

GULLY SURFACE AND SHALLOW SUBSURFACE STRUCTURE IN THE SOUTH FORK OF WRIGHT VALLEY, ANTARCTIC DRY VALLEYS: IMPLICATIONS FOR GULLY ACTIVITY ON MARS.
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Introduction: Gullies on Mars are a class of young features initially interpreted to have formed by flow of liquid water through groundwater discharge from underground aquifers [1,2], and are possibly still active [3]; numerous alternative explanations have been proposed [see summary in 4]. There is a rich literature on observations and candidate processes for gully formation on Mars [4], but most of the data that can be brought to bear on these issues is from orbiting sensors, and so cannot address the character of the terrain at extremely high resolution (cm-scale), and its shallow structure (the upper few meters). Although instruments currently in orbit (e.g., on MRO) will provide increased surface resolution, we are unlikely to obtain a comprehensive knowledge of the nature of the upper layers of the subsurface of gully terrain on Mars in the near future.

Terrestrial analogs to martian environments may provide insight into the processes operating on Mars, particularly at high horizontal and vertical resolution. We report on the results of ongoing field studies of gully systems in the Antarctic Dry Valleys (ADV), an extremely cold, hyperarid desert analog for Mars [5]. In the 2006-2007 austral summer field season we analyzed several gully systems in the South Fork of Upper Wright Valley [6-8] to address the questions: what is the three-dimensional structure of the shallow substrate where gullies form, what role does the ice table play, and what is relative role of deep groundwater and shallow active layer processes? The nature of gully systems in the ADV is described in [5-9]. Here we list a synthesis of the observations about the nature and three-dimensional aspects of the substrate in which they occur, and conclude with potential implications for Mars.

Synthesis of Observations in the South Fork ADV Gully Region: The subsurface structure of the gully terrain consists of continuous permafrost many tens of meters thick [5,8]; a dry active layer tens of cm thick is common, though locally a wet active layer is the norm in regions with elevated soil moisture. Colluvium consists of a range of mass wasting and fluvial deposits, many of which appear associated with gully formation and modification (alcove, channel, fans).

Polygons: Sand-wedge polygons [5] are present over virtually the entire surface of the region, except the steepest slopes at the top of the valley. Polygon centers are characterized by relatively flat, deflated boulder-and-cobble-covered surfaces; polygon troughs range

from cm to several tens of cm deep. Wedges commonly consist of coarse sands and pebbles, with minor, but variable amounts of cobbles and boulders. Polygon troughs play a significant role in the geomorphic evolution of the region. Together with the gully channels themselves [6-7] they serve as depressions to trap wind-blown snow in austral winter and serve as relatively porous conduits for the subsurface transport of trapped snowmelt in the austral summer. They are also topographic lows for the flow of surface meltwater in the austral summer, often serving as elements of small gully/channel systems; channels in larger gully systems often undergo "capture" along polygon troughs, following interconnected, local trough systems for portions of their lengths.

Seasonal Variations: During austral summer, portions of perennial snow and ice in alcoves and the seasonal windblown snow sequestered in polygon troughs and gully channels begin to melt, forming continuous gully streams, discontinuous flow activity in gully channels [6-7], and smaller scale gully systems (often initiated in snow-filled polygon troughs). During peak austral summer, liberated meltwater begins to flow downslope along the top of the ice table.

Water Transport in the Near Subsurface: The Hyporheic Zone: Evidence of recent water flow in gully channels at all scales consists of down-cut fluvial channels, channel sedimentary deposits (active and inactive), and the hyporheic zone (the wetted marginal and basal sediments through which some stream water passes) [7]. Progressive wetting and drying of the hyporheic zone often results in white salt deposits along stream margins.

As the hyporheic zone forms during surface flow advance in the channels, hyporheic zone pore water soaks into the substrate and descends, collecting at the top of the ice table (at depths of ~15-40 cm). Excavations show that the bottom part of the hyporheic zone at the top of the ice table can be saturated with pore water; even as the surface is becoming desiccated. The hyporheic zone thus represents an important part of the water transport system in gullies and channels [6-9], and stands in distinct contrast to deep underground aquifers associated with broader hydrologic cycles in less arid climate environments.

Qualitatively, it is clear from our observations and measurements that subsurface flow in the hyporheic zone is relatively more important in the early stages of melting, during short seasonal melting periods, and in situations where the water supply is rapidly depleted.

Once continuous surface flow is established [7], this rapidly becomes the most volumetrically significant water transport process. In the 2006-2007 austral summer field season in South Fork, continuous end-to-end channel flow was not observed, suggesting hyporheic zone and subsurface transport was the dominant transport mechanism during the study period.

Distal (downslope) hyporheic zones are very important in water transport and produced numerous examples of how the hyporheic zone transport system worked [7]. For example, when water flowing in channels at all scales reached sedimentary fans or porous polygon areas, a wave of surface dampening proceeded downslope. Excavations showed that water was soaking into the channel base, collecting along the top of the ice table, and moving downslope in the hyporheic zone along this interface. At slope breaks, water also flowed laterally, creating unusually wide hyporheic zones that extended tens of meters, producing widespread regions of extensive near-surface moisture. Water reappeared from numerous points in the form of small springs feeding micro-channels. Springs and seeps commonly occur on the down-slope side of boulders (Fig. 1).

Water Transport in the Near Subsurface: The Top of the Ice Table: A significant amount of water transport takes place at the very base of the hyporheic zone; the top of the ice table serves as an impermeable boundary for shallow water transport. Flow at the top of the ice table is evidenced by pit-wall collapse and water flow from the lower portions of the pit, at the top of the ice table.

Polygon trough location plays a key role in mediating water flow along the ice-table. On slopes, the downslope portion of polygons is commonly flattened out (low-slope) and surficially dampened. The region corresponds to locations with abundant, near-surface hyporheic flow; the latter gives rise to elevated rates of solifluction and to local downslope movement (see below). Capillary "wicking" onto partly buried cobbles and boulders is also common. In numerous places throughout the study area, surface wetting in distal portions of hyporheic zones was abundant enough to form broad dark streaks and dark patches visible in high-resolution orbital images (see [7], Fig. 1). Additional sources of water flowing above the ice cement surface include melting of near-surface ice from the thermal effects of melt water warmed during surface flow, and seasonally frozen hyporheic zone pore water mobilized during the subsequent spring and early summer.

Geomorphologic features related to channel and hyporheic zone water transport: Dampened, wetted and saturated hyporheic zones contain several features suggesting that this zone assisted in the movement of colluvium above the ice table. **a) Solifluction lobes:** Small fans that are saturated with water often display distal, downslope scarps, suggesting that the saturated

subsurface may cause small-scale mass movement of the hyporheic zone to produce solifluction lobes. **b) Deformed polygons:** In areas of surface dampening, polygon margins are often seen to be asymmetrical across troughs (flatter on the upslope side, slightly tilted downslope on the downslope side) suggesting surface flow/sliding of the active hyporheic zone. Some aligned boulders similar to stone stripes are observed in these regions. On other fans, polygon centers are shortened downslope, polygon trough intersections are deformed, and surficial trough orientations differ from wedge orientations frozen into the ice table, consistent with downslope movement.

Implications for Mars: The ADV examples illustrate that water in gully systems at all scales derived from melting of surface snow and ice can rapidly infiltrate the soil, travel along polygon troughs and along the top of the ice table (the hyporheic zone), and emerge as seeps and springs (Fig. 1). Features associated with the ADV gullies that could be diagnostic of the presence of shallow water transport on Mars include solifluction lobes, stone stripes, and deformed polygons. Salts are also preferentially deposited in the hyporheic zone and their presence in association with gullies on Mars could be evidence of the presence of water in gully formation. Spring and summer melting of ice sequestered in the hyporheic zone during the fall could also be an important source of continuing activity. The surface wetting formed by water in the distal hyporheic zone wicking to the surface forms albedo features visible from orbit and would be evidence of recent activity.



Fig. 1. Central part of a polygon below a gully channel whose meltwater water is soaking into the hyporheic zone, traveling along the top of the ice table, and reemerging locally in springs at boulders or other topographic prominences (see spring and ponded water at lower left of boulder).

References: [1] M. Malin and K. Edgett, *Science*, 288, 2330, 2000; [2] M. Malin and K. Edgett, *JGR*, 106, 23429, 2001; [3] M. Malin et al., *Science*, 314, 1573, 2006; [4] MEPAG SR-SAG, *Astrobiology*, 6, 677, 2006; [5] D. Marchant and J. Head, *Icarus*, in revision, 2007; [6] G. Morgan et al., *LPSC 38*, #1656, 2007; [7] J. Dickson et al., *LPSC 38*, #1678, 2007; [8] J. Head et al., *LPSC 38*, #1617, 2007; [9] D. McKnight et al., *BioScience*, 49, 985, 1999.