MULTI-PHASE, PUNCTUATED GULLY EROSION ON MARS: SEASONAL INSOLATION EFFECTS ON THE MELTING AND REFREEZING OF SURFACE ICE IN THE MCMURDO DRY VALLEYS

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Introduction: Gullies on Mars form in locations where H_2O ice is most likely to accumulate: steep pole-facing slopes in the mid-latitudes (30°-45°) and all slope orientations at higher latitudes (45°-70°) [1-3]. Melting of ice at these locations is difficult to achieve under typical/average conditions on Mars in the last several million years [4-5]. A "wet" hypothesis does, however, explain the formation of gullies in the most Mars-like region on Earth, the McMurdo Dry Valleys (MDV) of Antarctica [6-12]. A detailed understanding of MDV gullies will provide testable hypotheses for their Martian counterparts.

Like Mars, average conditions in the MDV do not favor the melting of surface ice, yet peak conditions allow small amounts of ice to melt during austral spring/summer [6-12]. Since November, 2006, we have instrumented a suite of gullies on the equator-facing wall of the South Fork of Upper Wright Valley (see [7]), at the limit of ephemeral fluvial activity within the MDV [12]. From these data, which include in-situ data loggers and time-lapse camera stations, we are able to describe the extreme conditions required to achieve net annual erosion of gully channels.

Gully activity (typical season): 6 of the 7 seasons showed the following sequence of fluvial activity through spring and early summer (Fig. 1 a-b; 2):

1) *Late-November to Early-December*: Melting of seasonal in-channel snow and in-channel ice remaining from the previous summer.
2) *January*: Diurnal pulses of meltwater originating in the gully alcove extend toward the gully fan, advancing at an average rate of ~8 m/day (Fig. 1).
3) *February*: Flow ceases and yields an ice-reservoir trapped on channel floors (Fig. 3), which is buried by sediment during winter katabatic wind events.

For these seasons, summer erosion (< 15 cm) is balanced by winter eolian sedimentation, and no net erosion has been observed at the annual scale.

Gully activity in 2010-2011: Both gullies in South Fork experienced punctuated flood events in early- and mid-December, a month before the typical arrival of alcove-sourced meltwater (Fig. 1 c-d; 2). This activity included (1) intense diurnal pulses of meltwater with rapid channel switching, (2) erosion rates of ~1.6 cm/hr, including incision into an impermeable permafrost layer during flow events, totaling 81 cm of erosion over 7 days in a 5 m-wide channel, and (3) emplacement of ~10 cm of new fan material on the floor of the valley.

Temperature records for December, 2010, when the flooding occurred, are comparable to previous seasons. Surface temperatures in November, 2010, however, show an exceptionally warm period along the valley wall, where temperatures reached 13°C. Of the 120 November days from 2007-2010, the 9 warmest were recorded in 2010, and 6 of those occurred early in the month. This warmth was not recorded at the gully fan, which was still under the mid-day shadow cast by the opposite valley wall.

Thermal gradient inversion: The cross-sectional profile of South Fork creates a geometry that yields warmer conditions along the wall than on the floor in spring and late summer (Fig. 4). This gradient is inverted when the valley floor is exposed to direct mid-day insolation over the northern valley wall (Fig. 4). Most often (as in 2009), this inversion occurs before melting conditions are achieved along the valley wall (Fig. 4a). In rare instances, this inversion happens after melting has occurred on the wall, as in November, 2010 (Fig. 4b).

In this latter scenario, conditions are such that intense early/late-season heating along the wall can produce meltwater that will freeze as it approaches the colder valley floor (Fig. 5). This creates a concentrated in-channel ice-reservoir in close proximity to gully fans. Once exposed to peak season insolation in December, this reservoir melts again and produces net-erosion conditions in gully channels and net-accumulation conditions on gully fans (Fig. 5).

Implications for Mars: Insolation geometry is critical to gully formation on Mars, based upon orientation and latitude trends measured in both hemispheres [1-3]. From these observations in the MDV, the gully channel itself may be an important reservoir for surface/near-surface ice. This sequence of ice concentration and melting under peak conditions could explain how fluvial features can form on an otherwise hyper-arid and frozen Amazonian Mars.

References: [1] Malin and Edgett, 2000, *Science*, 288, 2330. [2] Heldmann and Mellon, 2004, *Icarus*, 168, 285. [3] Dickson and Head, 2009, *Icarus*, 204, 63. [4] Costard et al., 2002, *Science*, 295, 110. [5] Williams et al., 2009, *Icarus*, 200, 418. [6] Levy et al., 2007, *LPSC*, 28, 1728. [7] Morgan et al., 2007, *LPSC*, 38, 1656. [8] Morgan et al., 2009, *LPSC*, 41, 1043. [9] Morgan et al., 2010, *LPSC*, 41, 1043. [10] Dickson and Head, 2011, *LPSC*, 42, 1252. [11] Head et al., 2007, *ISAES*, 151. [12] Marchant and Head, 2007, *Icarus*, 192, 187.

Figure 1. (a/b) Average season: Diurnal pulses sourced by peak-season melting of alcove snowpacks. (c/d) Flood season: High-energy braided streams in early season.

Figure 3. Late-season insolation in South Fork. Image acquired March 2, 2010. Meltwater that forms along the valley wall freezes in-channel at lower elevations.

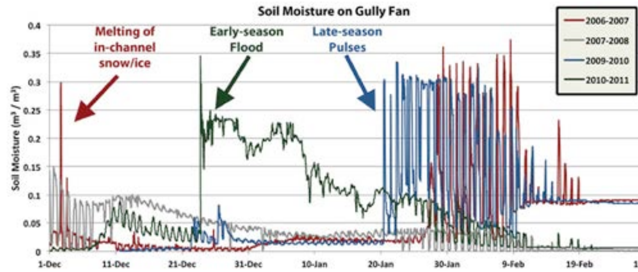

Figure 2. Average season conditions do not see significant fluvial activity until late January, if at all. 2010-2011 saw early-season flooding with standing water/ice on the gully fan.

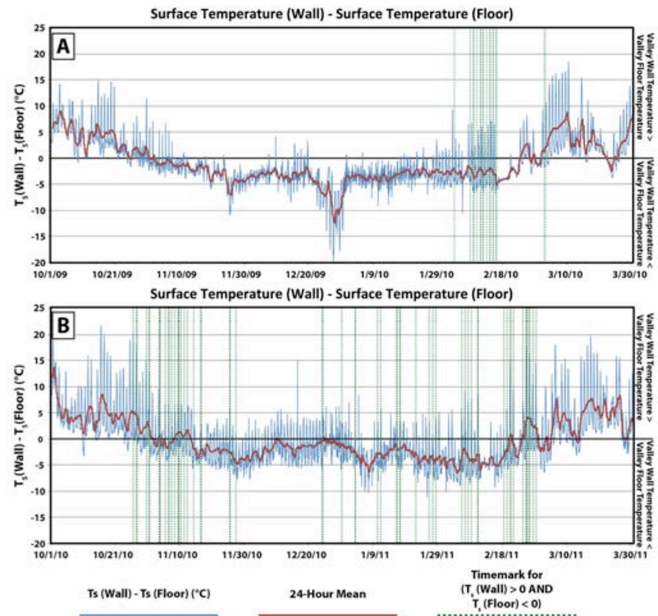

Figure 4. Difference between valley wall surface temperature and valley floor surface temperature. Green lines indicate when the temperature on the wall was greater than 0° while the temperature on the floor was less than 0°C.

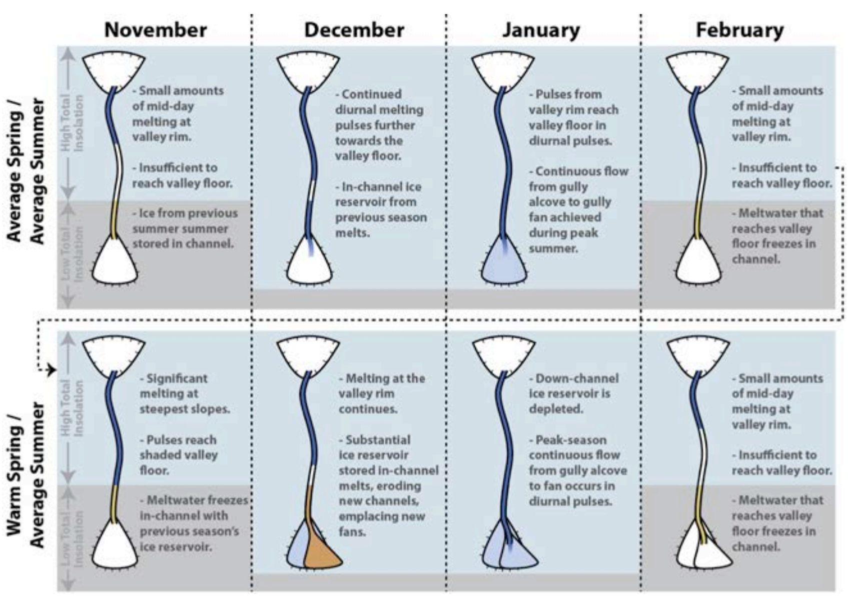

Figure 5. Schematic for differential insolation-induced concentration of in-channel ice deposits. In a typical spring (i.e. 2009-2010), meltwater formed along the valley wall is insufficient to reach the valley floor. In a warm spring (i.e. 2010-2011), this meltwater does reach the valley floor, which is still under low-insolation conditions due to the steep-wall geometery of South Fork. Thus, it freezes in-channel to create a hyper-concentrated ice reservoir. Once peak-insolation conditions occur on the valley floor in early-December, this reservoir is melted once again to generate exceptionally high-energy fluvial activity on the floor of the valley.