Proxy records of frost: Frost-driven geomorphic changes on martian sandy slopes.

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Introduction: Over the last ~decade, many small-scale geomorphological changes within martian sandy slopes have been identified and studied, occurring on ~annual timescales. In some sites where the timing of activity has been constrained to a portion of a Mars year, the formation of features has been tied to periods when frost is accumulating or sublimating. This, together with other data such as spatial distribution of the features, strongly suggests that *martian CO_2 frost and ice, especially when interacting with a granular surface, is an effective and primary geomorphic agent* (at least during the present and recent Amazonian) and should be considered, with wind and impacts, when interpreting martian geomorphology.

This work will summarize current results and ongoing studies of martian landforms observed to be active over seasonal-to-decadal-timescales and hypothesized to have activity connected to the accumulation and/or sublimation of seasonal frost (updated since the 2018 Amazonian Climate Wkshp). These types of studies are vital if we are to improve our ability to interpret these landforms as proxy markers of specific environmental conditions and thus use them to learn more about the Amazonian and present-day martian climate.

The landforms:

- Active martian **gullies** (Fig. 1) were first observed within the southern mid-latitudes, on both dune and rocky slopes [1-3], with present-day changes in alcove, channels, and aprons. The activity timing within the southern mid-latitudes has been constrained to late winter/early springtime, suggesting a connection to springtime sublimation-driven or initiated processes [4-6].
- *Superficially* similar features have been observed in the northern polar [7-10] and mid-latitude [11] dune fields. However, alcove formation within the north polar erg occurs before spring sublimation begins [13-15], possibly during early autumn [15]. Additional differences from the southern gully activities are found in the feature sizes and shapes, and locations of activity in subsequent winters, suggesting that the north polar alcoves may form through a different process [12].
- **Linear gullies** are long (up to 2 km), narrow channels that run downslope and are relatively uniform in width, ending in circular depressions referred to as terminal pits. Activity is tied to early spring, their location on pole-facing sandy slopes, and their general morphology [13,14] is consistent with a model of subliming CO_2 ice blocks sliding down the sandy slopes [14].
- New meters-scale **dendritic troughs**, carved into the surface, have been found in some polar, sandy regions and have been observed to be growing annually, likely due to scouring from sand [15]. The formation process is consistent with erosion by sublimation-induced gas jets fed by sub-ice gas flow [16,17]. Over time, this type of activity may form the araneiform terrain (AKA spiders) in the south polar region [18,19], with longer timescales not necessarily requiring the presence of sand.
- New **furrows** appear annually along the crests and margins of many dunes when the seasonal frost disappears [20]. Erosion of these features is also thought to be driven by cryoventing, with vents occurring where thermal and slope conditions change, leading to a weaker ice layer [21].

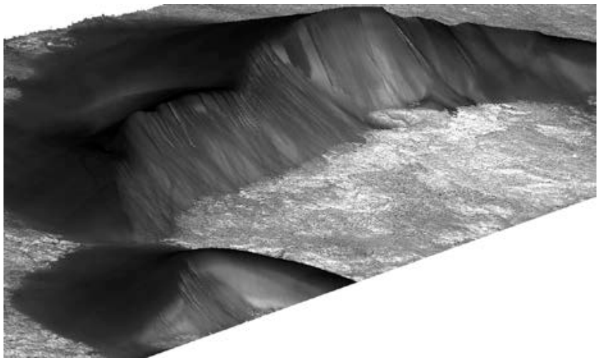

Figure 1. *Active dune gullies extend downslope on this megabarchan at the edge of Kaiser Crater dune field (46.8°S, 20.1°E). These are massive features (on a very large dune – 750 m tall), and some exhibit repeat activity over multiple Mars years. DTM was generated from PSP_006899_1330 and PSP_006965_1330.*

The drivers:

In this and many previous works, we have focused on CO_2 frost and ice as this volatile makes up 96% of the martian atmosphere [22]; accumulates on the martian surface in significantly greater amounts than water frost/ice (e.g., compare [23] with [24]); and – when information is available – coincides better with the timing of surface landform activity. Solid CO_2 can interact with the martian surface via these forms:

- As the autumn season cools, transient (diurnal) frost can condense on the martian surface. Such frost has been observed in low latitudes [25] and laboratory experiments have shown it can induce at least small-scale mass-wasting within granular material at or below the angle of repose [26].

- Seasonal frost accumulates within latitudes poleward of ~30d [27], with depths increasing up to tens of centimeters in the polar regions [23].
- As winter progresses, the CO2 frost anneals into denser slab ice [28].
- In the spring, blocks of CO_2 ice are cold-trapped in alcoves while ice on the slipface sublimes. If these ice blocks break free, they slide over the warmer exposed dark sand. Such blocks have been observed on the martian surface [e.g., 4]; terrestrial field experiments have shown that such blocks can easily ‘hovercraft’ down dune slopes, carving out a track [14,29]; and laboratory experiments under martian winter-time conditions show that stationary subliming blocks can create pits [20].
- Snowfall also occurs in the polar regions [30] and may influence some large-scale mass-wasting activity observed on north polar dunes [31].

Several CO_2-frost driven mechanisms have been proposed as possibilities for this present-day martian surface activity [e.g., 6,14,18,31-6], but the exact drivers/process(es) are still under investigation.

Implications for the martian landscape: Features such as martian gullies, linear gullies, and spiders/troughs/furrows are found over a range of latitudes [20,37-8] and are likely to reflect current or recent local-scale environmental conditions. Examining where different landforms are found may indicate where different types of solid CO_2 can be found on Mars, and what this implies about the martian volatile cycle.

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	Locations	Timing	Type of frost	Mechanism
Dune-gullies	S mid-lats	After spring sublimation starts	Seasonal frost	Sublimation leading to destabilization of the slope
Dune-alcoves	N polar and mid-lats	Early autumn, just after first frost?	Diurnal/early seasonal frost? Early snowfall?	Deposition on/within top layer and destabilization?
Linear gullies	S mid-lats	After spring sublimation starts	CO2 ice blocks	Sublimation exposing slope and breaking ice layer, block sliding down
Dune furrows	N polar + S polar and mid-lats	After sunrise in early spring?	Seasonal slab ice layer	Cryoventing due to solid-state greenhouse effect, and related CO_2 gas flux erosion under the ice slab
Araneiforms	70S-90S excl. perm. SPC	After sunrise in early spring		