CONCENTRATING ICE IN POLAR DESERTS: LESSONS FOR MARS FROM PUNCTUATED GULLY INCISION IN THE MCMURDO DRY VALLEYS.

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Introduction: The latitude dependent distribution [1-3] and non-uniform orientations [4-8] of young gullies on Mars suggest that their formation and modification are controlled by the activity of volatiles at or near the surface. Given the relative abundance of gullies and Mars' current thermal environment, CO_2 and H_2O are the most likely candidates for contributing to gully evolution. Contemporary modification of gullies in the southern hemisphere is temporally correlated with the removal of CO_2 frost [9-12], but morphologic properties [13-14], slope values [7], depths of incision [15], and thermal modeling [16-18] of gullies indicate that their formation may be controlled by the action of liquid water in recent high-obliquity excursions, when water ice was capable of accumulating in the mid-latitudes [19-21].

If water is a contributor to gully evolution, then understanding fluvial processes in polar desert environments on Earth is essential for formulating hypotheses for fluvial activity on Mars. The McMurdo Dry Valleys (MDV) of Antarctica host a spectrum of water-related landforms [22] that do not form elsewhere on Earth but are morphologically similar to Late Amazonian features on Mars [23].

Here, we outline the geometric and environmental conditions necessary for achieving net erosion of gully channels in the MDV and evaluate whether similar processes may explain their counterparts on Mars.

Erosion of Gullies in the MDV: Gullies generally form on relatively warm equator-facing slopes in the MDV [23-24] and exhibit similar alcove/channel/fan morphologies to gullies on Mars [1]. In the South Fork of Upper Wright Valley, which represents the most inland area/zone to experience fluvial erosion [23], alcoves are cut into bedrock cliffs while channel incision occurs along the valley walls below within the uppermost ~20 cm layer of colluvium. This superposes a pervasive ice-cement layer (which is an aquiclude during gully activity [25]). Alcoves serve as traps for windblown snow in the winter, then as inhibitors to rapid sublimation via topographic shielding in the summer [26]. This, in a region that experiences < 5 cm of snowfall annually [27], provides a method for net accumulation of ice in gully source regions.

Despite mean annual temperatures in Wright Valley of -19.3°C [28], peak surface temperatures in gully alcoves surpass the melting point on cloudless days in austral spring and summer. Due to the narrow geometry of South Fork, melting occurs in gully alcoves first while the floor of the valley ~1 km below is still below 0°C due to shadowing from the Dais, a ~700 m plateau that separates South Fork from North Fork (Fig. 1). Similarly, melting in gully alcoves and on valley walls persists later in the austral summer than it does on the valley floor.

In years when unusually warm late-summer or spring conditions lead to melting in gully alcoves, this meltwater freezes in the shaded gully channel before reaching the fan on the floor of the valley [29]. This generates concentrated in-channel ice reservoirs that provide an abnormally large volatile source once melting conditions are achieved on the valley floor in December/January.

Rapid discharge from melting of these in-channel ice deposits is capable of eroding ~5 m wide, ~80 cm deep channels within gully systems over just 7 days once melting occurs lower in the gully system [29]. This includes mechanical erosion through the ~20 cm colluvium layer followed by subsequent mechanical and thermal erosion of the underlying ice-cement layer, itself another potential source of meltwater. The channel then becomes a trap for wind-blown snow in the winter [26], providing a feedback process that amplifies activity within existing gullies: once gullies are formed, they become focal points for modification by processes not explicitly related to their initial formation.

Implications for Mars: Conditions for the accumulation [19-21] and melting [16, 18] of H_2O-ice in the mid-latitudes of Mars were significantly enhanced during recent high-obliquity excursions [30]. Stratigraphic relationships between gullies and the Latitude-Dependent Mantle (LDM) [19], including full inversion of gully channels, indicate that at least 30 m of LDM, which is known to be ice-rich [19], have been removed since many gullies in the southern mid-latitudes were formed [29]. These predictions and observations converge on a scenario in which H_2O-ice played a more significant role in the mid-latitudes during high-obliquity periods than it does today [19].

Gullies on Mars frequently incise mantling material [31], itself ice-rich [19] and broadly comparable to the ice-cement layer that is incised during peak flow events in the MDV. Measurements of neutron flux [32], lander observations [33], and excavations by recent impacts [34] indicate that the weight percent of H_2O in this substrate far exceeds that of ice-cement that is incised by MDV gullies. This provides an additional high-volume source of volatiles within martian gully systems and may help explain why gullies on Mars are more densely concentrated on host slopes than those in the MDV.

The methods by which ice is concentrated in the MDV are all potentially applicable to Mars at high-obliquity. Recent GCM simulations of Mars at 35° obliquity showed that several cm/yr can be accumulated poleward of 30° in each hemisphere, particularly with an active dust cycle [20]. Shaded gully alcoves on pole-facing slopes would be traps for ice and dust, such that a source for gully initiation is available.

In-channel ice-reservoirs similar to those observed in the MDV may form within gullies on Mars but likely due to different geometries. Martian gullies are most common on mid-latitude pole-facing slopes [1-8], such that insolation conditions would rarely be such that an opposing valley wall or crater rim would shield the lower reaches of gully channels and fans, as occurs on equator-facing slopes in the MDV. Due to their azimuth and slope angle, the upper reaches of martian gully systems will receive more direct insolation than their associated channels and fans, particularly early in local spring. This has the potential to generate meltwater early in the season that would refreeze and potentially accumulate in the lower reaches of gully channels. Peak-season insolation across the entire gully system could then rapidly melt this reservoir.

Multiple experimental [17] and modeling [16, 18] studies have predicted that brief melting could occur at gully locations at high-obliquity. Gullies in the MDV provide a more thorough model to be tested with high-resolution GCMs at gully sites on Mars: can ice on Mars be melted, refrozen and concentrated in reservoirs before it is lost to the atmosphere?

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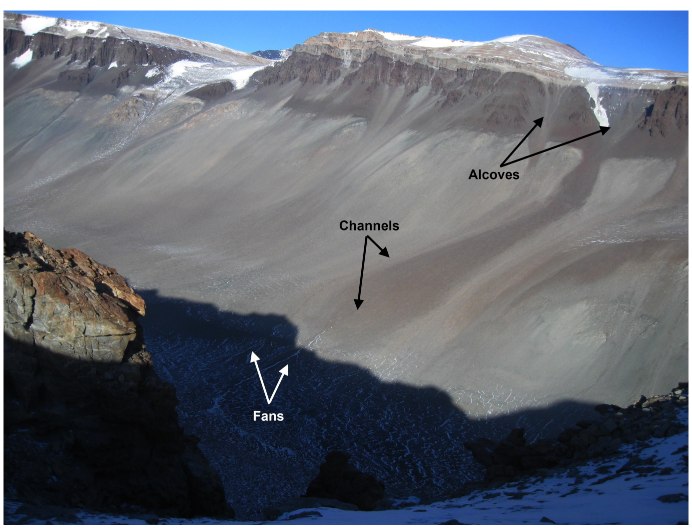

Figure 1. South Fork of Upper Wright Valley, McMurdo Dry Valleys, Antarctica. Image acquired March 6, 2010. During austral spring and late austral summer, temperatures on valley walls are above freezing while the valley floor is below freezing due to shielding by the opposing valley wall. This creates conditions where meltwater refreezes and concentrates in-channel. Once peak conditions are achieved in austral summer, this reservoir is capable of incising meter-scale channels.