

**SOURCES OF WATER FOR GULLY FORMATION IN THE ANTARCTIC DRY VALLEYS: MULTI-YEAR ANALYSIS OF PRECIPITATION AND TEMPERATURE IN THE SOUTH FORK OF UPPER WRIGHT VALLEY AND IMPLICATIONS FOR THE ORIGIN OF GULLIES ON MARS.** G. A. Morgan<sup>1</sup>, J. Head<sup>1</sup>, D. Marchant<sup>2</sup>, J. Dickson<sup>1</sup> & J. Levy<sup>3</sup>; <sup>1</sup>Geol. Sci., Brown U., Providence, RI 02912, <sup>2</sup>Earth Sci., Boston U., Boston MA 02215; <sup>3</sup>Geology, Portland State U., Portland OR 97207 (garth\_morgan@brown.edu).

**Introduction:** The youthful appearance of gullies and the apparent role of liquid water in their formation (even though liquid water was not thought to be currently stable on Mars), led to the initial interpretation that they were the result of groundwater discharge [1-3]. More detailed analyses showed the current metastability of liquid water on Mars and permitted alternative explanations, including atmospherically deposited sources of water [4-7] and ground ice [8]. Recent modeling work has demonstrated that snowfall [9] and the melting of such deposits [4,5,10] is possible in the regions where gullies are located under periods of higher obliquity. This has provided support for snowmelt/ground ice models of gully formation [4-6,8,10]. In question is the nature and distribution of candidate sources of water in these gully environments and the climate and temperature conditions necessary to provide liquid water on the surface for a sufficient time to carve the gullies. Among the candidate sources for liquid water on Mars, then, are: 1) seasonal snow and ice deposits, 2) perennial snow and ice deposits, 3) more ancient residual snow and ice deposits, 3) pore ice in a regolith ice table, 4) shallow groundwater aquifers, and 5) some combination of these.

Terrestrial analogs provide an essential natural laboratory for assessing the different candidate sources of water for gully formation. In this analysis we report on results from field studies within the McMurdo Dry Valleys of Antarctica (ADV), a hyper-arid polar desert that has long been considered one of the most Mars-like of terrestrial analogs [11-13] (Fig. 1). Within this environment, precipitation falls only as snow and so the availability of liquid water is restricted to meltwater generated by the solar heating of ice and snow deposits, as well as melting of ice-cemented soil and the top of the ice table [13].

The most Mars-like gully microenvironment is within the most elevated (and hence driest) portion of the intermediate microclimate zone [13] situated within the South Fork (SF) region of upper Wright Valley. This region marks the most inland extent of active fluvial features within the ADV and is most analogous to Mars during Amazonian periods of high obliquity in terms of precipitation and max T values [13] (Fig. 1). Unlike other gullied regions of the ADV, there are no major nearby glaciers to provide sources of surface meltwater, and so the most significant ice deposits are snowbanks that more closely resemble the deposits predicted to form on Mars during its recent history [4-6,10]. We found that there is significant inter-annual variability in the abundance of snow available for gully generation. However, even in years with minimal snowfall, windblown snow can be concentrated in specific geomorphic traps, such as depressions, lee sides of windswept features and

ridges and the gully channels themselves. Here we report on a four year timespan during which we observed the distribution of snow, its melting behavior, temperature profiles (depth and time), and gully activity/inactivity.

**2006-07: A 'Wet' Year.** The majority of the larger gullies studied in South Fork in 2006-7 exhibited fluvial activity associated with snowmelt from within two geomorphic traps, alcoves and wind-blown snow trapped in channels. *Alcoves.* The northern edge of the Asgard Mountains in SF contain a number of alcoves along the valley margins; upper slopes are in excess of 30° and exhibit cross-sectional profiles similar to crater walls into which the majority of martian gullies are carved. Many of the alcoves contain surface snow/ice that partially melts, providing a seasonal source of water to the gully systems. Observations of aerial photos for multiple years show that the majority of snow/ice in alcoves is perennial. During storm events low-lying clouds hug alcove walls and preferentially deposit snow, building up snow deposits over multiple years. By early Dec 2006, marginal parts of one snowbank examined had started to melt, and the gully channel below it was occupied by flowing water during periods of peak daily insolation. *Ephemeral Windblown Snow in Channels.* In the middle to lower reaches of these gully systems, water is derived from melting of ephemeral patches of windblown snow in channels (Fig. 2). Despite extremely low annual precipitation [13], strong winds are capable of transporting snow and concentrating it within these geomorphic traps, such as gully channels transverse to the dominant wind flow directions. In late Nov 2006, some of the lower channels were almost completely filled with snow. During Nov to Jan the snow banks shrank and eventually disappeared due to a combination of sublimation and melting. Melting was clearly modulated by insolation and air temperature, restricting peak meltwater generation to cloud-free conditions when the sun was at its highest point in the sky. In-channel surface flow was only achieved after a sufficient volume of meltwater had soaked into the dry active layer to create a hyporheic zone and permit runoff; the hyporheic zone formation advanced both cross and downstream, always well ahead of rapidly following surface flows (Fig. 2). Commonly, late in the day, surface water froze and created ice crusts that thickened and restricted meltwater movement.

During peak daily insolation and melting periods, surface runoff eroded inner braided channels (tens of cm-1 m wide) within the sediments lining gully channel floors. Throughout the activity period, small-scale fluvial features similar to those in HiRISE martian gully images [14] developed, including terraces several centimeters deep that were cut into channel floors (Fig. 2), and

which formed islands (longitudinal bars) of elevated debris. Gravitational slumps consisting of small boulders (>1 m long) within a sand-grain-sized matrix were actively observed to form along channel walls; these slumps appear related to the development of tension cracks within adjacent colluvium, causing blocks of wetted colluvium to slide into the channel. In the more distal parts of the gully systems, the slopes of valley walls shallow, and steep colluvium gives way to depositional fans formed from sediment transported in gully channels.

**2008-09. A 'Dry' Year:** No snowbanks were observed in any of the gully channels upon arrival on Dec 3rd, and the alcove snowbanks were significantly reduced in size. The consequence of the reduced snow distribution was that meltwater production was limited to the alcoves, where evidence for sheet flow and limited channel flow was seen in the form of regelation ice found only directly downslope of alcove snowbanks. Despite temperatures high enough to permit surface melting and runoff (Fig 1), no evidence for recent fluvial activity/erosion was observed in the lower sections of the gullies (such as soil darkening due to hyporheic zone development or small scale braided channels; Fig. 2). Many of the channels active in 2006-7 were highly subdued (Fig. 2), and were partially infilled with windblown sands. SF wind speeds were as high as  $16 \text{ ms}^{-1}$  over the previous two years, and small eolian ripples ( $\lambda \sim 30 \text{ cm}$ ) had formed in previously active fluvial channels. No evidence was found for water sources from either 1) deep subsurface groundwater springs (below the permafrost) or 2) melting at the surface of the ice table during either season. The strong correlation between fluvial activity and volume of snow at the start of the two seasons further demonstrates the importance of snowmelt as a source of water for fluvial activity to occur. Late in 2008-09 austral summer, gully-related hyporheic zone patches were observed in satellite images, suggesting that the melting isotherm may have eventually reached the top of the ice table; detailed data logger records are currently being recovered to test this.

**2009-2010. An 'Intermediate' Year:** Examination of satellite images obtained early in the current austral summer showed the usual perennial snow/ice patches, but only minimal evidence of annual snow cover and only very minor amounts of snow in gully channels, thus suggesting an 'intermediate' year. Upon arrival ~Nov 17, snow was seen only in the upper gully channels, was undergoing small amounts of melting, and the pond was dry. At the time of this submission (12/09) we are in the field making observations on snow cover dimensions, gully activity, and recovering/reinstalling data loggers to assess the behavior of the melting isotherm and sources of water contributions to gully formation.

**Application to Mars:** If this analog environment is applicable to Mars [13], then our findings demonstrate that fluvial activity and erosion can occur in a hyperarid desert environment from the influence of direct solar insolation on windblown snow deposits concentrated in topographic hollows (i.e., alcoves and channels). The

sensitivity of gully activity to snow volume demonstrates the importance of both snow accumulation and temperatures permitting melt generation in determining the location of gully activity. Unless the melting isotherm reaches the top of the ice table, melting conditions alone cannot form gullies; sufficient surface snow and ice accumulation is also a requirement [4-6]. On Mars this is likely to be determined not only by the latitude dependence of precipitation [9,13], but also by localized factors that determine where snow is able to accumulate prior to the onset of melting (e.g. such as under the conditions shown in Fig. 1); therefore aspect [7] and micro-environments [13] are clearly important factors. Our studies in SF also show the importance of wind activity in gully degradation processes between active gully periods (Fig. 2). Eolian activity is seen to fill gully channels between active fluvial periods, providing sorted sediment available for the next phase of fluvial activity, and potentially influencing the style of fluvial activity (e.g., channel incision versus slurries and debris flows).

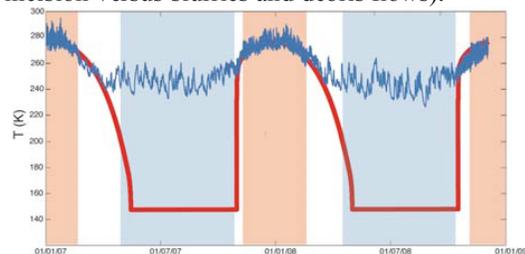


Fig 1. Ground  $T$  at top of gully fan in SF between two field seasons (blue line) compared to equivalent seasons for a Mars southern hemisphere, pole-facing slope at  $35^\circ$  obliquity (red line). Pink represents period of melting conditions ( $T > 273 \text{ K}$ ) on both planets, blue represents periods of surface ice stability ( $T < 200 \text{ K}$ ) for Mars when snow accumulation can occur. Mars model from LDM, Paris 1D model.

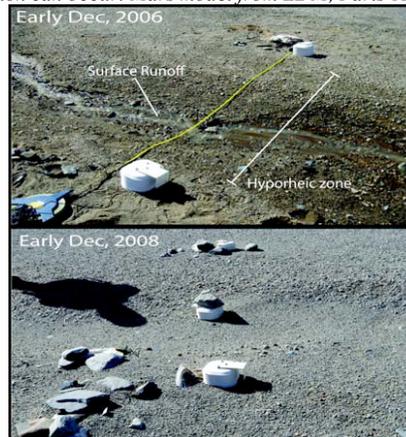


Fig 2. Difference in fluvial activity between two field seasons as a result of the lack of snow in 2008 relative to 2006.

**References:** 1] M. Malin & K. Edgett, *Science* 288, 2330, 2000; 2] *Ibid.*, *JGR* 106, 23429, 2001; 3] J. Heldmann et al., *JGR* 110, E05004, 2005; 4] M. Hecht, *Icarus* 156, 373, 2002; 5] P. Christensen, *Nature* 422, 45, 2003; 6] J. Dickson et al. *Icarus* 188, 31, 2007; 7] J. Head et al. *PNAS* 105, 13258, 2008; 8] M. Mischna et al. *JGR* 108, 5062, 2003; 9] F. Costard et al. *Science* 295, 110, 2002. 10] K. Williams et al. *Icarus*, 2009. 11] D. Anderson et al., *Antarctic J. US* 7, 114, 1972; 12] E. Gibson et al., *JGR* 88, A812. 1983; 13] D. Marchant & J. Head, *Icarus* 192, 187, 2007; 14] A. McEwen et al., *Science* 317, 1706, 2007.