ACTIVE EROSION AND EVOLUTION OF MARS NORTH POLAR SCARPS.

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Introduction: HiRISE has discovered two forms of mass-wasting in the north-polar region. One is scarpward-retreat of bright layers of the north polar basal unit (immediately underlying the north polar layered deposits, NPLD) by fracture-controlled and undercutting-assisted piecewise failure of layer edges, resulting in rockfalls and rockslides [1-3]. The overlying NPLD at these scarps is also typically fractured and apparently fails in the same manner. This is important as it suggests an alternative, significant mode of erosion in addition to sublimation which is traditionally held accountable for erosion of polar surfaces. The other form of mass-wasting, completely unexpected and caught in-action during imaging, comprises falls and avalanches of frost and dust over steep NPLD scarps during early spring [4]. Here we report the latest findings in both of these dramatic and currently active processes and assess their importance for the evolution and history of polar layered terrain.

NPLD and basal-unit mass wasting: The basal unit [5-7] is clearly subdivided into two main types of materials in HiRISE data [3]: 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 fractures or joints, delineating polygonal blocks. 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.

We have surveyed all HiRISE images covering ~70 individual basal unit-outcrop sections around the NPLD. Of these sites, ~20 showed evidence of recent block-wasting activity in the form of scattered blocks and debris on basal-unit slopes. Other sites were characterized by a lack of blocks and loose debris and significant dark-sand cover. Many of the more active outcrops also showed signs of debris likely detached from the above NPLD, in the form of wider patches and accumulating aprons of debris, more numerous and denser fields of individual blocks, and debris emplaced all the way up to the foot of the NPLD scarp [1,3,8], detailing a process of NPLD erosion proposed from MOC images [6]. Outcrops with the most debris appear to correlate with the steeper NPLD scarps. This further suggests that NPLD material is contributing to basal unit-outcrop debris, and that this type of mass-wasting is what is maintaining (and possibly creating) these steep scarps (often 45°-65°, with sections approaching vertical). An alternative for apparent lack of mass-wasting activity at basal-unit outcrops is a significantly higher rate of block destruction and/or a significantly higher rate of sediment (dark sand) through-transport by the wind. Possible scarp evolution is shown in Figure 1.

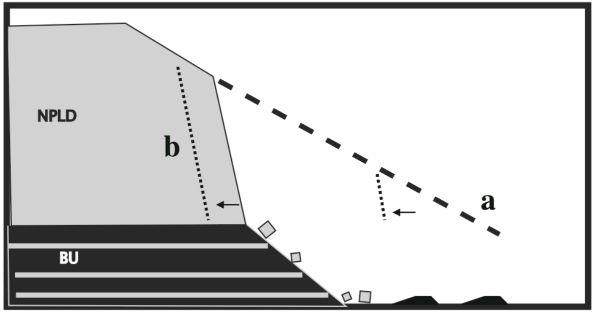

Fig. 2 Schematic of possible former (a) and future (b) configurations of NPLD and BU exposures. The BU may have first been exposed at point/time a.

Furthermore, none of the NPLD peripheral scarps without basal unit exposure have slopes above 40 degrees or likely mass-wasted NPLD detritus at their base. This suggests basal-unit exposure plays a role in over-steepening of the NPLD scarps and the mass-wasting process. Interestingly, the lower-sloped, non-basal unit scarps also do not display the severe fracturing that characterizes the steep NPLD cliffs directly above many basal unit exposures. There are several possibilities that may explain the interaction of these features and processes: 1) undercutting by the basal unit may cause fractures to propagate upwards into the NPLD, 2) the creation of extremely steep scarps due to undercutting by the basal unit changes the solar incidence angle significantly, resulting in higher thermal stresses on the exposed ice, leading to brittle fracturing. This process would also exacerbate mass-wasting erosion of the NPLD cliff itself, adding to the effects of basal unit undercutting, 3) the rapidity of the undercutting and steepening by the basal unit may uncover ice that was under compressive stresses quickly enough to cause fracturing as these stresses are relieved by exposure. We currently favor the second explanation, although have not yet completed modeling of any of these.

We seek to constrain the volumes and rates of erosion by comparing images from Mars Year 28 to images from Mars Year 29 and 30 (and 31 as they become available). For large deposits, an areal extent multiplied by an estimated average thickness yields volume. Shadow measurements and size of individual blocks yields volume of small events. These results are normalized by the length of scarp reimaged and the time between re-imaging.

CO_2 frost-dust falls and avalanches: Nine frost-dust avalanches were observed in northern spring, Mars Year 29 (2008), between Ls 27° and 39° [4] (Fig. 2). Only one image is available from earlier in the season (Ls 14°). In Mars Year 30 (2010), imaging could not start before ~Ls 25° due to prolonged MRO safing. 27 events, from avalanches to small falls, were identified, ceasing by Ls 50°. Several of these events occurred at scarps other than the discovery scarp from Year 29, although most were on that scarp. All scarps were steep, > 40°, and fractured. In Mars Year 31, 13 sites considered most likely to have an avalanche based on previous years were intensely monitored throughout early spring. In addition, during the period Ls 19.2° - 25.6°, 27 additional locations spread around the periphery of Planum Boreale and Chasma Boreale were imaged, yielding a snapshot of geographically and morphologically diverse scarps at a common moment in time. 7 images containing avalanches at the discovery scarp have been identified through Ls 42°, with the first occurring at Ls 8.9°. The extension of this onset time to such an early date suggests this is one of those processes that begins in response to faint, low-energy insolation [eg 9, 10]. Few avalanches have been detected on other scarps so far this year. A complete spatial, seasonal, and inter-annual comparison over the three years provides an increasingly robust database from which to analyze these features.

Loosely coincident timing with local and polar regional CO_2 frost sublimation generally suggests a causal relationship. This and an apparent origin location on the scarp face suggest the events are triggered by sublimation-related or scarp-proximal atmospheric (e.g., wind gusts) disturbances. Although there is direct evidence of wind gusts on the plateau above the scarp, no instances of particle clouds going over the scarp lip have ever been observed.

The Year 30 observation campaign has increased confidence in the ending Ls of these events. Thermal models of surface CO_2 balance and sublimation rate, suggest that such steep scarps should be free of CO_2 during avalanche season, although upper shallower sections (~30°) may retain CO_2 through part of the season [see also 11]. Constraints on nearby CO_2 presence are provided by seasonal CRISM observations. However, spectral analysis of steep scarps is complicated by their small size, high relief, and poor early-spring coverage. The scarps are far from smooth, with ubiquitous crevasses, recesses, and fractures. The discrete, sudden, isolated nature of these events suggests a non-uniform process, likely involving a build up of factors before a disturbance. CO_2 persisting in dark niches on the scarp may be retained until disruption by building sublimation pressure.

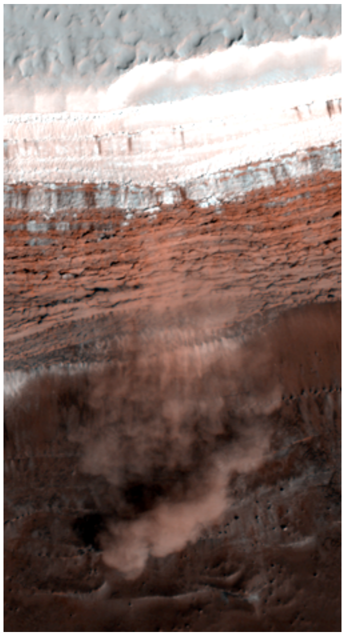

Fig. 2. Frost-dust avalanche in HiRISE PSP_007338_2640, Ls 34°, false color. White at top is CO_2 frost-covered polar plateau; light red mid-image is very steep (at least 70°) fractured NPLD; dark at image bottom is basal unit outcrop.

We specifically target the question of whether these avalanches are an expression of the mass wasting of NPLD blocks as discussed above. Before, during, and after images (as available) are scrutinized at the several-pixel scale in the areas immediately adjacent to and down-slope of observed avalanches. To date, the only potential instance of block fall correlated with an avalanche is the appearance, within a window of 29 days, of two new blocks on the BU. However, they are a few meters below an apparent disturbance in a basal-unit bright layer, suggesting that the passing avalanche cloud disrupted blocks at the edge of basal-unit bright layers that were on the verge of falling already. The powdery nature of the falling debris suggests it is already in fine components, and the white powdery aprons along the base of the NPLD are much better candidates as potential avalanche deposits.

References: [1] Russell P. S. et al. (2007) *LPSC XXXVIII* #2358. [2] Russell P. S. et al. (2008) *LPSC XXXIX* #2313. [3] Herkenhoff K. E. et al. (2007) *Science, 317*, 1711-1715. [4] Russell P.S. et al. (2008) *GRL 35,* L23204, doi:10.1029/2008GL035790. [5] Byrne S. and Murray B. C. (2002) *J. Geohys. Res., 107 E6*, 5044. [6] Edgett K. S. et al. (2003) *Geomorph., 52*, 289-297. [7] Fishbaugh K. E. and Head J. W. (2005) *Icarus, 174*, 444-474. [8] Russell P. S. et al. (2007) *7th Int. Conf. Mars* #3377. [9] Hansen C. et al. (2010) *Icarus, 205*, 283-295. [10] Hansen C. et al. (2011) *Science, 331*, 6017, 575-578. [11] Becerra P. et al. (2011) *5th Mars Polar Sci. Conf.* #6024.