Mars landscape evolution: Influence of stratigraphy on geomorphology in the north polar region

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Abstract. Lithology and physical properties of strata exposed at the Earth's surface have direct influence on the erosion and geomorphic expression of landforms. While this is well known on our planet, examples on Mars are just coming to light among the tens of thousands of airphoto-quality images (resolutions 1.5–12 m/pixel) acquired since 1997 by the Mars Global Surveyor Mars Orbiter Camera (MOC). Specific examples occur among Martian north polar layered materials, which MOC images reveal are divided into two distinct stratigraphic units: a lower, dark-toned layered unit and a younger, upper, lighter-toned layered unit. The lower unit is less resistant to wind erosion than the upper unit. The upper unit most likely consists of stratified dust and ice, while the lower unit contains abundant, poorly-cemented sand. Sand is more easily mobilized by wind than dust; the lower resistance to erosion of the lower unit results from the presence of sand. Where wind erosion in polar troughs has penetrated to the lower unit, geomorphic change has proceeded more rapidly: sand has been liberated from the lower unit, and arcuate scarps have formed as the upper unit has been undermined. Wind erosion of the lower unit thus influences the geomorphology of the north polar region; this result likely explains the genesis of the large polar trough, Chasma Boreale, and the relations between dunes and arcuate scarps that have puzzled investigators for nearly three decades. The properties of the stratigraphic units suggest that the upper limit for the amount of water contained in the north polar layered materials may be 30–50% less than previously estimated.

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1. Introduction

The existence of Martian polar caps has been known for nearly four centuries. Images of the caps and their surroundings were acquired from orbit by Mariner 9 (1972), Viking 1 and 2 (1976–1980), Mars Global Surveyor (1997–present), and Mars Odyssey (2002–present). In recent years, the polar regions have generated substantive interest in both the Mars and Earth geoscience communities (particularly terrestrial polar, periglacial, and alpine geomorphologists), as indicated by strong attendance and published results of the first two International Conferences on Mars Polar Science and Exploration held in 1998 and 2000 (Clifford et al. 2000, 2001) and by selection (though subsequent failure of) a NASA lander dispatched to south polar terrain in 1999. Water and ice are of great interest in Mars exploration and the search for evidence of life on the planet. The south polar residual cap is predominantly frozen CO_2 (Kieffer 1979; Malin et al. 2001), but the north polar cap in summer gives off water vapor and has temperatures consistent with the presence of frozen water (Kieffer et al. 1976; Farmer et al. 1977).

Although considered to be an ice-rich body, some investigators have surmised that much of the present morphology of the Martian north polar cap and its underlying mound of layered material (commonly called "layered deposits," despite the genetic implication of the term, "deposit") can be explained by wind erosion. In particular, Howard (2000) proposed that strong, katabatic winds are the primary erosive agents, accompanied by ice sublimation and ablation. Eolian processes, in Howard's view, explain the genesis and subsequent erosion of shallow-sloped (< 10°) "spiral" troughs, steep (typically, 30°–50°) arcuate scarps, dune fields associated with the scarps, and the large, broad valley, Chasma Boreale (Fig. 1). Thomas and

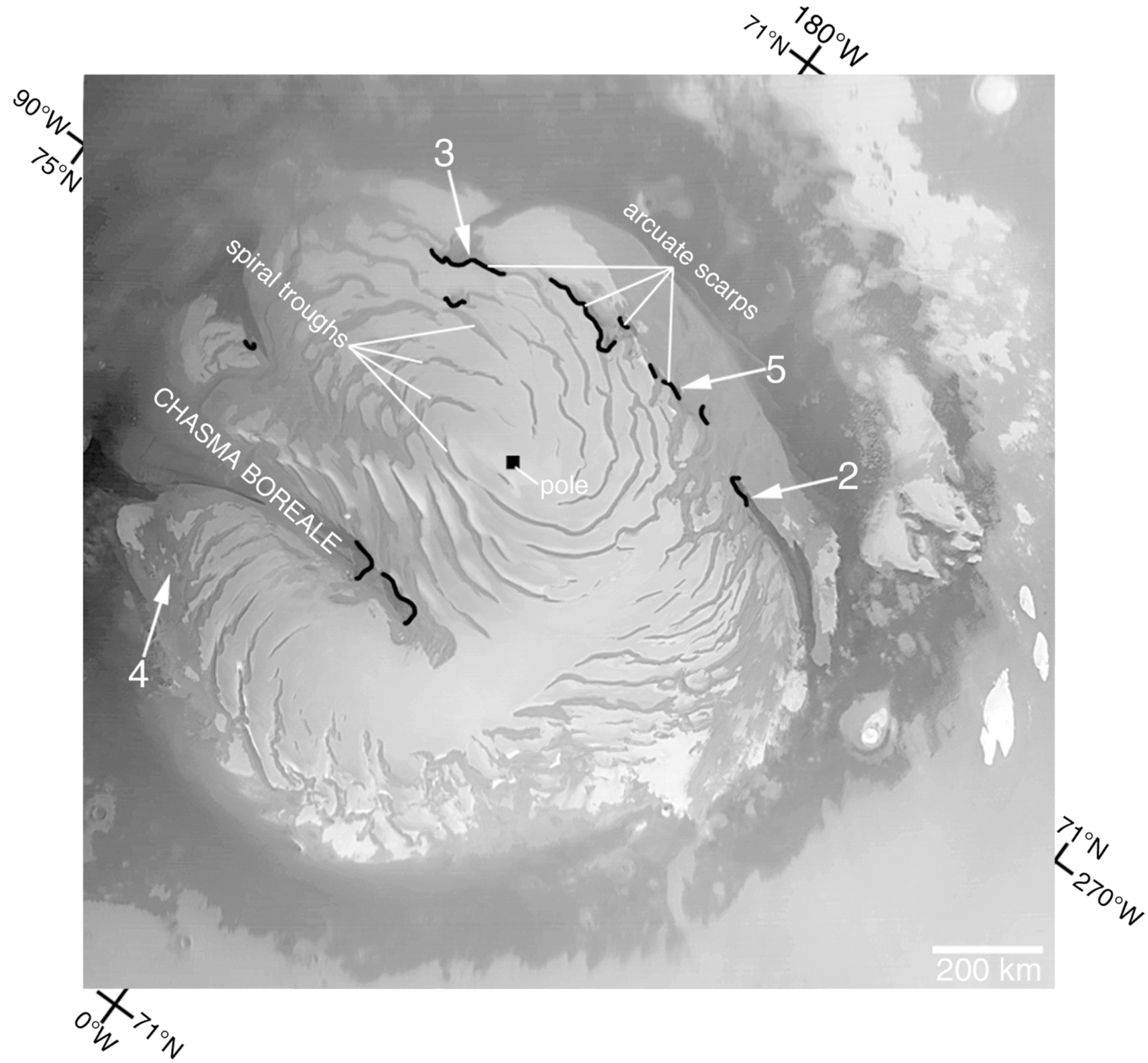

Figure 1. Polar stereographic projection view of the martian north polar region; MOC red wide-angle image FHA-00710. Black arcs are the locations of arcuate scarps that have outcrops of the upper and lower polar stratigraphic units. Numbers indicate locations of Figs. 2–5.

Weitz (1989) showed that dune orientations indicate sediment transport away from the arcuate scarps, and Howard (2000) suggested that the scarps form by undermining at each scarp base, which leads to oversteepening, collapse, and eolian removal of debris. However, the reason that wind would preferentially undermine material at the base of each scarp was not known. In this report, we show that the physical properties of strata comprising the Martian north polar layered materials directly control their geomorphic expression. Such a result would not be news on Earth, but for Mars it represents a significant advance over suppositions dating back three decades.

2. Observations

2.1. Background and Data

The north polar layered materials, although not necessarily lithic, form a broad, eroded mound that covers ~ 8.4 x 10^5 km^2 of the Martian northern plains. We targeted hundreds of Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) high resolution images (1.5–12 m/pixel) during a clear-atmosphere period in northern summer, January–April 2001, to observe the relations between strata and geomorphology of the region. Earlier MOC images from 1999, of reduced quality because of frequent dust storms and haze, showed that the layered terrain displays two distinct stratigraphic units: an upper, lighter-toned unit and an older, lower, darker-toned unit (Malin and Edgett 2001, pp. 23499, 23510; Byrne and Murray 2002). Outcrops of these units occur throughout the polar region. Prior to the MGS mission, the north polar layered materials were assumed to be a single geologic unit (the "polar layered deposits" of Tanaka and Scott (1987)). The layers were believed to be composed of stratified water ice mixed with dust (grains typically < 10 μm in diameter) settled from suspension, and, possibly, dust brought to the surface via precipitation as nuclei in grains of ice or snow (e.g., Cutts 1973; Thomas et al. 1992).

In addition to MOC images, we also examined relevant Viking orbiter images, topographic profiles (across simultaneously acquired MOC images) from the MGS Mars Orbiter Laser Altimeter (MOLA), and mid-infrared spectra of dunes from the MGS Thermal Emission Spectrometer (TES). Through April 2002, MOC acquired ~ 2800 high resolution images (usually 1.5–3 km wide by 20–80 km long) in the north polar region. Many of the observations described here are illustrated by MOC image E01-01773 (Fig. 2). The image shows a portion of one of the steep, arcuate, north polar scarps. At this location, as at all other arcuate scarps, the upper and lower stratigraphic units are both exposed. Also present are talus and eolian dunes.

2.2. Upper Unit

Strata of the upper unit are exposed in three settings: arcuate scarps, spiral troughs, and slopes around the outer margins of the polar cap. The slope expression of the upper unit on the left side of Fig. 2 is the same as that of typical spiral trough and cap margin exposures; other examples are seen in Malin and Edgett (2001, pp. 23495, 23498). The outcrop on the steep slope in Fig. 2 is typical of polar arcuate scarps. Beds of the upper unit are relatively thin (~ 30 ± 15 m); on shallow slopes they are displayed as broad bands up to several tens of meters wide. Although the layers vary in resistance to erosion from one to the next, they are much more uniform than those of the lower unit. Other MOC images show that the beds maintain constant or nearly constant thickness and stratigraphic relations over distances > 100 km within a given trough and from one trough to another (Malin and Edgett 2001, pp. 23498, 23510; Kolb and Tanaka 2001, pp. 32–36). Beds of the upper unit are horizontal or nearly horizontal; contrary to earlier impressions (Malin and Edgett 2001, pp. 23500–23501, 23510), beds are not deformed. Rather, upon closer examination, the appearance of deformation was found to result from subkilometer variations in local slope and erosional expression. The uniformity of bed properties has one exception: in an arcuate scarp at 84° N., 130° W., dark lenses mark a single, discontinuous bed among the lower layers of the upper unit (Fig. 3).

2.3. Lower Unit

The lower unit is distinguished from the upper by a darker tone, although there are some beds, as in Fig. 2, with the same tone as the upper unit. The lower unit does not outcrop in the spiral troughs, but is exposed in all of the arcuate scarps; it also comprises the floor of Chasma Boreale. Some beds form resistant shelves. Other, usually darker-toned, beds are in some places recessed under the shelf-forming layers. Planimetric exposures of the lower unit are more difficult to recognize, except where they occur with arcuate scarp outcrops. The floor of Chasma Boreale exposes the lower unit in planimetric configuration; in this case, the shelf-forming layers cap mesas. Morphologic features similar to those in Chasma Boreale lead us to infer that

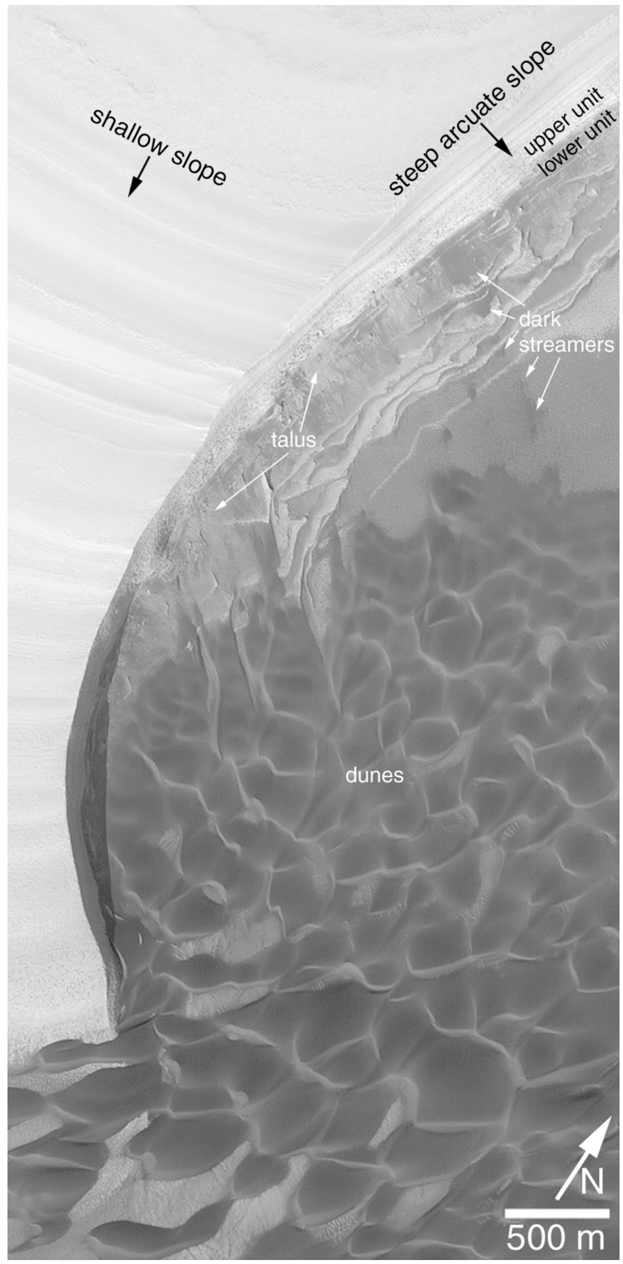

Figure 2. Summary view of relations between arcuate scarps, dunes, and strata of the upper and lower north polar units. This is a sub-frame of MOC image E01-01773, 83.5°N, 241.4°W, illuminated from lower left.

outcrops of the lower unit are common around the outer margins of the polar cap, particularly in places that do not retain frost in mid-summer (e.g., MOC images M04-00539, E02-02506, E02-02849). In a few of the latter locales, dark, semi-crescentic mounds appear to be in a state of exhumation from within the lower unit (Fig. 4).

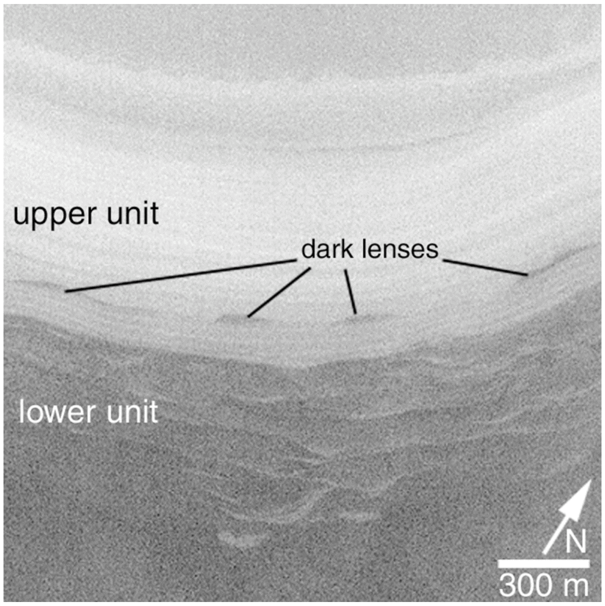

Figure 3. Dark, discontinuous layer (lenses) among lower beds of the upper stratigraphic unit in an arcuate scarp near 84°N., 130°W. This is a sub-frame of MOC image E05-01531, illuminated from lower left.

2.4. Contact

The contact between the upper and lower units is sharp and distinct. At arcuate scarps between latitudes 83°–85° N. and longitudes 120°–250° W., the contact is at a nearly uniform elevation of −4330 ± 110 m relative to the Martian datum. In Chasma Boreale, the contact is located ~190 m lower, at −4520 ± 80 m elevation. These elevations are consistent with those determined by Byrne and Murray (2002). Whether the differences in contact elevation indicate an erosional surface between the two units or a shallow, regional dip toward Chasma Boreale cannot be determined. Outcrops in some images seem to suggest that the contact marks a severe erosional unconformity, but this impression is illusory. Figure 5 shows an example in which the contact undulates across the scene; this apparition results from retreat of scarps formed in the lower beds of the upper unit. Piles of talus, derived from the upper unit, obscure the contact and beds of the lower unit in some places (Figs. 2, 5).

2.5. Dunes

Eolian dunes are darker than the lower unit, although locally within the lower unit (and, in one case, in the lower beds of the upper unit, Fig. 3) there are patches of material that are as dark as nearby dunes. Each arcuate scarp has an attendant dune field, located within 0–5 km of the scarp (Fig. 2), and slip faces indicate movement away from the scarps (Thomas and Weitz 1989). In Fig. 2, dark streamers extend from dark patches in the upper beds of the lower unit to a nearby dune field; this relationship is found at most arcuate scarp outcrops.

3. Discussion

3.1. Dune Sediment

Dark streamers indicate pathways of sediment transport from the lower unit outcrops to nearby dunes. We interpret this observation to indicate that the dune sediment is derived from erosion of the lower unit. Thus, the properties of dune sediment constrain the properties of lower unit materials. We interpret the dune sediment to be sand. Dunes are well-sorted deposits consisting of grains transported by saltation and traction. On Mars, sand (62.5–2000 μm) is the particle size most easily mobilized at threshold friction velocities and is the most likely to saltate (Iversen and White 1982); it is also the size inferred from thermal infrared observations for most Martian dunes (Edgett and Christensen 1991). However, based on Viking Infrared Thermal Mapper data, Herkenhoff and Vasavada (1999) proposed that north polar dunes consist of grains smaller than sand (e.g., silt, clay, or aggregates thereof) because their thermal inertia, derived by model-dependent means, is low relative to that of other Martian dunes (Paige et al. 1994). The

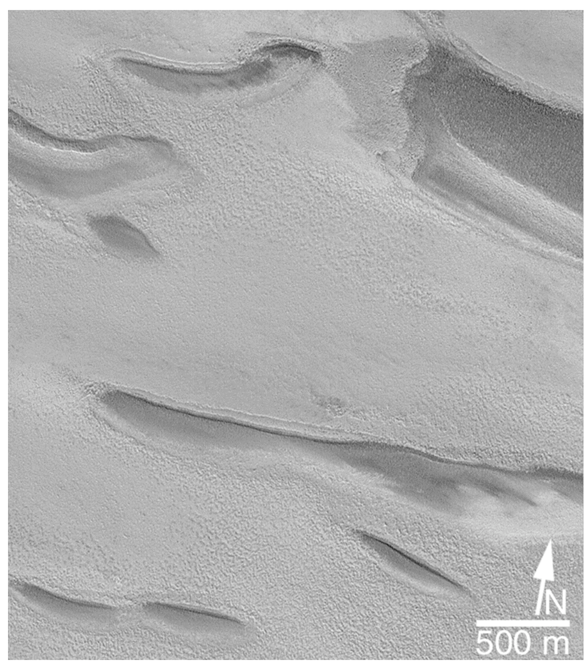

Figure 4. Dark, dune-like patches exhumed by erosion of layers within the lower stratigraphic unit at an elevation of −5020 ± 20 m relative to the martian datum near 79.7°N, 36.4°W. This is a sub-frame of MOC image E02-00629, illuminated from lower left.

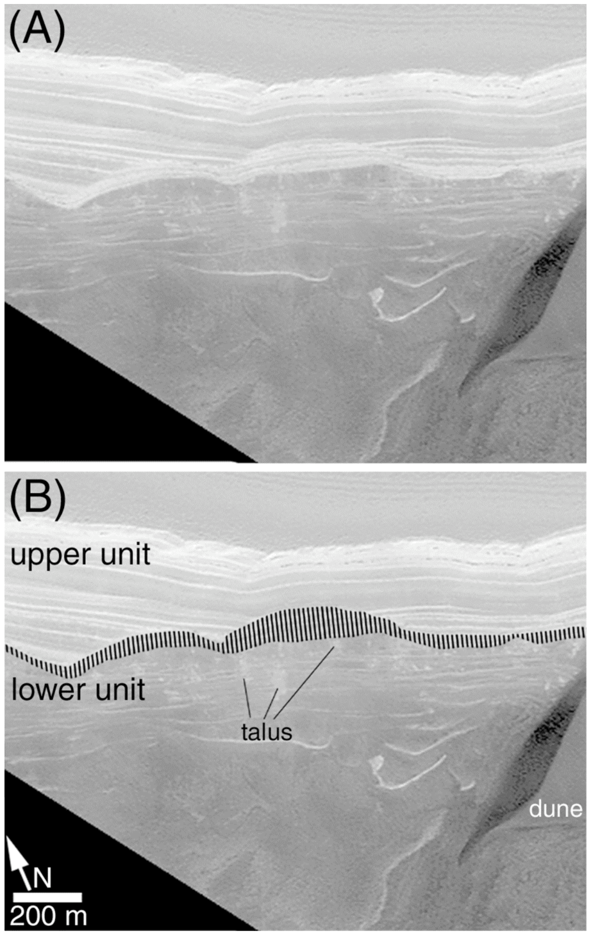

Figure 5. (A) Example of undulating contact between upper and lower units. **(B)** Annotated view, with scarps in lower beds of the upper unit indicated by diagonal bars. This is a sub-frame of MOC image E03-00270, located near 85.2°N, 209.2°W. Illumination is from the bottom.

hypothesis that north polar dunes are composed of particles finer than sand has been tested by a direct method that requires no intricate thermal modeling: the presence of sand-sized material was confirmed by thousands of MGS TES emissivity spectra of north polar dunes, including those associated with arcuate scarps, which exhibit silicate absorption features (with minima 0.92–0.95) in the 8–12 μm region. Bandfield (2002) noted that these spectra indicate a mixture of clasts with a bulk composition similar to andesite. To have distinct spectral features in the 8–12 μm region requires that the dunes, at least on their uppermost surfaces, consist of grains coarser than ten times the wavelength (i.e., 80-120 μm, fine sand). In addition, visible and near-infrared spectra of north polar dunes acquired by the Hubble Space Telescope have been interpreted by Bell et al. (1997) to indicate coarse, granular material. The low thermal inertia first described by Paige et al. (1994) is difficult to explain in the context of strong geomorphic and spectroscopic evidence for sand; perhaps it results from an incomplete assumption used in the thermal modeling process (e.g., regarding the specifics of thermal behavior of north polar dunes in summer), or an incomplete understanding of the relations between thermal inertia and particle size in the Martian polar environment (e.g., a lack of laboratory experiments on thermal conductivity of sand mixed with dust, ice, or water vapor at polar atmospheric pressures and temperatures).

3.2. Upper and Lower Unit Materials

The lower and upper units are very different: the lower erodes in a manner consistent with material that is easily disaggregated, the upper does not. Erosion of the lower unit undermines strata of the upper unit, thus generating and maintaining arcuate scarps. The lower unit is less resistant to erosion than the upper unit; Byrne and Murray (2002, paragraph 14) were incorrect in stating that the lower unit is more resistant. Streamers of dark sand from exposures of the lower unit indicate contribution of sand to nearby dunes. The latter observation argues that sand, perhaps poorly cemented (if at all), is the material that lowers the unit's resistance to erosion. The observations further suggest that wind is the agent of erosion and removal of sand from the lower unit.

The upper unit is not an important source of sand. While there is one location at which lenses of dark material, possibly sand, are exposed among the lower strata of the upper unit (Fig. 3), little other evidence is available to indicate that sand occurs in the upper unit. The talus piles derived from mass wasting of the upper unit in arcuate scarp exposures do not contribute streamers of material to nearby eolian dunes. Spiral troughs, which are only cut into the upper unit, do not have dunes or other evidence of sand in their slope materials.

The composition of the upper unit is unknown, but two lines of evidence permit speculation that it consists of layered ice and dust, as has long been postulated for all of the polar layered materials (Cutts 1973). First, the talus deposits are small relative to the size of upper unit outcrops in arcuate scarp areas. This observation suggests that, over time, talus is removed from the scarp vicinity. However, the talus material exits the area without leaving behind particles coarse enough to be included in dunes. A mixture of dust and ice (whether CO_2 or H_2O) in any proportion would allow the observed absence of abundant talus: ice would sublime, and dust would be blown away in suspension. Second, the lighter tone of the upper unit is circumstantial evidence for ice •and dust because, on Mars, these have a higher albedo than most other surface materials. However, short of *in situ* observations, we cannot be certain that the upper unit contains ice and dust. No spacecraft observations have detected ice *within* layers of the north polar region. Even indirect evidence of ice is missing; we have found no glacial landforms (e.g., terminal or medial moraines, eskers, drumlins) nor evidence of glacial flow (crevasses, deformed layers). Rather, the near horizontality of beds, uniform layer thickness, and lack of evidence for deformation argue that there is no geomorphic evidence for glaciation, notwithstanding that idea's recent popularity (e.g., Zuber et al. 1998; Fishbaugh and Head 2000; Nye 2000).

Despite the lack of evidence for ice in strata of the polar region, evidence is compelling (and has been for several decades) for water ice at the uppermost surface of the summertime residual cap, the brightest material in Fig. 1. As noted previously, Viking orbiter observations indicated that the bright material is, at least in part, water ice (Kieffer et al. 1976; Farmer et al. 1977). Unfortunately, we cannot determine whether the bright material is an expression of the uppermost layers of the upper unit or a thin veneer covering the upper unit. We suspect the latter because the uppermost bright material is brighter than exposures of the polar strata and, in some places, has been observed to disappear in some summers (and not others) within a few days time (Malin and Edgett 2001, p. 23513; Cantor et al. 2002).

Although the amount of water in the layers of the north polar region is unknown and largely unknowable from remote observations, attempts have been made to estimate the volume of the layered materials, and use this volume as an upper limit on the amount of water ice present. These estimates are important because they help constrain the present magnitude of the volatile inventory for Mars. The most accurate volumes have been determined using topographic data from the MGS MOLA; published values are ~ $1.1–1.7 \times 10^6$ km^3 (Zuber et al. 1998; Smith et al. 2001). If only the upper stratigraphic unit (a unit unknown when previous estimates were derived) contains ice, then the volume of the unit provides a maximum constraint on the amount of water present. By fitting a plane to the elevations of the contact between the upper and lower unit, we estimate the volume of the unit (from the plane upward to the present topographic surface) to be $8.0 \pm 2.0 \times 10^5$ km^3, in which the uncertainty conservatively accounts for the total range of observed contact elevations. The maximum volume of water, if any is present in the polar layers, may thus be 30–50% less than previously published estimates.

3.3. Lower Unit Role

Images from orbiting spacecraft show that the north polar layered materials are eroding; little evidence exists that new materials are accumulating. Erosion of the material is dominated by the sandy nature of the lower unit; a unit not known when Howard formulated his eolian erosion hypothesis. With this new observation, the genesis and maintenance of arcuate scarps becomes clear, as does their association with dunes moving away from the scarps. Howard (2000), and others preceding him and referenced therein, proposed that the spiral troughs widen and deepen slowly by eolian erosion and ice sublimation/ablation. MOC images, indeed, show that wind does remove dust from the spiral troughs (Fig. 6). The spiral troughs cut only the upper polar stratigraphic unit. Once a spiral trough has eroded to a depth at which the lower unit is exposed, the morphology of the trough changes; it widens and deepens as the upper unit is undermined. As Howard (2000) proposed, undermining, collapse, and eolian removal of debris (e.g., dunes) forms the arcuate scarps. The hypothesis also extends to Chasma Boreale. Some researchers favored origin of this chasm by catastrophic flood (Clifford 1987, pp. 9145-9146; Benito et al. 1997; Fishbaugh and Head 2002), but we have found no landforms (e.g., streamlined hills, current ripples, butte-and-basin scabland) like those that occur in catastrophic flood channels elsewhere on Mars or Earth (e.g., Bretz et al. 1956; Malin and Edgett 2001, pp. 23520–23523). Abundant evidence is available, however, for wind erosion and dune deposition in Chasma Boreale (Howard 2000).

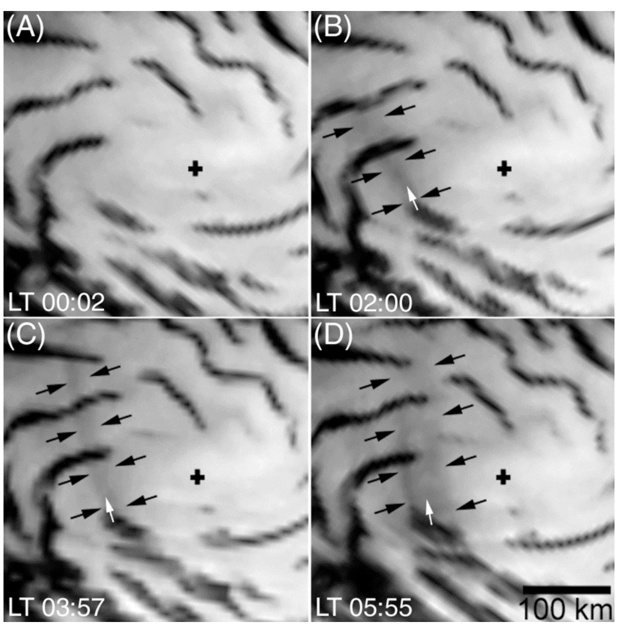

Figure 6. Examples of a plume of dust raised by wind from a small trough in the north polar region on 3 April 2001. The black arrows indicate the location of plume margins; the white arrows originate at the plume source and indicate inferred wind direction. Each image is a polar stereographic projection of a sub-frame of a MOC blue wide-angle image. Crosses indicate the location of the north pole. The MGS spacecraft passes over the pole about once every two hours; the local time (LT) is indicated at the lower left in each view. **(A)** The first picture shows the region before the plume was generated. It is a sub-frame of MOC image E03-00191. **(B)** The second view was acquired nearly 2 hours later and shows a dust plume in MOC image E03-00197. **(C)** Two hours later, the plume had lengthened and rotated poleward in MOC image E03-00205. **(D)** Later, the plume widened and rotated further toward the pole in MOC image E03-00211

The provenance of sand and origin of the lower unit are impossible to determine from remote sensing observations. Byrne and Murray (2002) speculated that the unit consists of an ancient, eolian sand sea. MOC image resolution is sufficient to show evidence of crossbedding in lithified sand seas on Earth, such as the Navajo Sandstone of North America, but we have found no evidence of eolian crossbedding in any of the MOC images of arcuate scarp outcrops of the lower unit. The presence of mesa-forming and shelf-forming layers in the lower unit show that it is not entirely composed of poorly-cemented sand. We do, however, believe there is evidence that the lower unit contains at least some buried dunes; the evidence is the semi-crescentic patches, which resemble dunes in terms of shape and tone, that are being exhumed at a few locations around the margins of the north polar cap (Fig. 4). The geologic history recorded by strata in the north polar region remains elusive; but their subsequent geomorphic evolution is now more clearly understood.

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