LANDSLIDE EROSION RATES OF NORTH POLAR LAYERED DEPOSIT CLIFFS AND THE UNDERLYING BASAL UNIT.
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Introduction: While the north polar layered deposits (NPLD) have long intrigued scientists as potentially Mars' best climate record [e.g., 1,2], it is only recently that explanations have detailed the processes by which the polar deposits have evolved to their current form, e.g., Chasma Boreale [3], interior troughs [4], and steep marginal scarps, as discussed here. The mass wasting activity reported here significantly extends the MRO-view of polar margins as extremely geologically dynamic environments.

MGS revealed the presence of a significant unit below the NPLD, termed the basal unit (BU), outcropping around some of the NPLD margins, notably beneath steep scarps [5-7] (Fig. 1). The BU was described as composed of interbedded thicker dark layers likely to be sand and thinner, more resistant bright layers, constituting a paleoerg deposit [5-7]. Bright markings below the NPLD/BU boundary [6,7] were interpreted as talus deposits of NPLD material that had collected on the BU [7]. [7] hypothesized that the poorly cemented dark BU material is easily removed by the wind, causing undercutting and hence mass wasting of the overlying NPLD, resulting in the landslide deposits as well as the maintenance of the steep NPLD scarps.

HiRISE has confirmed and clarified the general nature of the BU while revealing further details, including pervasive fracturing of BU bright layers in a polygonal texture and overlying NPLD scarps in a scale-like slab texture (Fig. 1) [8, and at Mars 7 in 9]. In addition, [9] describe a range of types of landslide deposits and fill out the details of the process of undercutting-assisted, piecewise mass wasting of pre-fractured ice layers, not only of the NPLD but within the BU as well, elaborating on the hypothesis of [7], as we continue to do here.

Since Mars 7, comparison of images of steep scarps within and between the 1st and 2nd year of HiRISE observation revealed what was suggested and predicted by work up till then [8, 9] – that these landslide deposits are currently appearing and that the mass wasting is an active process, both in the BU [10] and NPLD [11]. Most of these landslides classify as rock falls, a term we keep as an accurate descriptor of process, and because ice in this setting shares many aspects of rock.

Methods: We have undertaken a systematic survey of nearly 5 years of MRO north polar observations with the goal of quantifying the rates of mass wasting of ice from the NPLD and BU and to assess the implications for north polar landscape evolution and release of water to the atmosphere. To quantify erosion rates of the BU and NPLD, we need to measure the volume of material involved in each event, the frequency with which events occur, and the length of scarp observed and searched. To constrain models explaining the factors causing and influencing these events, we also look to determine any seasonal preferences for when in the year they occur, which can then be related to local coincident environmental conditions such as presence of frost, solar heating, and thermal state of the surface.

Although there are many scarps showing strong evidence for currently active mass wasting, we first concentrate on the one that is among the longest, steepest, and most imaged. Images are split into two seasons. The boundary between "Spring" (Ls <0°-80°) and "Summer" (Ls 80°-145°+) is roughly when the BU is mostly free of CO_2 frost, providing an initial guage of rock fall seasonality. On average there is a difference between images of 11° Ls in summer image and 3° Ls in spring. To assess rock fall activity over the fall-winter period of no observations, we compare the last summer image of one year with the first summer image of the next, ensuring that no rock falls found in the intervening spring are double counted. The first spring image is not used for this because the scarp is blanketed in patterned CO_2 frost, obscuring the BU.

Image to image comparison was done in *ArcGIS* software. To correct for relative registration errors of ~100+ m, images were first shifted to match a reference image. For each identified new rock fall, both the area of the deposit and the area of the vacant gap left on the source BU ledge or NPLD scarp were outlined. The first image of the deposit and the last image of the intact source provide the Ls bounds on when the rock fall happened, and their common overlap of the scarp is the applicable length. In most cases, there are two opportunities to measure the volume for a given rock fall: the vacant gap left in the source scarp/ledge and the collection of blocks and rubble of the deposit, each with its own challenges to estimating.

Results: Preliminary results at this one scarp over all 5 years, broken down by season, reveal several interesting and informative trends. First of all, the presence of an average of ~50 rock fall events per year along this ~ 20-km long scarp is the first quantified estimate of just how active, currently, this scarp is, as previously postulated by [8, 9]. While there are more events from the BU, the volume of most NPLD events is greater (Figs. 1, 2). Estimated volumes and absolute rates are being developed from these results.

Period	From BU	From NPLD
Spring	6	1
Summer	13	0
Fall/Winter	27	6

Table 1. Mass wasting events, yearly average.

BU and NPLD events also occur with different seasonal behavior, suggesting they are not simply extensions of each other but may be triggered by different conditions. The low number of BU spring rock falls may be a visibility issue, although it is more likely a protection issue, in which blanketed ledges don't collapse. Twice as many BU rock falls occur in the summer. This may reflect a dependence on high seasonal temperatures or on increased seasonal removal of underlying sand due to high seasonal wind activity. The latter process would also be "turned off" or blocked by protective CO_2 cover in the spring. The greatest number of BU rock falls occurs between late summer and the next spring, although the average frequency over this longer period is less than in summer. However, given that BU rock falls are more common in frost-free summer than frost-covered spring, it may be that the occurrence of rock fall from late summer to the next spring is not evenly spread over that period – the recorded number is also consistent with having a summer-like frequency from late summer to early fall and a spring-like frequency from then to the end of winter. The timing of NPLD rock falls is usually hard to pin down because they are there at the beginning of one summer when they were not there at end of the last summer, yet they don't appear in intervening spring on top of frost, instead becoming revealed as the frost disappears. This means they occurred before, or during, frost emplacement – late summer through early winter. Unlike with the BU, there is no separate clue as to how they may be partitioned in this time. This timing suggests they may be influenced or triggered by cooling temperatures or with physical emplacement of frost.

Conclusions: Mass wasting of the BU and NPLD is currently highly active. BU activity prefers summer, indicating the effects of high temperatures and/or an active undercutting (sand-removal) mechanism which would be promoted by frost-free surfaces and strong winds. Activity likely occurs throughout the fall, perhaps elevating the undercutting mechanism in direct importance. NPLD events largely occur when HiRISE is not imaging, coincident with the period of annual cooling. Thus, the fractures and scale-like slabs of the NPLD cliff face may form, and eventually fail, due to thermal-stress induced contraction on the ice cliff [see discussion in 12]. Deposits on BU noted by [7-9] likely are the transformation or "aging" of these deposits and indicate that this process has been ongoing for some time. This process is capable of being the one responsible for numerous instances of BU and associated NPLD erosion [3, 13]. Mass-wasting rates determined here will help constrain the duration of such erosion.

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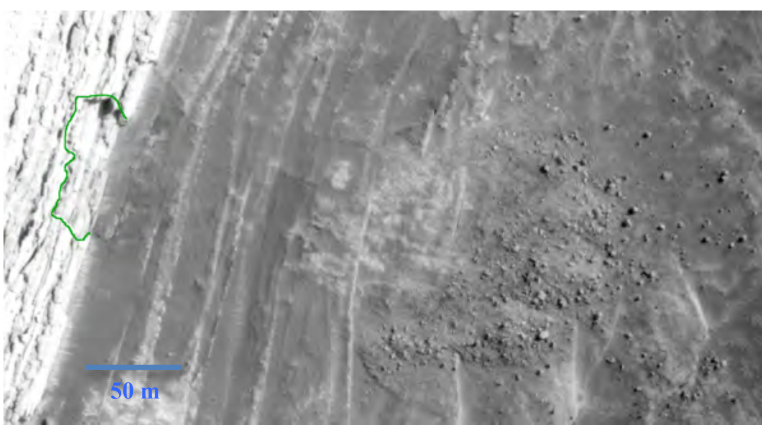

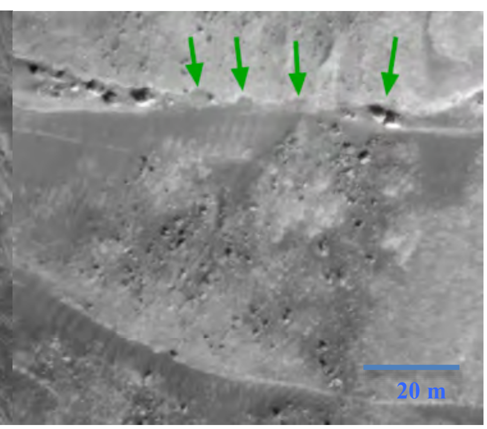

Fig. 1 (left). Landslide deposits on BU resulting from failure of steep (~70° [14]), slab-fractured NPLD, Mars Year 30. Green outline = gap vacated by fallen slabs. Little to no trace of landslide on upper slopes; bulk of deposit came to rest in multiple-lobed, thick, rubble piles; individual boulders continued further and are strewn beyond. **Fig. 2 (right).** Actively eroding basal unit layers. Several notches in bright layer edge (green arrows) indicate source of MY 30 rock fall deposited on the ledges below, comprising two proximal ~4 m boulders, scattered blocks, and minor/thin debris cover.