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Meter-Scale Morphology of the North Polar Region of Mars

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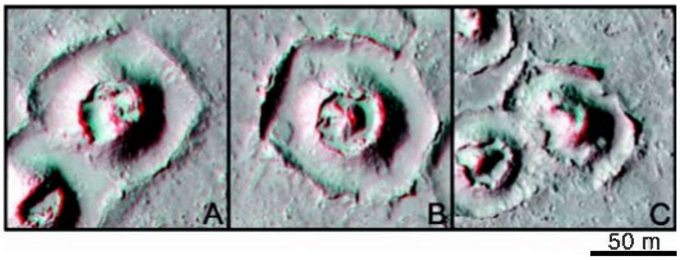

Fig. 3. Anaglyphs from subsections of HiRISE stereo image pairs PSP_001606_1900 and PSP_002226_1900 (**A** and **B**) and PSP_001540_1890 and PSP_002371_1890 (**C**). The thin flowtop cracked, shifted, and foundered under the weight of RMLs, producing a continuum of moat morphologies from (A) ring fractures, to (B) tilted plates that jut over the surrounding flow surface, to (C) foundering plates exposed edge-on.

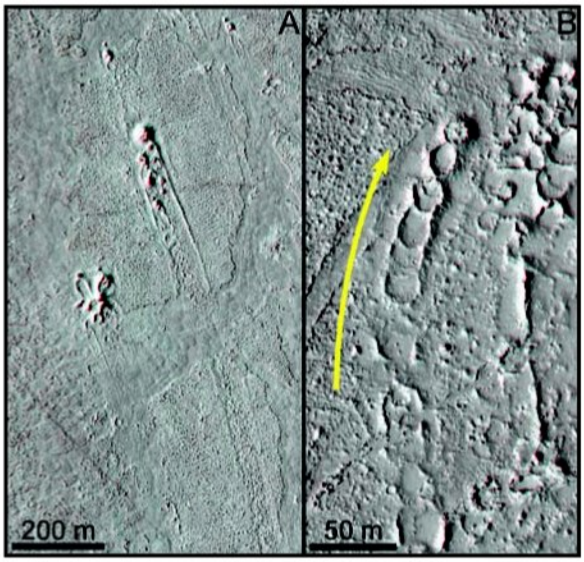

Fig. 4. (**A**) Anaglyph of a subsection of HiRISE stereo image pair PSP_001540_1890 and PSP_002371_1890 showing RMLs with wakes severed along rafted plate boundaries. Compressional ridges cover the plates, and polygonal terrain occupies the interstitial space. (**B**) Anaglyph of a subsection of HiRISE stereo image pair PSP_002938_1890 and PSP_003083_1890 showing a chain of overlapping RMLs. Cross-cutting relationships indicate that the RMLs within the chain become younger in the upstream direction (yellow arrow).

HiRISE data show that Athabasca Valles is draped by lava and riddled with hydrovolcanic cones. The purported frozen sea in Cerberus Palus (*6*) is instead a ponded distal section of this lava flow. HiRISE has imaged similar lava flows within other channels (e.g., Marte Vallis and Kasei Valles), which suggests that Athabasca Valles may be unique only in that it is exceptionally well preserved. Although it remains likely that the outflow channels were carved by aqueous floods (rather than lava), surface exposures of flood sediments may be rare on Mars. This could partially explain why every Mars lander sent to investigate fluvial or lacustrine landforms has found a surface dominated by lava.

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REPORT

Meter-Scale Morphology of the North Polar Region of Mars

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Mars' north pole is covered by a dome of layered ice deposits. Detailed (~30 centimeters per pixel) images of this region were obtained with the High-Resolution Imaging Science Experiment on board the Mars Reconnaissance Orbiter (MRO). Planum Boreum basal unit scarps reveal cross-bedding and show evidence for recent mass wasting, flow, and debris accumulation. The north polar layers themselves are as thin as 10 centimeters but appear to be covered by a dusty veneer in places, which may obscure thinner layers. Repetition of particular layer types implies that quasi-periodic climate changes influenced the stratigraphic sequence in the polar layered deposits, informing models for recent climate variations on Mars.

Planum Boreum (the martian north polar topographic dome) has been stratigraphically divided into the irregularly layered "basal unit" (*1*–*3*), the classical polar layered deposits (PLD) (*4*), and the residual cap, which covers most of the planum and maintains a high albedo throughout the northern summer because of its relatively clean water ice composition (*4*, *5*). All of these deposits overlie older materials with a complex history (*6*). Recent climate

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variations, mainly caused by changing orbital parameters, are widely believed to control the deposition of ice and dust in the PLD, creating a record of global climate history within the layers. Therefore, images that resolve PLD layer thickness and their stratigraphic variations can be used to address key questions regarding their origin and evolution, and in turn these observations can be related to theories for recent climate change on Mars (*7*). The basal unit is thought to be the source of dark sand-sized material in the circumpolar dune fields (*1*–*3*). Dark material in this unit is interbedded with brighter layers that were previously thought to be composed mostly of dust (*3*). High-Resolution Imaging Science Experiment (HiRISE) images of these strata provide new information regarding the relations between them and their geologic history.

HiRISE (*8*) uses time delay integration, which yields signal-to-noise ratios far in excess of previous high-resolution cameras. HiRISE has collected 85 images of the north polar deposits, with more images covering outlying polar material and dune fields. Most of these images were acquired between the beginning of MRO's primary science phase at solar longitude L_s = 133° (*9*) and the onset of polar cloud formation at about L_s = 150°. All the data discussed here were acquired during northern summer.

Previous observations of the patchy distribution of dark layers in the basal unit were interpreted as evidence for large-scale cross-bedding (*3*). HiRISE images show potential cross-bedding at smaller scales (Fig. 1), implying that this material was saltating before deposition and burial by overlying layers. We therefore infer that the dark material in the basal unit is composed of solid sand grains that are currently being eroded and remobilized into dunes.

HiRISE data show that the interbedded bright layers have substantial thickness and material strength and are not just thin accumulations of dust. Polygonal fracturing has broken these layers into meter-scale blocks. On the basis of the morphologic similarity between these polygonally fractured layers and the overlying ice-rich (*10*) PLD layers, we interpret the bright basal unit layers to be volatile-rich. In several locations, perhaps assisted by undercutting caused by removal of the interbedded sand-rich material, these blocks have detached from the bright layers and now lie at the bases of the scarps (Fig. 2). This style of mass wasting was not previously recognized in the polar regions. The debris at scarp bases is less common than expected from the abundance of blocks near layer edges, indicating that when these blocks detach, they are quickly eroded. This relatively rapid ablation of fallen blocks is probably due to disruption of any thin preexisting lag and increase of exposed surface area by the mass-wasting process. The persistence of recesses from which blocks have been dislodged suggests that mass wasting contributes more strongly to scarp retreat than in situ ablation of fractured layers.

Debris fans or aprons, intermediate in brightness between the darker material and brighter layers of the basal unit, are present on some basal unit erosional scarps. Large (100- to 200-m wide) fans accumulate at the break in slope below relatively steep sections of basal unit outcrop, and smaller examples occur up to the contact of the basal unit with the overlying PLD. The overall form and surface morphology of the fans are consistent with construction through a series of individual discrete, dry, granular avalanches and/or debris flows with low liquid water content (Fig. 3). Their brightness, polygonal surface texture, incorporation of bright blocks, and strong

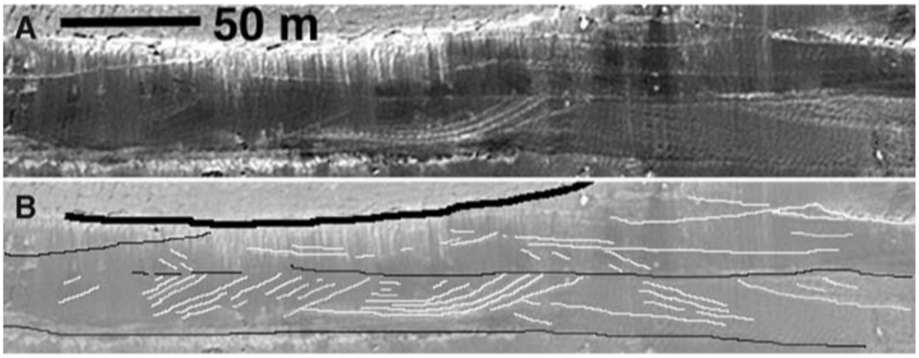

Fig. 1. Section of HiRISE image TRA_000863_2640, at 83.80°N, 235.50°E, illumination from bottom-right, slope dips toward bottom. (**A**) Section of polar scarp containing uppermost section of basal unit (dark material) and contact with PLD (brightest material). Dark basal unit layers contain structures interpreted as cross-bedding. (**B**) Annotation of beds showing truncations.

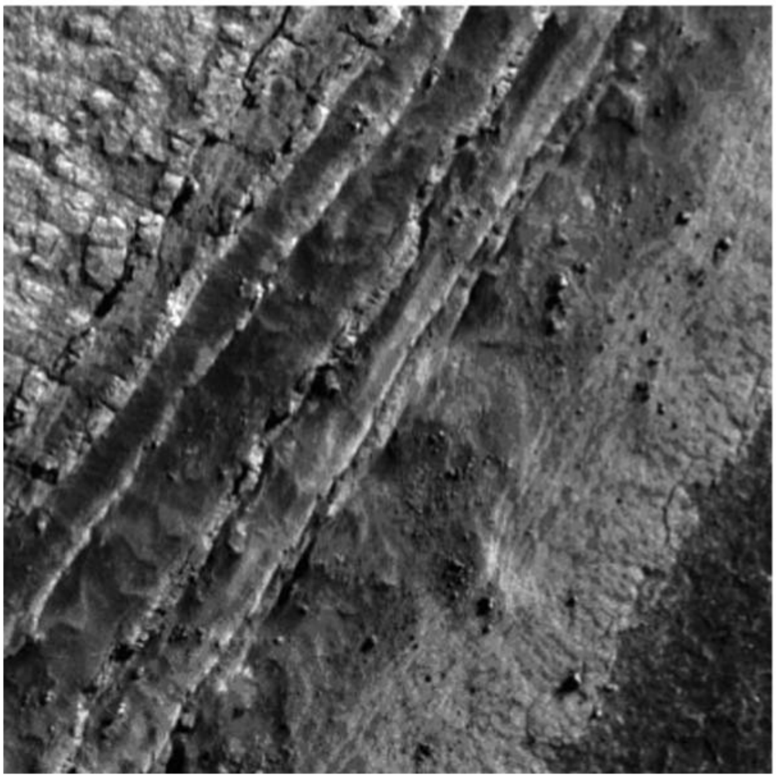

Fig. 2. Debris shed from polygonally fractured layers in basal unit. Section of HiRISE image TRA_000845_2645, at 84.635°N, 3.375°E; scene is 100 m across. Illumination from upper right, slope dips toward lower right.

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water ice absorption bands in Compact Reconnaissance Imaging Spectrometer spectra (*11*) indicate that the fans contain ice. The primary source of fan material appears to be debris wasted from the ice-rich, highly fractured lower PLD.

Some of the most distinct sets of basal unit features indicative of flow are rilles associated with fans, especially at distal margins (Fig. 3). Individual and paired rille flank deposits are probably levees formed in the flow stage, during which deposition is largely occurring at low-energy lateral margins (whereas the high-energy central flow leaves little material behind). A morphological gradation of rilles to positive-relief digitate lobes represents the transition to a lower energy stage, during which relatively steep, lobate flow fronts are preserved as the flow comes to rest [e.g., (*12*)]. We see no evidence requiring the presence of liquid water and therefore favor dry granular flows to explain the observed fans and related rille features, but wet debris flows cannot be ruled out.

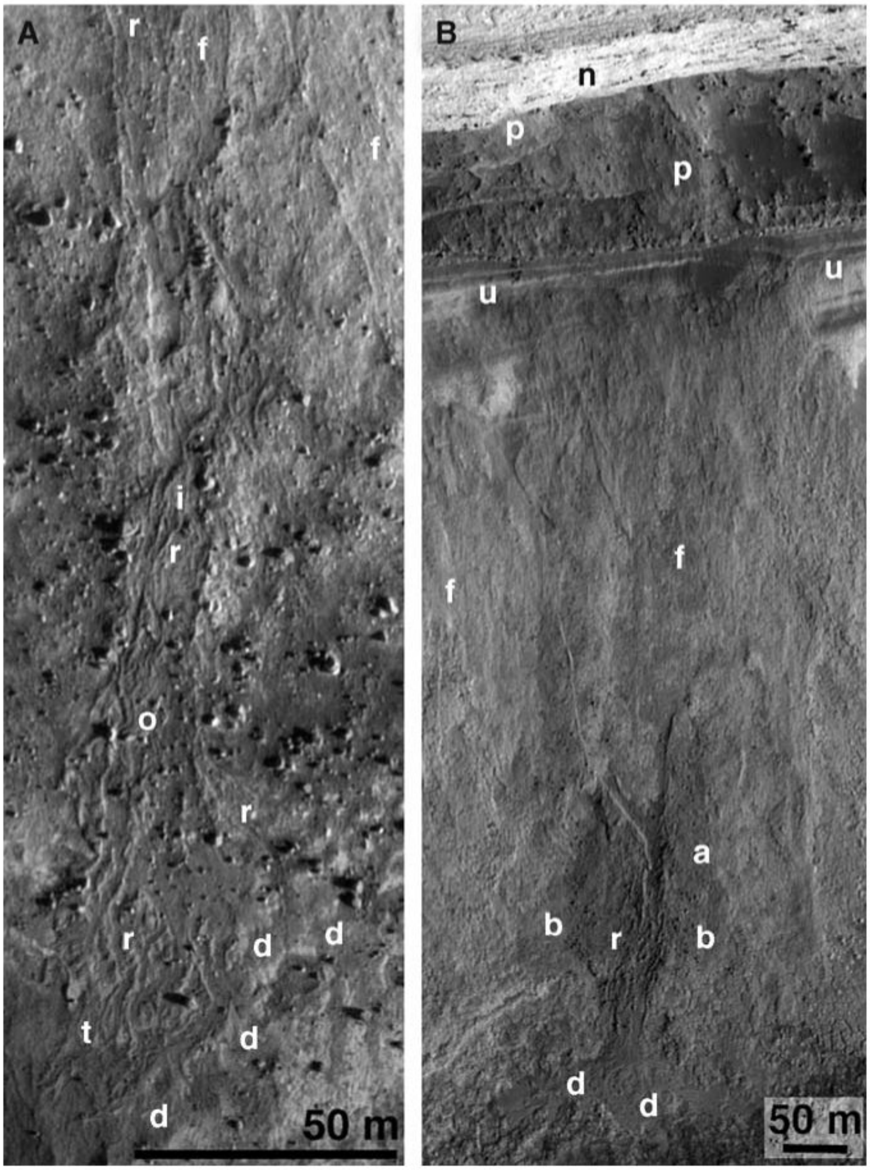

Fig. 3. Portions of image PSP_001412_2650, at 84.75°N, 3.85°E, illumination from right, slope dips toward bottom. (**A**) Rilles defined by segments of parallel ridges with little to no medial incision (r), resulting from flow of dry to low-water-content debris. Fan surface appears striated (f). Course-altering influences on flow may include obstacles (o), topography (t), or irregularities in deposition of flow fronts (i). Rilles may transition into relatively high-standing, branching, narrow, digitate lobes with abrupt fronts at mouths (d). (**B**) Similar features (r), seen in context at foot of fan (f) emplaced on basal unit layers (u) with patchy material (p) reaching up to base of lower PLD (n). Full path from mass-wasting origin to distal accumulations of large blocks (b) and digitate terminal lobes (d). Late-stage rilles may have cut through initial larger avalanche deposit (a).

The minimal apparent modification and lack of superposed aeolian bedforms suggest that these distal rille and digitate deposits represent the most recent and/or largest of the type of mass wasting-initiated flow events that contribute to the growth of the large fans. Current activity, such as fracture-aided mass wasting, raises the potential that changes in fan or scarp appearance, including the appearance of blocks or avalanche deposits, could be observed over the course of the MRO mission.

The high-relief exposures of PLD at the head of Chasma Boreale and along the margin of Olympia Planum exhibit two distinct sections on the basis of presence or absence of polygonal fractures. The lower section appears similar to the polygonally fractured bright layers in the basal unit, whereas the upper section shows no evidence of this polygonal fracturing (Fig. 4A). Dark, sandy material has not been observed in the upper section and rarely occurs in the lower section of the PLD. The lower PLD is typically exposed on steeper slopes, indicating a different resistance to erosion and/or more effective mass wasting there, perhaps enhanced by erosion of the basal unit and consequent undercutting. Although we cannot exclude the possibility that the fractures in the lower PLD are not representative of its bulk properties and were formed during erosion of the scarps, Shallow Radar (SHARAD) results (*13*) indicate that these sections differ in dielectric properties throughout the PLD. We therefore interpret the polygonal fracturing of the lower PLD to be a result of inherent material properties or historical processes that are not common to the upper PLD.

The lower-relief troughs within the northernmost PLD typically only expose layers in the upper section. Here, layers within Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) images range in apparent thickness down to the image scale [~1.5 m/pixel at best (*14*, *15*)]. However, HiRISE observations show that apparent layer thickness ranges down to the pixel scale (30 cm) only where foreshortened on relatively steep slopes. Therefore, on more typical trough slopes, HiRISE has resolved the thinnest layers visible from orbit. For example, image PSP_001738_2670 (*16*) shows layers with ~1-m apparent width on a slope (derived from MGS Mars Orbiter Laser Altimeter gridded topographic data) that implies a true thickness of ~10 cm. Any thinner layers that may exist appear to be obscured in many places by surficial deposits of frost and/or ice (white in Fig. 4, B and C) and dust (red in Fig. 4B and gray in Fig. 4C).

HiRISE images of the PLD indicate that the apparent brightness of the layers is likely controlled by topography, texture, and surficial frost distribution (Fig. 4B) and is therefore not directly related to the internal composition of the layers. This implies that apparent layer bright-

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ness profiles cannot be directly compared with calculations of obliquity- or precession-driven changing insolation in an attempt to date layers (*15, 17, 18*).

Stratigraphic analyses using Viking and MOC images have shown that some layers can be correlated within one trough (*14*, *19*), across several troughs (*20*, *21*), and even across wide areas of the PLD (*15*, *22*). One easily traceable layer is the "marker bed" (*14*), so called because of its distinctive, knobby morphology (*23*). At full HiRISE resolution (Fig. 4C), this layer appears to have undergone localized slumping, perhaps of an overlying dust lag, and has linear grooves (possibly created by eolian erosion) and tiny knobs and pits dotting its surface near the top of the layer. The marker bed protrudes, in most places, from the surrounding layers, indicating that it is relatively resistant to erosion. By using these defining characteristics, we have identified six such layers within one HiRISE image, four of which are also traceable to another HiRISE image in a nearby trough. The presence of these newly discovered "marker

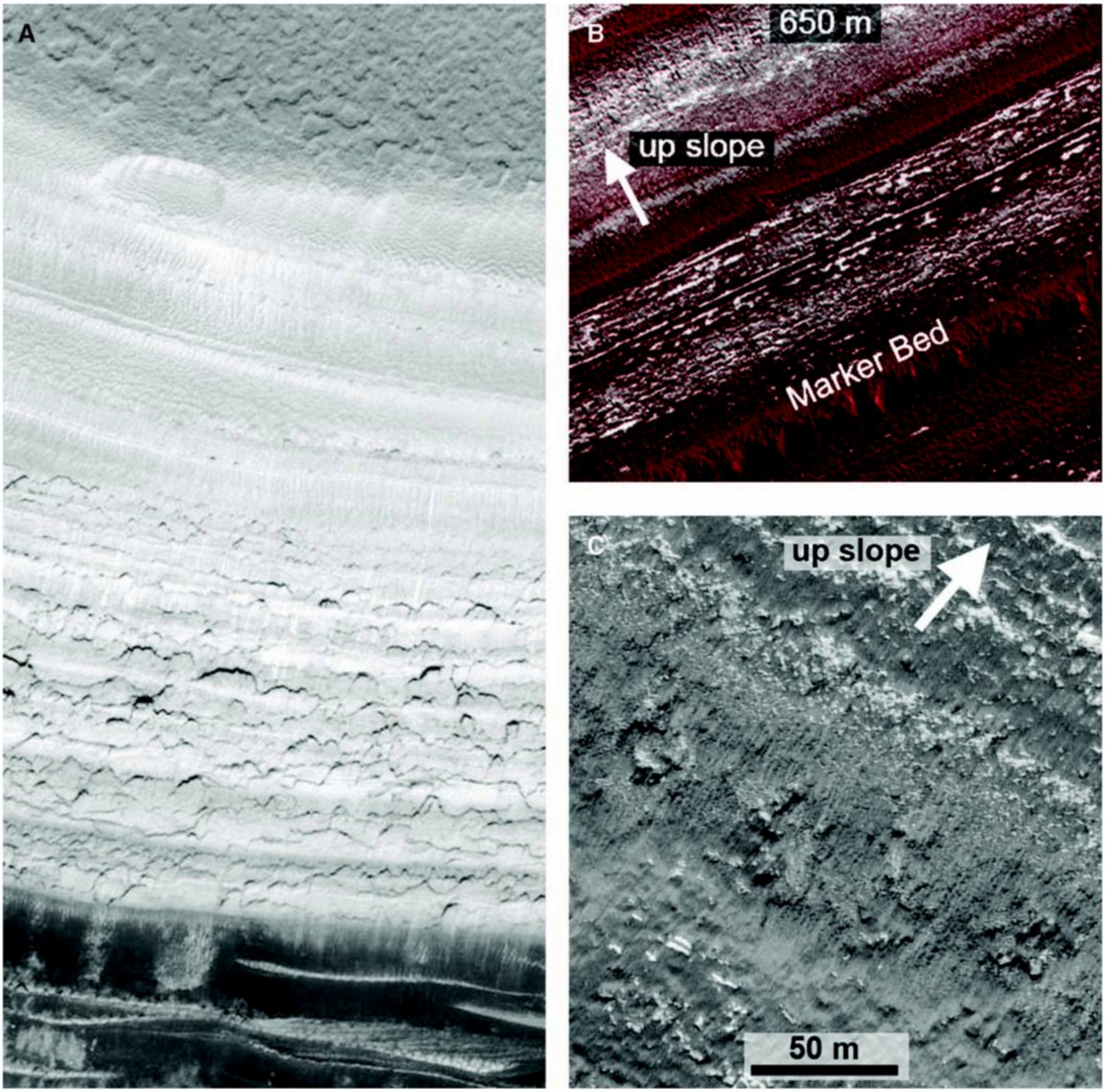

Fig. 4. North polar layered deposits. (**A**) Transition in layering over polar scarp, section of HiRISE image P5P_001550_2640, at 83.83°N, 235.30°E. Slope dips toward bottom, illumination from bottom, scene is 540 m across. (**B**) Portion of false-color HiRISE image (P5P_001738_2670, centered at 87.1°N, 92.6°E) of layers in upper portion of PLD. Illumination from upper right. (**C**) Portion of HiRISE image P5P_001488_2665 (centered at 86.51°N, 80.0°E), showing original "marker bed" (diagonally across center). Illumination from lower right.

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beds" is suggestive of a repeating climate signal within the upper PLD.

These observations are consistent with the following general history of the north polar region. (i) Dark sand saltates into the north polar region during periods (possibly high obliquity) when thick accumulations of ice do not form at the north pole. (ii) Alternating with sand migration, ice accumulates and inhibits saltation of underlying dark sand (possibly during lower obliquity). (iii) Several such depositional cycles produce alternating brighter (ice and dust) and darker (sandy) layers in the basal unit. (iv) Icy layers, similar in morphology to those in the basal unit, are deposited with little or no dark sand to form the lower (polygonally cracked) PLD. This transition from the previous depositional cycles may indicate that the sand supply was exhausted or no longer transportable onto these growing deposits. (v) The upper PLD accumulates, and varying conditions during its accumulation lead to the development of the layered sequences that have been correlated in multiple exposures (*6*, *22*). (vi) Most recently, the thin north polar residual cap forms on top of the PLD and evolves to its present state by condensation and sublimation of water ice. Mass wasting of the PLD at steep scarps produces icy debris fans.

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REPORT

Accumulation and Erosion of Mars' South Polar Layered Deposits

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Mars' polar regions are covered with ice-rich layered deposits that potentially contain a record of climate variations. The sounding radar SHARAD on the Mars Reconnaissance Orbiter mapped detailed subsurface stratigraphy in the Promethei Lingula region of the south polar plateau, Planum Australe. Radar reflections interpreted as layers are correlated across adjacent orbits and are continuous for up to 150 kilometers along spacecraft orbital tracks. The reflectors are often separated into discrete reflector sequences, and strong echoes are seen as deep as 1 kilometer. In some cases, the sequences are dipping with respect to each other, suggesting an interdepositional period of erosion. In Australe Sulci, layers are exhumed, indicating recent erosion.

A marked similarity between Mars and Earth is the presence of thick polar ice caps, which potentially provide a wealth of data about recent climate and atmospheric history (*1*, *2*). The martian polar plateaus are as much as 3.5 km thick (*3*) and composed of layers overlain by a residual (i.e., perennial) ice cap that, according to recent analyses, is no more than a few tens of meters thick (*4*–*6*). The polar residual ice in the south is predominantly CO_2 ice containing trace amounts of dust and water ice (*5*). Compared to the north, the residual ice covers only a small portion of the south polar layered deposits (SPLD), which are offset from the pole by ~2° and are asymmetrically distributed between latitudes 70°S and 80°S (*3*). Most plateau surfaces are buried under an optically thick layer of sand or of seasonal frost accumulations (*7*). The layers are composed of water ice mixed with dust, with layer thicknesses and ice/dust ratios possibly controlled by orbital cycles (*8*). They apparently formed by deposition of ice condensates or precipitates and atmospheric dust (*9*, *10*). The polar plateaus are considered to be very young. On the basis of crater counts, the surface age of Planum Australe is estimated to be on the order of tens of millions of years (*11*, *12*).

Planum Australe was probed previously with the Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) onboard the European Space Agency's Mars Express (*6*, *13*). The MARSIS radar signals penetrated to depths estimated to be greater than 3.7 km (*6*). Subsurface echoes are frequently very strong, indicating minimal attenuation of the signal through

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