THE FORMATION OF SAND FURROWS BY CRYO-VENTING ON MARTIAN DUNES.
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Introduction: Sand furrows are a new geomorphic feature identified on Mars' polar dunes [1] (Fig.1). They are shallow (~.25 m) and narrow (~1.5 m) erosion forms which can extend upto 300 m along the dune surface. Furrow planforms may be straight or highly sinuous and network patterns vary from radial to rectilinear, tributary and distributary (Fig. 2). They are important dune surface features, occurring at 95% of North Polar HiRISE dune image locations.

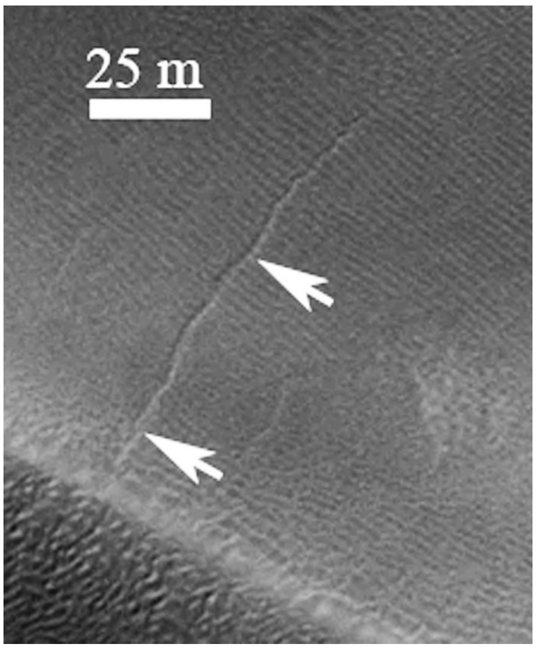

Figure 1: Example of a sand furrow on a dune in Olympia Undae.

Furrow formation: Furrows display planforms reminiscent of fluid flow, perhaps even fluvial flow [e.g., sinuosity, braiding, anastomosing, tribituary, distributary patterns and slope-normal alignment, 2] (Fig. 2). However, furrows also display patterns that defy gravity, [e.g., they display upslope trending radial patterns, cross up and over dune brinks and extend both up and down local dune convexities, 2]. In addition, furrows are not associated with terminal deposits. This suggests that the formative fluid is likely to be a pressurized gas. The gas venting model (sensu Kieffer) [3], referred to here as cryo-venting, has been proposed to explain the formation of dark albedo features on the southern hemisphere seasonal ice cap (e.g., spots, 'fried eggs' and 'spiders') [3-6] and the formation of araniform in the southern hemisphere [7, 8] and dark spots, cracks, and fans on the seasonal ice cover of dunes [6, 9-11]. Here the model is invoked to explain the formation of furrows on polar dunes.

A schematic diagram of the venting model for a dune surface is presented in Figure 3. Condensation and precipitation of the seasonal ice cap onto the Northern Polar dunes occurs during the polar autumn and winter (Fig. 3 a). Sublimation occurs during spring and local gas pressures at the confined and sealed interface between the seasonal ice and the dune surface increases. This build up of gas caused the overlying ice to levitate forming an accommodation space for gas mobilization at the dune surface. Ice cap flexure increases stress in the ice that can lead to the formation of cracks (Fig. 3b) [7, 9]. Some cracks become conduits (linear vents) along which CO_2 gas, ice and sediment are transported from the sub-surface and elevated in jets high above the dune (Fig. 3c) to be deposited in fans, spots and supra-ice grain flows (Fig. 3d). This sub-ice sediment transport erodes sand furrows and deposits the furrow sand on top of the overlying ice. The earliest spring time images at the study sites (Ls=29.7°, MY 30) show that polygonal cracks are already present, and cryo-venting continues for a further ~ 40 sols. It is during this time that sand furrows form.

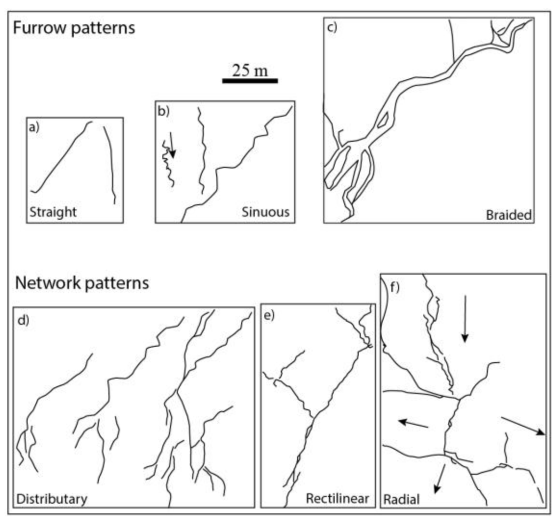

Figure 2: Sand furrow patterns mapped from HiRISE images.

Controls on furrow location: Mapping data show that not all darkened polygonal cracks on dunes are associated with furrow formation. Furthermore, the straight-edge of the polygonal ice crack patterns does not reflect the predominantly dendritic often sinuous sand furrow planforms (Fig. 2). This suggests that furrows are either decoupled from vent geometry or they seldom form along linear vents.

There may be several reasons as to why gas transport at linear vents does not have an enduring geomorphic effect. First, darkened cracks are not always associated with fans [9] suggesting that cracks do not always evolve to linear vents. Without venting the sub-ice sediment system is transport-limited. A second limiting factor may be vent spacing. The close spacing of vents is reported to reduce venting efficiency [5]. Fan (vent) spacing in the study area averaged 6 m – considerably smaller than previous estimate of 300 and 100 m for the northern and southern hemispheres respectively [7]. Fan dimensions associated with close-spaced vents are also small forming 5 m diameter spots (measured at Ls= 61.8°). This suggests limited sediment evacuation from the subsurface.

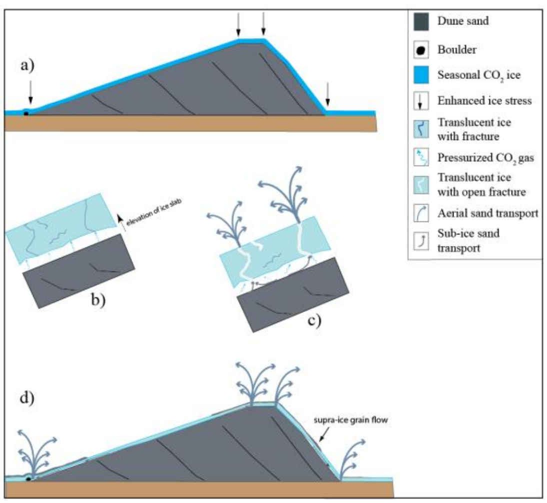

Figure 3: Conceptual model of cryo-venting leading to the formation of sand furrows.

A third factor is that the erosive power of the confined gas can be limited by the vent geometry [7, 12].

It is likely that the topography of the dune surface also influences cryo-venting efficiency. Changes in slope on dune surfaces will induce stresses that can affect the structural integrity of the seasonal ice cover. Locations where structural stresses in the ice may be higher dune to changes in slope include the dune footslope, the dune brink, crest-brink separations and surface wave instability features (arrows in Fig. 3a). This is supported by observations of large sediment fans at the dune brink which form supra-ice sediment flows [11]; dark dune spots at the dune footslope which are spatially correlated with furrows. There may also be additional local topographies such as protruding boulders or interdune polygons ridges that cause stresses in the ice. That many furrows intersect boulders and boulder clusters in the study area supports this inference [1,2].

Conclusion: Furrows on Martian dune surfaces are proposed to form by sub-ice erosion and transport of sand during cryo-venting. Efficient vents that form at 'sensitive' locations likely facilitate higher sediment fluxes. These locations are associated with well-developed furrows. Linear vents that form along seasonal ice polygons also contribute to furrow formation, but may not be as effective due to the close spacing of vents.

That some furrows extend up to 300 m across dunes suggest that sub-ice gas mobilization is extensive and that the energy required for sub-ice sand transport towards a vent can be sustained for significant distances. Numerical modeling of cryo-venting can now employ these observations using coarser (sand) grain sizes and longer sub-ice gas transport pathways to more accurately characterise the sediment-transport process of cryo-venting.

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