ACTIVE MASS-WASTING PROCESSES ON MARS' NORTH POLAR SCARPS DISCOVERED BY HIRISE.
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Introduction: A distinct, dark basal unit (BU) underlying the north polar layered deposits (PLD) has been described from 1.4-6 m/pxl-resolution MOC images [1-3]. 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 potentially active in shaping steep polar scarps. Among the most intriguing are 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 indicating a high degree of fluidization in some events [5-7]. Here we further investigate the processes of erosion and secondary deposition via block-fall on north polar scarps, and directly demonstrate that is is currently active at HiRISE-observable scales.

Stratigraphy and block-wasting: In HiRISE data, the basal unit is clearly subdivided into two main types of materials: a bright material expressed in outcrops as thin resistant layers, steep cliffs, and plateaus within the section, and intervening, dark material exhibiting lower slopes. 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. 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. Isolated clusters of loose blocks and fragments on shallower slopes below indicate that pieces of the layer edge eventually break off and fall away. This process is termed block-wasting here for brevity. A polygonally shaped recess in the edge of the fractured bright layer often indicates where a block has fallen away (Fig. 1).

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. The second is of material that appears to have been eroded out of dark layers and redeposited on the BU in the form of uniformly and gently sloping aprons. 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 is less competent and/or less cemented than the bright material. In addition to these characteristics, the occurrence of bright layers overhanging underlying dark deposits suggests 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. Relatively rapid removal of dark material likely quickens or even enables the process of block-wasting from the edge of overlying bright layers.

Active block-wasting: The prevalence of blocks on slopes directly below fractured bright layers in HiRISE images of the BU located around the north polar deposits suggest that this process is wide-spread and not unique to a certain outcrop. The stratigraphic position of these blocks on the outcrop, sitting on top of BU layers and rippled dark- material aprons, suggests the block-wasting process has been ongoing relatively recently. As there is no reason to think it is not currently ongoing [6,7], we had planned to examine HiRISE images of the same locations during successive observation seasons for the appearance of new instances of block-wasting. However, in comparing two images from the *same* season taken very early in the mission (TRA_000845_2645 on Oct. 1, 2006, and PSP_001412_2650 on Nov. 14, 2006) we found that a block-wasting event had actually occurred within the span of only 44 days (Fig. 2).

Before the slide, the slope was generally dark, although densely covered with slightly lighter streaks. These streaks are likely fine-grained debris shed from the overlying bright layers. The slide is visible as a broader swath of mid-toned, fine (unresolveable) material stretching from the base of the uppermost competent bright layer to the foot of the slope. The deposit is characterized as thin because the dark slope and intermittent bright layer outcrops are still visible "through" the slide material. At the foot of the slope in the second image are two large blocks with prominent shadows, and another lies just beyond the foot of the slope. Variation in brightness at the single pixel level may indicate the presence of additional, smaller blocks on the lower reaches of the slope. The concentration of the largest blocks at the foot of a slope, or just beyond, is a typical characteristic of terrestrial rockslides as they require the most energy dissipation to be brought to a stop.

Unfortunately, neither image of the pair in Fig. 2 is full resolution, decreasing the precision of any spatial measurements. The three large blocks with prominent shadows are roughly 2.5-3.5 m on a side, although their shape is undetermined, and 1.0-2.5 m high based on their shadow lengths. Assuming blocks can't get any larger while sliding, the minimum observed block dimension (~1.0 m) suggests the originating layer must be at least 1 m thick. A very rough estimate of the cumulative surface area of the blocks is: $(2.5\ m)^2$ to $(3.5\ m)^2 \times 3 = 19$ to 37 m^2. The amount of slide material deposited on the slope in addition to the three blocks is unknown. The surface area of the block that disappeared from the bright originating layer is roughly 21 m^2, which is within the range of the estimated area covered by the three large blocks, providing a consistent argument that not only is the slide material distinguishable, but also the source material. Using the latter estimate of surface area, the total volume of slide material is roughly 21 to 53 m^3. It is difficult to construct an estimate of the rate of weathering of this scarp from these observations because there is only one occurrence. However, re-imaging of the area during the currently dawning northern spring may help to constrain the degradation and erosion of the debris.

The respective solar longitudes (Ls) of the images in Fig. 2 are 114.3° and 135.3°, in the northern mid-summer, when activity in the polar regions may be expected to be high. More sun leads to more, and differential, heating which causes 1) increased sublimation, 2) thermal expansion, which may minorly disrupt competent bright layer fragments at scarp edges, and 3) increased winds which remove and redistribute the dark sandy material, which may in turn contribute to detachment and eventual fall of blocks by undercutting the edge of the competent bright layers.

Block-wasting implications for scarp erosion: The overall lack of blocky debris accumulation over the face of the BU suggests that the block-wasting process either occurs infrequently, or that detached blocks are removed at the same or higher rates than erosion of bright material from in situ layer edges. Five lines of reasoning favor the latter over the former. First, the above observation of newly fallen blocks within ~7 weeks suggests that the block-wasting process is not uncommon. Second, 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. Third, the increase in exposed surface area of detached and broken blocks will enhance sublimation (if the material is dominantly ice) and/or eolian abrasion and degradation (if the material is dominantly particulate) of the blocks over that of the in situ layer edge. Fourth, 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 detachment of blocks - the observation of overhanging bright layers indicates that removal of the underlying dark material proceeds faster than erosion of in situ bright layers. Fifth, a recess in the scarp edge sometimes persists in cases in which blocky debris is no longer present below. The last point also suggests that scarp retreat by mass-wasting has been more effective than in situ erosion at that locality since the block fall occurred. Thus it is 1) probable that the process of mass-wasting (with subsequent erosion of debris) accelerates erosion and removal of BU bright material over *in situ* erosion alone, and 2) possible that, if the occurrence of block-fall is frequent enough along the scarp as 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.

Undercutting by easily erodable and removable dark sandy material is the result of a primary characteristic of dark layers deposited as a dune field [5,6]. Block-wasting is facilitated by heavy fracturing of BU bright layers, a secondary characteristic likely related to composition and post-depositional environments. Thus, current polar scarp processes, and hence the appearance of the scarp itself, are related to the formation processes and environments of the BU. On a regional scale, these material and structural properties of the BU influence erosional style of the north polar BU and layered deposits and likely help account for the variation in morphology between smooth troughs and steep scarps in the north polar deposits [3].

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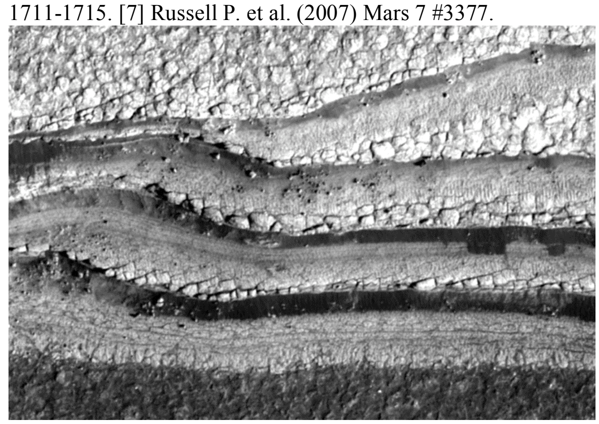

Fig. 1. Portion of TRA_000845_2645 illustrating alternating bright and dark materials in BU, bright layer fracturing, and features of the block-wasting process: wider edge fractures, edge recesses, and blocks on slope below. Up-slope is to top; sun from lower right; frame is ~350 m across.

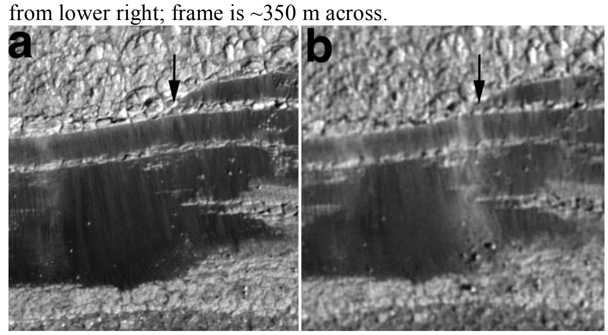

Fig. 2. Portions of a) TRA_000845_2645 and b) PSP_001412_2650, showing the same location on Mars before and after, respectively, a block fall occurred. Images separated by only ~44 days. Source region indicated by black arrow. Small differences in viewing and illumination geometry are insufficient to account for the appearance of the bright swath of the slide and the 3 large blocks in the second image: a) i=62.3°, e=0.096°, sun dir.=111°, local time=13.6; b) i=67.4°, e=8.9°, sun dir.=99.6°, local time=12.9. Up-slope is to top; sun from lower right; frames are ~230 m across.