2b) (Tanaka and Scott 1987).

Shifting of the rotational axis due to polar wander has been proposed (e.g., Schultz and Lutz 1988) and might produce antipodal retreat. Examination of Fig. 8, however, reveals that the offset cannot be explained by a shift of the axis from a position connecting the centers of symmetry of the caps to the

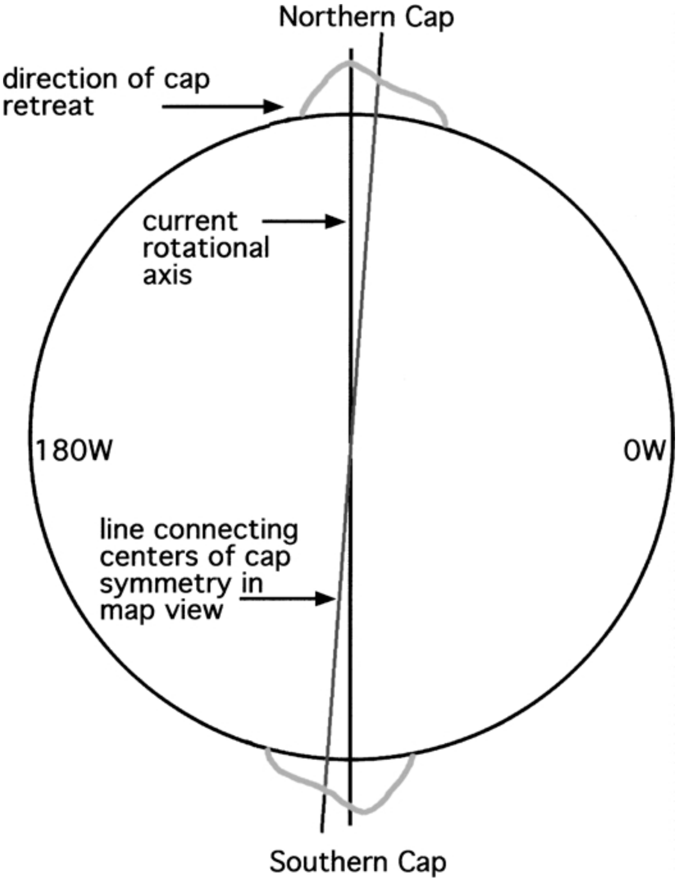

FIG. 8. Diagram showing the positions of the current caps with respect to the current rotational axis and the direction of retreat of the northern cap. The planform centers of symmetry of the caps are offset in antipodal directions from the current rotational poles. Part of this offset in the north has been attributed to possible retreat of the cap (Fishbaugh and Head 2000).

present position. If polar wander were the cause, then the anticipated direction of retreat of the north polar cap would be from the 0°W longitude direction, the opposite direction from that observed (Fig. 8). A polar wander scenario would require several phases of movement relative to the pole. Could obliquity variations be responsible for asymmetrical and antipodal deposit distribution in map view? In such a scenario, an obliquity maxima would bring the polar caps toward the plane of the ecliptic, causing deposit melting and retreat. This would be followed by a return of the rotational axis toward its previous position away from the plane of the ecliptic. This scenario, however, is not consistent with the observations. First, cap melting from obliquity variations should be symmetrical about the polar axis; however, the proposed direction of the retreat of the north polar cap is very asymmetrical (Fig. 4, 8). Secondly, the present deposit symmetry offset in map view (Fig. 2, 8) would require that the rotational pole is migrating more rapidly away from the plane of the ecliptic than the polar deposit itself. The relative rates of obliquity change and polar cap response are not known, nor is the full range of factors that might cause cap asymmetry understood. Thus obliquity variations remain a candidate factor in the observed polar deposit asymmetries.

The observed differences in the location of the topographic summit of the polar deposits may be related to underlying topography. The present south polar topographic summit is offset from the rotational pole and (Fig. 3) is located in the vicinity of the extension of the rim of the ∼875-km-diameter Prometheus Basin beneath the Amazonian cap deposits (see Fig. 2b, 3, and 5) (e.g., Schenk and Moore 1999, 2000; Fishbaugh *et al.* 2000). Preferential accumulation of polar deposits on the topographic high of the basin rim may have been responsible for the offset of the present topographic summit.

In summary, several of the outstanding questions and issues include the following: Why are the centers of map view symmetry of the two polar caps antipodal to each other and offset from the current rotational poles? Is there evidence for offset of the southern cap due to retreat, in a manner similar to that proposed for the northern cap? Can this antipodal offset in map view symmetry be related to polar wander, obliquity variations, or to other processes, such as the substrate topography and different behavior between the poles during cap evolution?

2.5. *Stratigraphy and Polar Cap Ages*

The stratigraphy of geologic units at the poles and the ages of the caps themselves provide a basis for assessing the origin of antipodal offset of the polar caps and potential ages of melting and cap retreat. Several authors (Dial 1984, Tanaka and Scott 1987, Fishbaugh and Head 2000) have shown that the various members of the Hesperian Vastitas Borealis Formation (Hv) underlie the Amazonian cap (Apl, Api) in the north. Thus the cap was deposited upon previously modified ground of Hesperian age and is now surrounded and partially mantled by Amazonian mantling material (Am) and Olympia Planitia, the largest dune sea on Mars (Greeley *et al.* 1992, Fishbaugh and Head 2000) (Fig. 1, 2a, and 4).

In the south (Fig. 1, 2b, and 4), heavily cratered Noachian terrain (Npl, Npld) underlies the Amazonian-aged polar units and the Hesperian-aged Dorsa Argentea Formation, but is sometimes exposed as plateaus (e.g., Tanaka and Scott 1987; Schenk and Moore 1999, 2000). The ridged plains (Hr) and undivided material (Hnu) overlie the Noachian terrain. In some places near the cap, HNu lies at elevations similar to the Apl, suggesting that these units may be related. The Dorsa Argentea Formation (Hd) generally occupies elevations lower than the HNu and Noachian plateaus. The polar cap (Apl, Api) overlies the Hesperian and Noachian terrain. The cap itself consists of a dome-like shape surrounded in many places by a plateau-like shape, which has been cited as evidence of partial retreat of Apl and Api (e.g., Schenk and Moore 1999, 2000; Head and Pratt 2001).

In summary, the stratigraphy at both poles shows that the Late Amazonian caps are underlain by Late Hesperian and sometimes Noachian material. Therefore, there is a significant stratigraphic hiatus between the Late Hesperian and the Late Amazonian at both poles. According to the most recent analyses, the end of the

Hesperian is estimated to have occurred either 2.9 or 3.3 byr ago (Hartmann and Neukum 2001). This means that the Amazonian period is about 3 byr in duration. Estimates from recent dating of the Late Amazonian caps indicate that the south polar cap is ~7–15 × 10^6 years old while the northern cap is <100 × 10^3 years old (Herkenhoff and Plaut 2000). Thus, the ages estimated for the present polar caps are at most less than 1/200th (0.5%) of the total duration of the Amazonian. What might explain this observed extremely long hiatus in the geologic record between the Late Hesperian and Late Amazonian? We list several possibilities.

(1) Polar caps are recent events in the history of Mars: In this scenario, conditions in the Late Amazonian would have been more favorable for cap formation than previously, and thus the caps accumulated here only recently. If the polar caps are indeed entirely of Late Amazonian age, then this raises the question of what sort of geological activity was occurring during the time between deposition of the surrounding Hesperian deposits and the deposition of the polar deposits in the Late Amazonian.

One possibility is the influence of a proposed northern lowland ocean (e.g., Parker *et al.* 1989, 1993; Clifford and Parker 2001) and its fate. If such an ocean did exist, as atmospheric conditions typical of those today emerged, the body of water would begin to freeze throughout and sublimate. As pointed out by Clifford (1993), a north polar cap would not form and accumulate until the ice surface of the ocean thickened sufficiently to ground against the substrate (see also Kargel *et al.* 1995, Clifford and Parker 2001). Although such a set of circumstances provides a basis for delaying the onset of a north polar cap, this scenario is not supported by stratigraphic relationships that show a Late Amazonian age for the polar cap. For example, the Vastitas Borealis Formation underlies the cap and appears to consist partly of the residue of outflow channel deposits (e.g., Head *et al.* 2001). This unit is of Late Hesperian age, implying that any ocean or resulting ice layer must have been gone by the end of the Hesperian. Thus, a cap produced by this mechanism should be Late Hesperian in age. In addition, lobate flows and channel-like deposits from the Elysium rise deposited in the Utopia basin are interpreted to have been emplaced in the Early Amazonian, subsequent to the presence of any standing body of water (e.g., Ivanov and Head 2001). This relationship also suggests that a cap produced by the ocean evolution scenario should be Late Hesperian or no younger than earliest Amazonian in age, in contrast to the observed Late Amazonian age.

A second candidate explanation for the recent formation of polar caps is polar wander (e.g., Schultz and Lutz 1988). In this scenario, the polar deposits were being deposited elsewhere on the planet in previous times, but only recently did the pole migrate to the position where the present polar deposits accumulated.

(2) The polar caps are oscillating: In this scenario, polar caps are periodically deposited and then retreat and disappear. Such oscillations could be caused by extremes in the obliquity cycle such that at maximum obliquity, the poles sublimate and disappear, but then reform during other parts of the obliquity cycle. In this model, the presently observed caps are simply the latest incarnation of caps that have come and gone many times during the Amazonian period. Each episode of retreat has erased the record of the previously deposited polar cap. This would make the present polar cap the most recent example of numerous polar caps that have existed at the current poles throughout earlier Amazonian history. The obliquity cycle may regulate this oscillation in cap deposition and retreat, with the caps almost, if not completely, disappearing during extreme high obliquities.

(3) The present caps are old, but have been renewed so that they appear young: In this scenario, the caps may have been in their present positions for much of the Amazonian, but some process or processes (e.g., melting, flow) periodically destroys preexisting craters to produce cap surfaces that appear to be very young from the standpoint of superposed craters. The Late Amazonian age of the caps could thus be due to periodic mobilization of the cap as a whole, or to renewal of a surface layer through deposition and flow, with deeper older underlying layers remaining below. Increased mobility of the caps at high obliquity (e.g., Pathare and Paige 2000) may permit such renewal. One interpretation of the relatively younger ages of the north polar cap is that this process may be operating more efficiently there. Craters that are presently observed on the polar deposits appear nearly pristine, and evidence for transitional morphologies has not been found. Thus, if this model is correct, periods of crater accumulation and stability might alternate with periods of crater obliteration.

In summary, several of the outstanding questions and issues are as follows: Do the surface age estimates based on crater density represent the real ages of the entire polar caps? Are there processes operating, such as ice flow or deposition, that could eradicate craters on the cap surfaces, thus yielding very young surface ages? Could such processes be more efficient in the north, thus making the northern cap appear younger? Given these uncertainties, could the lower layers of the polar layered terrain be wholly or at least partly Early to Mid-Amazonian in age? Alternatively, are the current caps merely the latest, Late Amazonian manifestation of polar deposit deposition that has been alternating with nearly complete ablation and loss since the Hesperian, possibly due to extremes in obliquity?

3. SUMMARY AND OUTSTANDING PROBLEMS

Building on previous observations using *Viking* data (e.g., Tanaka and Scott 1987, Kargel and Strom 1992, Kargel *et al.* 1995) and *Mars Global Surveyor* data (e.g., Clifford *et al.* 2000), MOLA has provided new evidence for large-scale changes (e.g., flow, melting, and retreat) in polar deposits at both poles. Preliminary analyses suggest the role of several factors in these changes but many outstanding questions remain. The differing nature of the polar cap substrate between the two poles may have affected the small scale topography of the caps and the troughs/scarps within them by influencing cap flow. The distribution and transport of possible meltwater could also be related to substrate material and subcap topography, as well as to the geometry and slope of the cap itself. The relative influence of these factors has yet to be determined.

MOLA data have further documented the differences in the planform shapes of the present polar caps as well as the offset of their centers of symmetry in map view from the current rotational poles in antipodal directions. Retreat of the north polar cap may be a factor in its offset from the rotational pole, but an explanation for the asymmetry in the south has not been forthcoming. Could a similar scenario account for offset of the southern cap? The exact cause of the antipodal offset is not well understood and does not appear to be readily explained by a single polar wander event or by obliquity variations. Because the caps were deposited on substrates whose topography (at both large and small scales) and physical nature were different, the evolution of their planform shapes and the results of any processes that have influenced them (e.g., melting and retreat) could well be different. While similar processes have affected both caps, albeit in different ways, these processes need not have operated simultaneously, just as large-scale flow, melting, and retreat events do not always occur simultaneously in Iceland, Antarctica, and Greenland. Multiple causes of melting, flow, and retreat may need to be invoked for both caps, but the antipodal offset of the planform center of symmetry of the caps suggests that the histories of the two caps are interrelated in some fundamental way.

Documentation of the ages of the caps themselves, and of the processes that have affected them individually and together, is crucial to linking the nature of the caps to the climatic and geologic history of Mars. Crater dating (Plaut *et al.* 1988, Herkenhoff and Plaut 2000) has led to the interpretation of Late Amazonian ages for both caps. Yet, because the caps overlie Late Hesperian material, this implies a stratigraphic hiatus (and perhaps a hiatus in polar geologic activity) between the Late Hesperian and Late Amazonian at both poles, a period of more than 200 times the estimated age of the present caps. We have outlined several possibilities to explain this apparent Late Hesperian to Late Amazonian hiatus. The caps may in fact be recent events in Mars' history, with conditions not being conducive to the deposition of polar caps in their present locations until the Late Amazonian.

Alternatively, the caps may have gone through oscillations, or cycles of deposition and loss, since the Late Hesperian, possibly correlated with extremes in the obliquity cycle. In this case, the present deposits are just the latest manifestations of polar cap deposition. Because retreat and readvance are likely to destroy evidence of past activity, it is not known whether such events may have occured once, several, or many times. During the approximately 3-byr-long Amazonian period (Hartmann and Neukum, 2001), Mars would have reached its maximum obliquity over 2000 times (e.g., Ward 1979). Thus, if maxima in obliquity can cause complete or partial retreat and melting of the polar caps, then there has been ample opportunity for polar deposit transformation.

A third scenario is that the caps have been at or near their present position throughout the Amazonian, but some processes, such as enhanced cap flow during periods of higher obliquity, caused surface craters to be destroyed and the surfaces renewed. Until the depositional processes and time scales of the polar caps and the crater retention ages of impact craters in the polar cap materials are well understood, the true age of the polar materials beneath the cap surface will remain in question.

The *Mars Global Surveyor* data have thus provided new insight into many aspects of polar processes and history and have outlined and clarified a number of outstanding questions. Further exploration of Mars and analysis of these data will help to resolve these important issues.

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