**GULLY FORMATION ON MARS: TESTING THE SNOWPACK HYPOTHESIS FROM ANALYSIS OF ANALOGS IN THE ANTARCTIC DRY VALLEYS.**

G. A. Morgan, J. W. Head, D. R. Marchant, J. L. Dickson, and J. S. Levy; Dept. Geol. Sci., Brown Univ., Providence, RI 02912 USA (gareth_morgan@brown.edu; james_head@brown.edu), Dept. Earth Sci., Boston Univ., Boston MA 02215 USA (marchant@bu.edu).

**Introduction:** The Martian gullies have attracted significant attention due to the apparent role of liquid water in their formation and because of the very youthful nature of their appearance [1,2]. They were initially interpreted to be the result of groundwater discharge, though further considerations regarding the current metastability of liquid water on the surface of Mars generated a host of alternative explanations for the gullies, including H₂O flowing as a liquid in the current Mars environment [3,5]. This discussion has been intensified by recent observations interpreted to mean that gullies are currently active [6]. One interpretation of the source for the water thought to have formed the gullies on Mars is snow [7]; in this scenario, the gullies are eroded by the melting of water-rich snow that has been transported to mid-latitudes from the poles during periods of high obliquity [7]. Among the main features of the model [7] are: 1) The melting of the snow takes place at lower obliquity when mid-latitude temperatures increase; 2) Melting produces liquid water that is stable below an insulating layer of overlying snow; 3) Gullies form on snow-covered slopes (through meltwater erosion or due to meltwater seeping into loose slope materials and destabilizing them); 4) Snow patches remain today, protected from sublimation by a layer of desiccated dust or sediment; indeed melting might be occurring today in currently favorable snowpack locations [7].

In this analysis we report on field work conducted in the Antarctic Dry Valleys (ADV) during the austral summer of 2006-7 in order to gather insights into whether snow might serve as a source of liquid water for gully formation in a terrestrial analog environment. The ADV are a hyperarid, cold polar desert in which sublimation exceeds precipitation [8] and thus provide one of the closest terrestrial analogs for the current Martian conditions. Our work consisted of the study of a series of gully systems along the southern wall of the South Fork of Wright Valley, just south of the Dais. As is the case on Mars, the majority of the gullies contain alcoves, channels and fans and some flow into ice-covered lakes [9].

**Fluvial activity in the ADV:** Despite the extreme cold conditions prevalent in the ADV, fluvial activity does occur for short durations during the austral summer within microenvironments in the form of streams and gullies [8]. Major streams are fed by the melting of cold based glaciers; meltwater forms at unique positions on some glacier fronts and surfaces related to seasonal insolation intensity and geometry [13] (insolation-assisted melting). Melting can be enhanced by the lower albedo of some substrates (albedo-induced melting) [8]. Analysis of multi-year sets of ADV satellite images and aerial photographs allowed us to asses the spatial duration and longevity of snowbanks within South Fork. This revealed a concentration of perennial snowpacks within alcoves and alcove-like terraces and depressions along the margins of the northern edge of the Asgard Range alongside upper Wright Valley. On the basis of this we focused our research in this area, concentrating largely on two of the gully systems located there (Fig. 1); we report our observations and results here.

![Fig 1. The study region along the southern flanks of Upper Wright Valley, highlighting the two gullies investigated](image_url)
the upper part of the channel was cloudy, the sediment load was minimal and largely confined to bedload movement of sand-sized particles. Subsequent to the flow of water over the scarp, the water was lost in the coarse boulder deposits on the steepest and most inaccessible parts of the cliff.

**Upper Channel.** Along the steepest sections of the valley wall (<30º), 1 m high levees were present (Fig. 3). The channels in this section consist of meter scale angular boulders interspersed with sediment. Small snow banks were present amongst the boulders along the channel bed. No fluvial features were observed in the channel floor, though this may be a function of the coarse material in which the channel is eroded into, as any liquid water would flow through the large pore spaces without any significant alteration of the bed.

Fig 2. Photo and sketch highlighting the stream connecting the alcove snow patch to the main channel.

**Mid-Section of Channel.** In the intermediate parts of the slope, the channel cuts into slope colluvium, and displays many of the characteristics of martian gullies, including: v-shaped cross sections and secondary channels [1] (Fig. 4). Here the channels act as they do in the lower sections of the slope, as a trap for windblown snow which accumulates during the winter, forming snowpacks, tens of centimeters to meters thick (Fig. 5). During periods of peak insolation, melting occurs, with resulting intermittent surface flow. The surface runoff consists of low discharge events < 0.004 ms⁻¹, sufficient to erode cm scale fluvial features in the channel bed (Fig. 5). As is the situation with the streams, surface runoff is associated with a hyporheic zone. This is the area surrounding the stream in which moisture flows through the active layer in the downslope direction and exchanges with the surface runoff component [9].

Fig 3. Leveed upper channel. White arrow indicates the channel bed. Channel width is ~8 m.

Leveed channels are a common feature of many of the martian gully systems [1]. The levees in the ADV bear resemblance to lateral deposition of material as a result of water lubricated debris flows. This may provide an explanation for the origin of this portion of the gully which may have formed by the downslope movement of material above the ice table lubricated by an influx of water from the alcove above.

**Fig 4. Secondary Channels. View from the alcove down toward the valley floor.**

Despite the low discharge, the gully channel banks displayed relatively high erosion rates. Cracks 5 cm wide (Fig. 6) locally ran along the length of the main channel and as a result whole blocks of bank material (Fig. 6) were observed to fall into the channel. This is likely due in part to the melting of interstitial ice along channel banks and the removal of buttressing channel ice via melting and sublimation (Fig. 6). The added influence of wind-blown sand on the surface of the snowbanks in the channel aided the ablation of the snow through albedo-induced melting.
Lower Channel. In the lower sections of the valley the channel broadens and becomes shallower. The bed material is dominated by sand-sized sediment and as a result the hyporheic zone associated with runoff events was more apparent. In some areas water generated from the melting of snowbanks infiltrated into the channel bed sediment above the ice table and resurfaced several meters downslope (Fig. 7). Overall surface flow volumes from snowmelt were insufficient to produce continual surface flow connecting all the snow banks in the gully channel. Salt deposits were apparent in areas where the hyporheic zone had dried up and snow banks had ablated. These were up to several meters in length.

Terrace-like lobes ~10 cm high were a common feature throughout the lower half of the main channel. These consisted of small boulders (tens of cm in diameter) and sediment (Fig. 8). Such features appear to be caused by solifluction resulting from the action of liquid water within the hyporheic zone. The occurrence of these lobes indicates that the downslope movement of material in the vicinity of the channel takes place in association with surface runoff, thus demonstrating the potential of the hyporheic zone for geomorphological work.

Fans. In the more distal parts of the gully system toward the valley floor, the slope shallows and the steep colluvium gives way to a series of fans, which appear to be formed from sediment and reworked colluvium transported in the channel. Observing the fans from an upslope perspective revealed that the sediment appeared darker to the east indicating that more recent fan-building events have taken place in this direction. This observation is supported by the occurrence of an abandoned channel at the head of the fan and activity observed in an apparent younger channel diverging out in a westward direction. These
observations demonstrate how gully fans can also extend in a lateral direction over time.

The second gully system. This was located less than
~200 m to the west in a dark debris tongue (Ferrar
Dolerite) extending from a snow and ice-filled alcove
(Fig. 1, second gully), down to the valley floor; the
channel part of the gully system is most prominent in
the lower part of the tongue and in the valley below.
Channel and water activity in the second gully system
were clearly related to the melting of wind-blown
snow [11] that had accumulated in the protective
environment of the channels during austral winter. At
no time in December 2006-early January 2007 was
continuous surface flow observed from the alcove to
the snowbanks sources below. A significant amount of
water transport took place in the colluvium both
adjacent to the channel, and below it (in the hyporheic
zone) along the top of the ice table [11,12]. Melting of
snow patches sequestered in the channels was clearly
driven by favorable insolation/air temperature
conditions (insolation-induced melting). Albedo-
induced melting at all scales also influenced water
flow; 1) in individual snowbanks where sand had
blown on top of the snow, and 2) in the second gully
system, where lower-albedo dolerites clearly assisted
production of snowmelt relative to other gullies.

Summary: 1) These ADV gullies form from the
melting of annual/perennial surface snow and ice
accumulations; 2) Surface water flow in ADV gullies
and channels varies widely in occurrence and flux,
based on local environments and albedo, and daily,
intaseasonal and interannual variations in insolation; 3)
Flow in gully channels can be maintained beyond the
period of initial channel formation by topographic
trapping of windblown snow and its subsequent
melting [see 11], 4) The formation of the gully system
is a product of various geomorphic processes involving
varying amounts of water generated from snow melt.

Application to Mars and Assessment of
Snowpack Hypothesis: 1) These observations show
that surface snow and ice deposits in a variety of
microenvironments in the ADV serve as sources for
water channels and morphologies associated with the
formation and evolution of gully systems, even when
mean annual snow accumulation is minimal [8]; 2) In
contrast to the requirement for more ancient favorable
conditions for Mars gully formation proposed by [7],
these observations show that conditions for melting in
the ADV can occur on an annual basis and can
fluctuate over a wide range of time scales. Melting
does not need to be restricted to a specific obliquity
value as favorable insolation conditions could occur in
a variety of microenvironments, on a variety of
different time scales (e.g., day, season, year, etc.); 3)
Water derived from the melting of snow banks can
erode channels on slopes by a range of processes over
similar time scales [11-12]; 4) The ADV examples
show that complete snow cover [7] is not required;
wind-blown snow in a region of extremely low annual
precipitation is sufficient to form significant local
snowpack accumulations [8,11-12] and snow is likely
to form on Mars under a variety of conditions [e.g.,13-
14]. We thus conclude that the formation and melting
of snow provides a compelling interpretation for the
formation of gully systems on Mars [7], particularly in
light of the observations of gully-forming processes in
the ADV [8,11-12].

References: [1] M. Malin and K. Edgett, Science,
2002; [4] MEPAG SR-SAG, Astrobiology, 6, 677,
Dickson et al., Mars 7, this volume, 2007; [12] J.
Levy et al., Mars 7, this volume, 2007; [13] F. Forget et al.,
Science, 311, 368,2006; [14] J-B. Madeleine et al.,