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Mars polar cliffs: stressed out and falling apart

S. Byrne (1), M.M. Sori (1), P. Russell (2), A. Pathare (3), P. Becerra (4), J. Molaro (5), S. Sutton (1), M.T. Mellon (6) and the HiRISE Team (1). (1) University of Arizona, Tucson, AZ, USA. (shane@lpl.arizona.edu) (2) UCLA, Los Angeles, CA, USA. (3) Planetary Science Institute, Tucson, AZ, USA. (4) Physikalisches Institut, Universität Bern, Bern, Switzerland. (5) Jet Propulsion Laboratory, Pasadena, CA, USA. (6) Southwest Research Institute, Boulder, CO, USA.

Abstract

Steep, icy, north polar cliffs are actively retreating through fracturing and blockfalls and are scoured clean of dust by avalanches each spring. We explain this activity through thermoelastic stresses.

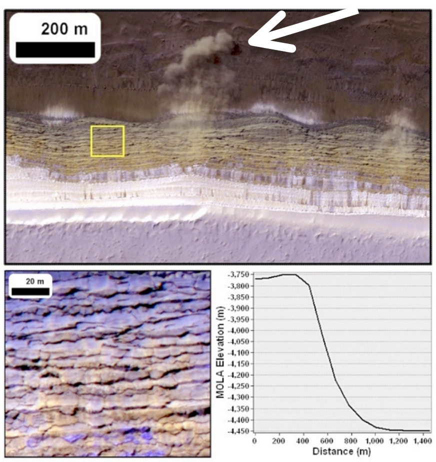

Figure 1. HiRISE image (PSP_007338_2640, L_s 34) of 70° scarp (MOLA topography at bottom right) at 84°N 235°E with avalanche (arrow) in progress [10]. Box shows location of scarp texture in bottom left.

1. Introduction

The martian North Polar Layered Deposits (NPLD) are a stack of contiguous layers of dusty water ice that record paleoclimate [1,2]. Dust content varies from layer to layer, but is minor overall [3,4].

Strong local effects on erosion and deposition patterns can be seen. Poleward-migrating spiraling troughs pervade the NPLD interior [5]. At the NPLD boundaries, steep scarps up to 800m in relief and 70° in slope (Figure 1) exist. These scarps typically overlie exposures of a sandy basal unit [6,7] and removal of this friable material may be undermining the NPLD and leading to their steepness. Their steep equatorward-facing orientation mean these cliffs defrost early and receive intense summertime insolation with a strong diurnal cycle and low incidence angles. In contrast to troughs in the NPLD-interior, steep scarps appear heavily fractured with jagged slab-like fragments (Figure 1) and lack the usual thick slumping dust covers [9].

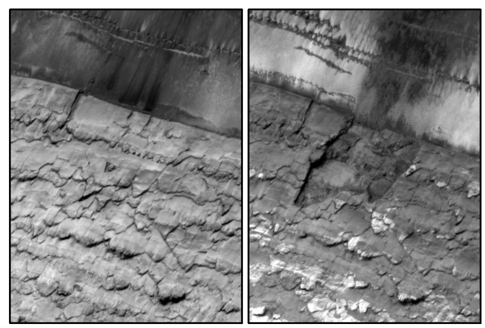

Figure 2. HiRISE images ESP_016292_2640 (left) and ESP_024639_2640 (right) show collapse of a 70m wide slab during MY30.

Fresh basal debris [8] is common and exfoliation of large slabs (Figure 2) indicates the prevalence of active sheeting joints in addition to surface-normal fractures. HiRISE observations show springtime (L_s 0–50°) dust/frost avalanches (Figure 1) are frequent [10]. The geometry of these icy scarps, and the absence of a thick dust cover suggest they are likely subject to high ablation rates. Springtime avalanches may scour these scarps of any thin dust lags acquired the previous summer. However, HiRISE color data show enough dust exists to darken their surfaces.

2. Thermo-mechanical Model

We simulated temperatures of the steep scarps with a standard 1D semi-implicit thermal diffusion model with radiative boundary conditions at the top surface and negligible heat flow from beneath. The steepness of these slopes means that they exchange reflected and emitted radiation with surrounding flat terrain as well as open sky. To account for this, we separately simulated the temperatures of the surrounding terrain (assumed to be dark sand, albedo 0.15, thermal inertia [TI, MKS units] 225) to calculate the upwelling fluxes onto the scarp face. The thermophysical properties of the scarp itself were taken to be those of water ice at 200 K (TI 2130) overlain by a thin dust cover (albedo 0.25, TI 85). The thickness of this dust cover is a crucial controlling factor on the thermal behavior of the ice and also strongly affects the season at which the scarp losses its CO_2 frost cover. HiRISE shows a defrosted scarp at L_s 350°, so dust provides negligible insulation, although still affects albedo.

We follow the approach of [11] to solve for the time varying stress in a viscoelastic solid. No lateral strain can occur, so surface-parallel thermal expansion and contraction at each depth is opposed by elastic stresses on short timescales that viscously decay over longer timescales. Viscous strain rate is grain-size dependent, we use the Zenner pinning approach of [12] with NPLD dust abundances [3] to constrain ice grain sizes to be 10–1000 μm. Large summertime diurnal temperature oscillations cause surface stresses to vary by several MPa and alternate between extensional and compressive (Figure 3). Compressional stresses occur during warmer periods and are thus more effectively viscously relaxed than extensional stresses. Colder ice in winter allows for greater extensional stress.

3. Discussion

The tensile strength of water ice ranges from 1–2 MPa. Peak extensional stress at the surface exceeds this by an order of magnitude (Figure 3). Thus, these steep scarps cannot remain unfractured and cracks are expected to depths of 5–10 m. Opening of cracks can reduce extensional stress and the fracture spacing should decrease until all points on the scarp face are near enough to a crack to avoid further fracturing.

In addition, surface-parallel compression in concert with surface curvature can generate extensional stresses below (and normal to) the surface [13]. It is believed that this effect is responsible for large surface-parallel sheeting joints forming on terrestrial granitic domes. High compressional stresses on these martian scarps are relatively easy to generate, so only modest surface curvature is required to overcome the increasing pressure with depth [13]. Peak compressive stresses (Figure 3) occur in the upper few meters in spring, coinciding with the seasonality of (and potentially triggering) avalanche activity.

Fast viscous relaxation of these scarps is expected [14], but blockfalls (Figure 2) provide competition. A self-perpetuating cycle of dust-free steep cliffs causing thermoelastic fractures that drive avalanches and blockfalls has been established in these locales.

References

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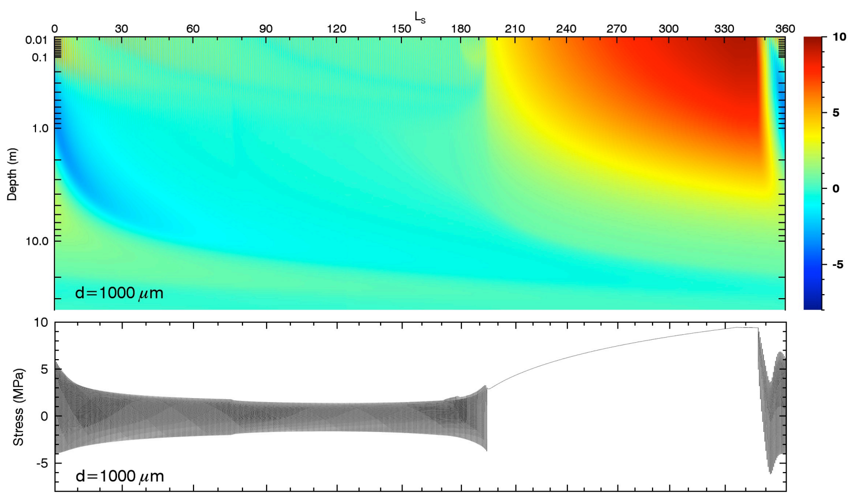

Figure 3. (Top) Thermoelastic stresses (positive is extension) on a southwest facing 70° slope as a function of depth and season. (Bottom) Stresses at the surface. Results shown for an ice grain size of 1mm. Stresses are similar for grains of 100 microns and a factor of several lower for grains of 10 microns.