NORTH POLAR BASAL STRATIGRAPHY AND ACTIVE MASS-WASTING PROCESSES FROM HiRISE WITH IMPLICATIONS FOR POLAR SCARP EVOLUTION.  P. S. Russell\textsuperscript{1}, S. Byrne\textsuperscript{2}, K. Herkenhoff\textsuperscript{2}, K. Fishbaugh\textsuperscript{4}, C. Hansen\textsuperscript{3}, N. Thomas\textsuperscript{1}, A. McEwen\textsuperscript{1}, and The HiRISE Team. \textsuperscript{1}Physikalisches Institut, U. Bern, Bern, Switzerland, \textsuperscript{2}Lunar and Planetary Lab, U. Arizona, Tucson, USA, \textsuperscript{3}Astrogeology Team, USGS, Flagstaff, USA, \textsuperscript{4}International Space Science Institute, Bern, Switzerland, \textsuperscript{5}Jet Propulsion Lab, Pasadena, USA. patrick.russell@space.unibe.ch

Introduction: A distinct, darker basal unit (BU) underlying the north polar layered deposits (PLD) has been described from 1.4-6 m/pxl-resolution MOC images [1-3]. The BU is significant as a potential geologic and climatic record of polar region and global history during the long period of time between the deposition of underlying northern plains materials and overlying PLD [3]. HiRISE targeted the BU with the goal of describing formation processes and environments, and of building a picture of the current polar region at sub-meter scale. High resolution images (0.3-1.2 m/pxl), stereo anaglyphs, and 3-band color data from the High Resolution Imaging Science Experiment (HiRISE) [4] on Mars Reconnaissance Orbiter (MRO) provide an unprecedented, dynamic, new perspective of the BU and of processes active in shaping steep polar scarps. Along with details that support or clarify previous observations and interpretations, many new stratigraphic, sedimentary, and erosional features within the BU are apparent in HiRISE data. Among the most intriguing are cross-bedding within dark BU material; fracture- and undercutting-assisted block-fall that may be the predominant means of bright BU material and PLD material erosion and steep scarp maintenance; mass-wasting and flow processes leading to the accumulation of large debris fans on the BU outcrop; and rilles that call into possibility the presence of liquid water in some mass-wasting events. The processes of erosion and secondary deposition described here are largely new, likely currently active, and may play a greater role in polar scarp modification than more traditional sublimation processes.

Previous Observations: In MOC images, the BU appears composed of thicker dark layers and thinner, interbedded bright layers [3]. Layering within the BU has been described from MOC observations as irregular, discontinuous or patchily distributed [3], platy and less uniform than in the PLD [1], and near flat-lying, although generally confusing outcrop expression makes this uncertain [1,3]. Steep slopes suggest a certain degree of cohesion and resistance of the BU as a whole [1,2], although a stair-stepped pattern reflecting differential erosion of layers suggests variability in composition [1-3]. Distinction of bright material and dark material [2,3] is loosely correlated with more resistant, shelf-forming layers and less resistant, easily eroded layers, respectively [2]. Dark layers are often featureless, with little evidence for mass-wasting, although the form of some dark material deposits indicates reworking by the wind [3]. The distributional correlation of lower polar outcrops with large dark dunes nearby [1-3,5], including the traceability of dark material from dark BU layers to dunes [2,3], indicates dark material has a sandy grain size. The bright BU material is often similar to the PLD in tone [2]. Bright, resistant material composition is uncertain, with possibilities ranging from high ice-content versions of the dark layers [1] to coverings of atmospherically deposited dust or dirty frost [3].

It has long been believed that sublimation has been the dominant process responsible for the erosion and shaping of polar ice-rich material, mainly the PLD, aided perhaps by katabatic winds from above [6], and melting events from below [7]. However, [2] hypothesize that the poorly cemented dark BU material is easily removed by the wind, causing undercutting of the overlying PLD, facilitating mass-wasting of the overlying PLD and hence the creation and maintenance of the observed steep scarps. The combined potential of eolian and mass-wasting as outlined by [2] would have significant implications for current polar studies assuming a largely sublimation-driven erosional processes, including insolation feedback in the formation of steep scarps [8], the formation of Chasma Boreale [7], and dynamic modeling of PLD terrain evolution[e.g., 9]. Description of mass-wasting of polar deposits from MOC data is limited to bright streaks observed below the PLD/BU boundary [2,3] and purported talus deposits of PLD material collected on the BU [2].

Here we expand on many of the key observations and interpretations covered by [10] and presented preliminarily by [11,12]. Complementary treatment of the PLD, residual cap, and polar region geologic history is presented by [13].

Basal Unit Stratigraphy: In HiRISE data, the basal unit is clearly subdivided into two types of materials: a bright material forming cliffs and plateaus within the outcrop section, and an intervening, dark material exhibiting lower slopes in outcrop profile (Fig. 1).

Bright layers: Bright layer characteristics are consistent along layers within an image, but vary from one layer to another. Outcrop expression varies from thin plates emerging from a dark background, to dominating local cliffs separated by strips of dark material (Fig. 1), both of which indicate relatively resistant, competent material. Striations or laminations are visible within some bright layers. Variation in tone of bright layers overlaps the range in tone exhibited by overlying PLD layers.

Most bright layers are cut by polygonal fractures or joints, delineating triangular, rhombahedral, or hexagonal shaped blocks, typically ~4-10 m across (Fig. 1). This type of fracturing is also typical of the overlying lower PLD [13]. Shadowing indicates that fractures between blocks become wider and deeper towards the layer edge, and some blocks here have rotated slightly away from the scarp face (Fig. 2). Isolated clusters of loose blocks and fragments on shallower slopes below indicate that pieces of the layer edge eventually break off and fall away (Fig. 2). A polygonally shaped recession in the edge of the fractured bright layer often indicates where a block has fallen away. Removal of detached blocks and implications for scarp erosional processes are discussed below.
This process of fracture-aided mass-wasting of blocks is here termed block-wasting, for brevity.

Similarities to the lower PLD in brightness, fracturing, competence, and general morphology suggest the BU bright layers may likewise be ice rich. However, CRISM does not observe any water absorptions from BU layers [14]. Thus, it may be that the BU bright layers are ice-rich but have developed a lag deposit on their outer surfaces.

**Dark material:** There are two general outcrop expressions of dark material in the BU. The first appears to be in situ exposures of dark layers on slopes (Fig. 3). Dark material within in situ layers is likely cemented, as some slopes and structures are supported, but cementation is probably weak as will be discussed below. These exposures are often located in, but not restricted to, the upper part of the BU. The second outcrop expression appears to have been eroded out of dark layers and redeposited on the BU in the form of uniformly and gently sloping aprons (Fig. 1). The apron material occurs between outcrops of successive bright layers, based on the plateau surface of the lower bright layer and banked up against the cliff face of the upper bright layer. Thus, the outcrop profile as a whole is that of a smoothed stair-step, with the dark material creating ramps or aprons between the steps of the bright layers.

Several exposures of in situ dark layers exhibit small-scale cross-bedding (Fig. 3), providing the strongest evidence yet that the material was saltating during deposition, that particles are sand-sized, and that dark layers represent a paleo-erg. We find that solid sand grains are more likely to account for dark material particles than dust agglomerates [15,16], which are not likely to survive burial, exhumation, and incorporation into dunes associated with basal unit outcrops [1,2,3,5]. Many exposures also contain tentative examples of cross-bedding, identification of which is made problematic by the complex interaction of layering with topography within the BU.

The aprons of dark material are often rippled with dune ridges (~3 m crest to crest) aligned parallel to slope, evidence that the material eroded out of the dark layers is transportable by the wind (Fig. 1). The dark aprons occasionally display slope-parallel, shallow troughs or chutes (~1-5 m wide), indicative of down-slope movement of material over their surfaces. Formation into rippled dunes, gentle surface features, uniform and relatively shallow (non cliff-forming) slopes, and a lack of large dark blocks, all suggest that dark material is mobile on the BU outcrop, is relatively fine grained (e.g., sand-sized), and does not form competent deposits.

**Inter-layering of bright and dark material in the BU:** In many cases it is not clear whether the locations of dark apron material on the outcrop result from direct erosion of in situ dark layers (by mass-wasting initiated by the wind, saltating grains, or deposition), or if the stair-steps of eroded bright layers simply provide a sheltered place amenable to secondary deposition of dark material. Aeolian ripples and mass-wasting troughs or chutes indicate transport but do not specify source. Laterally discontinuous aprons could reflect either discontinuous or overhanging in situ dark layers, or uneven secondary deposition. The ramp or apron form itself is consistent both with sandy talus from an above source, and with erosion of an in situ dark layer at a level even with or above the apron apex. The differential erosion of the bright layers resulting in the stair step suggests there may be an intervening layer of less resistant dark material, although the erosion profile could be due solely to variation in bright layer composition or structure.

Analysis of anaglyphs from stereo images along with high resolution imagery helps clarify some of the confused stratigraphy and irregular layering of the BU. In dramatic illustration of relative material strengths, bright layers are often seen to overhang dark material aprons and in situ outcrops. The smoothed stair-step expression of bright layers and dark aprons is also emphasized. Dark aprons stretching from the cliff of a higher bright layer to the lip of a lower bright layer may have shallow slopes, such that their area (as seen from the spacecraft vantage point, above) appears large, while the stratigraphic thickness of the corresponding in situ dark layer (if it exists beneath the apron) may in actuality be minimal. Likewise, the thickness of bright layers has probably been underestimated due to their steep to near-vertical outcrop expression, as well as to the presence of aprons banked up against bright layer cliff exposures. Thus, the predominance of dark material in the BU may not be as great as previously believed. In fact, the stratigraphic column of the basal unit may actually be dominated by bright layers. These assertions are consistent with the observation that some dark material exposures may be secondary deposition and not represent in situ strata. Additionally, HiRISE reveals that the apparent discontinuousness, pinching-out, convergence/divergence, flatness, non-flatness, and non-uniformity of BU layers may in many cases (but not all) be explained by a combination of overhanging bright layers, variable amounts of scarp-wards erosion of bright layers both along strike and relative to each other (resulting in outcrop alcoves, promontories, and transitions), and partial covering by blown or mass-wasted dark material.

The abundance of dark apron material over the outcrop, its mobility, and the overhanging profile of bright layers, suggest the in situ dark material is relatively easily eroded and removed. This characteristic of dark material leads to the potential for undercutting and destabilization of overlying bright layers, as evidenced in the overhangs. Relatively rapid removal of dark material likely quickens or even enables the process of block-wasting from the edge of overlying bright layers. Occasionally a recess left by detached blocks reveals the surface of the partially undercutting dark layer below.

While many apparently irregular layer configurations may be explained as above, stereo anaglyph analysis also reveals that some layers (of bright material) within the BU are not horizontal. Slightly dipping but planar bright layers capped mounds of dark material (some with bright laminations, see below) exist. Some surface exposures of bright layers appear gently undulating.

Some BU layers appear to display surface characteristics of dark in situ or apron material, but contain alternating bright and dark sub-parallel laminations. The bright laminations appear brighter in tone than most bright layers yet have
the soft appearance of dark material. The variability in these laminations and their relationship to the bright and dark layers discussed above is not yet clear. In some cases they may record smaller-scale cycles of the type responsible for the bright and dark BU layers. In other cases they may be surface phenomena resulting from aeolian redistribution of eroded bright and dark material.

**Basal unit formation:** Observations require formation processes that can lead to non-horizontal layering and non-parallel bedding; alternating regimes of sand abundance, mobility, and deposition, with temporary quiescence in which sand activity is dominated by ice deposition; some erosion to plane-off sloping sand layers; but gentle enough transitions such that later, ice-rich deposits may be draped over sandy lenses [10,13].

**Erosional Processes on North Polar Scarps:**

**Block-wasting and scarp erosion:** The overall lack of blocky debris accumulation over the face of the BU suggests that the block-wasting process either occurs infrequently (most or all erosion of bright layers occurring directly, *in situ*, from the edge of the layer), or that detached blocks are removed at the same rate or faster relative to *in situ* erosion of bright layers. Four lines of reasoning favor the latter over the former. First, the abundance of blocks at layer edges generally suggests the potential for frequent block-fall events is high, raising the likelihood of accumulation if blocks are not quickly removed. Second, *in situ* erosion of bright layers and of detached blocks is presumably by sublimation, aeolian erosion, and/or disintegration. In the case that the bright layers are ice rich, as we suggest, *in situ* sublimation of bright layers could be relatively slow due to the presence of a lag. Disruption of the lag by mass-wasting may expose the icy interior of fallen blocks to isolation and allow more rapid sublimation. The increase in exposed surface area of detached and broken blocks will enhance sublimation whether a lag is present or not. In the case that bright layers are not ice rich, increased exposure should likewise hasten degradation and removal of fallen blocks. Third, the prevalence of undercutting of bright layers due to removal of underlying dark layer material, and the pervasiveness of significant fractures in the overhanging bright layer almost requires eventual mass-wasting of blocks (the blocks would not erode *in situ* before falling because removal of the underlying dark material is known to proceed faster than *in situ* bright layer erosion by the mere presence of the overhang). Fourth, the persistence of a recess in cases in which blocky debris has disappeared indicates not only that erosion of the detached block occurred quickly relative to blocks remaining on the layer edge (i.e those still defining the recess), but also that scarp retreat by mass-wasting has been more effective than *in situ* erosion at that locality. Thus it is probable that the process of mass-wasting (with subsequent erosion of debris) accelerates erosion and removal of BU bright material over *in situ* sublimation alone, and possible that, if the occurrence of block-fall is frequent enough along the scarp, we suggest could be accommodated by observations, the process of mass-wasting (with subsequent erosion of debris) could be contributing more to retreat of the BU scarp as a whole than *in situ* erosion is contributing.

**Debris fans and rilles:** Emplaced along the face of some basal unit outcrops are deposits of intermediate-toned material on the scale of ~100-200 m across that clearly cross-cut BU layers (Fig. 4). Widening downslope and gently arched in the along-outcrop direction, they have a fan-like appearance. Upslope, the fans may originate diffusely or abruptly, often banked up against a relatively steep section of the basal unit outcrop. Smaller fans and patches of fan-like material extend, often discontinuously, up to the contact of the basal unit with the overlying PLD. Downslope, the fans extend to a significant break in slope in the lower basal unit section. Fans may occur individually or coalesce laterally.

Fan surfaces appear moderately rough due to the superposition of several types of features, all roughly oriented subparallel to the fan outline, including single and paired ridge segments; raised tongue-shaped lobes tapering downslope; paired ridges converging downslope in the form of a blunt V; occasional high-standing knobs tapered on the upslope ends; and digitate, positive-relief lobes with abrupt margins. Blocks from several meters to the limit of HiRISE resolution are present in scattered clusters. In some areas, the above features are muted, blocks relatively scarce, and the surface fractured into roughly hexagonal polygons.

There are many instances of the fan-shaped outlines being cut by scarps, indicating that material has been removed. The occasional presence of darker, smoother, more gently sloping material beneath the carapace of fan material exposed along these scarps indicates that fan material may have been emplaced on dark material aprons here, consistent with an underlying BU outcrop typical of that described in previous sections.

Based on overall form and surface morphology of the fans, we conclude they are consistent with construction through a series of individual, discrete dry granular avalanches and/or debris flows with low water content. Distribution of fan material over the BU outcrop suggests the primary source of flow material to be debris wasted from the ice-rich, heavily fractured PLD. As demonstrated above, mass-wasting of bright BU layers is likely accelerated by the prevalence of polygonal fractures and the underlying presence of weakly consolidated, easily removable dark layer material. It is reasonable that the lower PLD may respond similarly and that the amount of resulting debris accumulation below the much thicker PLD would be proportionally larger. Initial stages of mass-wasting may involve falling, sliding, or rolling of debris, breaking-up of larger blocks, incorporation of additional material dislodged along the way (including entrainment of basal unit material), and formation into a body of material moving as a flow.

Some of the most distinct sets of features indicative of flow on the basal unit are rilles occurring in association with fan margins (Fig. 5). Individual and paired rille flank deposits are probably levees formed in a stage of flow during which deposition largely occurs at low-energy lateral margins (while 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., 17].

While both dry and wet flow of debris may be responsible for observed flow features, we see no evidence requiring the presence of liquid water. Given the difficulty of generating liquid water at high latitude in the present epoch on what is likely ice-rich substrate, we favor dry granular flows over wet debris flows to explain the observed fans and related rille features.

Polygons, the presence of large visible blocks, the inferred sources of material, and an intermediate tone, suggest that fan material is likely ice-rich. CRISM spectra of these fans show a strong 1.5 μm water absorption [14]. Furthermore, the persistence of surface relief features, the support of steep erosional scarps, and the presence of polygons, suggest that the fan material is currently fairly coherent. These observations confirm ice as a major component in the flows and suggest that the competence and preservation of the fan deposits is due to reconsolidation of debris facilitated by this icy component. The means by which ice promotes reconsolidation likely include settling and compaction, recrystallization, and possibly slight melting in response to pressure, warm (>273 K) entrained dark material, or friction within the flow. After emplacement, polygon development and smoothing of surface features (the latter possibly due to sublimation) seem to reflect aging of the surface.

The minimal apparent modification of the distal rille and digitate deposits and the lack of superposed aeolian bedforms suggests that they are among the youngest features observed on north polar scarps. As such, they probably represent the most recent of the type of mass wasting-initiated flow events that have contributed to the growth of the large fans.

**Recent activity:** From what we have seen of the current state of the BU with HiRISE, there is no reason not to believe that activity such as fracture- and undercutting- aided mass-wasting is presently occurring, contributing to the ongoing growth of the fans and constantly altering the face of the basal unit outcrop. This 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.

**Conclusions:** HiRISE has the ability to clarify many of the previously confusing stratigraphic relationships key to understanding the nature and formation of the BU (see [13] for synthesis of geologic history). In addition, it has revealed the polar scarps containing BU outcrops to likely be currently dynamic places where discrete mass-wasting events may play a greater role in scarp retreat and maintenance of steep scarps than direct sublimation. Properties of BU materials constitute both of the major, or perhaps necessary, contributors to this relatively rapid and efficient form of erosion. Undercutting by easily eroded and removed dark sandy material is the result of a primary characteristic of dark layers deposited as a dune field. Block fall is facilitated by heavy fracturing of BU bright layers, a secondary characteristic likely related to composition and post-depositional environments experienced. Thus, current polar scarp processes, and hence the appearance of the scarp itself, are related to the formation processes and environments of the BU. [2] provides a good explanation, supported and expanded upon here, of how the style of erosion and resulting morphology in the north polar deposits may change as removal of overlying PLD exposes the BU.


![Fig. 1: Thick bright layers and dark apron material in the BU, with surface features. PSP 001334 2645. ~250 m across.](image1)

![Fig. 2: Mass-wasting of heavily fractured bright BU layers. TRA_000845_2645. ~140 m across.](image2)

![Fig. 3: Cross-bedding in dark sandy layers. Also, light streaks emanating from overlying PLD. TRA 000863 2640. ~320 m across.](image3)

![Fig. 4: Exposure of several debris fans on BU outcrop. PSP 001412 2650. ~680 m across.](image4)

![Fig. 5: Rilles at the base of a fan. PSP_001412_2650. ~230 m across.](image5)