RAPID GROWTH AND DECAY OF MARS-ANALOG GULLIES IN BURIED ICE AND SEDIMENT-RICH SUBSTRATES: NEW VIEWS OF GULLIES AS DISEQUILIBRIUM LANDFORMS IN GARWOOD VALLEY, ANTARCTICA .

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Introduction. The McMurdo Dry Valleys of Antarctica are a key location for documenting the physical processes associated with Mars-analog gully formation under cold, polar desert environmental conditions [1-2]. Mars-like attributes of Antarctic gullies include ephemeral and sporadic flow associated with peak insolation, top-down melting of surface snow and shallow ground ice, and bounding of gully hydrological processes by underlying ice-cemented permafrost [1,3]. Like martian gullies, Dry Valleys gullies are thought to form through sediment transport by fluvial/alluvial processes, punctuated by debris-flows [1, 4-6].

Gullies and Buried Ice on Mars. Recent HiRISE observations have raised the intriguing possibility that many martian gullies formed directly in the latitude dependent mantle (LDM)—a geologically recent, surface deposit on Mars composed primarily of ice admixed with internal and surficial (lag) sediments [7-8, 15]. Key observations supporting this hypothesis are the erosion of gully channels into LDM-surfaced slopes and the preservation of remnant gully fans (not associated with a visible channel) at low latitudes in locations where the LDM has become dissected (depleted in ice) [8]. These results suggest that buried, debris-bearing ice, rather than regolith or bedrock, may be the primary substrate in which many gullies form on Mars.

Concurrent with these observations, analyses of ten southern hemisphere gully sites showing evidence of seasonal change suggest that "dry" (CO_2-dominated or volatile-free) geomorphic processes are at work in some modern gully environments [13]. These sites show modification of gully channels and fans that occur during the winter season on Mars, during which water ice melt or water-based brine flow is not expected to be an active geomorphic process.

Gullies and Buried Ice in Antarctica. Buried or debris-covered glacial ice is common in the McMurdo Dry Valleys, Antarctica [9, 16]. However, much of this massive ground ice is present in the Upland Stable Zone (e.g., Beacon Valley), where ground ice melting does not occur [2]. Garwood Valley, one of the southern, coastal Dry Valleys (78ºS, 164ºE) provides a unique terrestrial analog for studying the rates and mechanisms of gully formation in massive, debris-bearing, buried ice deposits (Figs. 1-2). Intriguingly, Garwood Valley gullies are modified by both "wet" (meltwater-related) geomorphic processes (during summer months) and "dry" (volatile-free) geomorphic processes (during winter months).

In Garwood Valley, a reentrant lobe of the West Antarctic Ice Sheet/Ross Ice Shelf was stranded at the close of the last glacial maximum (LGM), ~6-12 ky before present [10]. The LGM ice lobe fills the middle and lower portions of the valley and is surfaced by a silt-sand drift that is capped by a cobble and boulder desert pavement. The valley is drained by the glacier-fed Garwood River, which produced a closed-basin lake delta complex in the valley during LGM time [14], burying a mass of ice sheet ice. River-initiated incision into the buried ice produces a 15-20 m tall "ice cliff" composed of glacier ice interbedded with sediment-rich river ice lenses, and capped by sandy drift and ice-cemented fluvio-deltaic sediments.

Gullies, consisting of a recessed alcove, sinuous channels, and a sedimentary fan or apron [11] have formed in this unusual sediment-capped ice deposit. Field observations of Garwood gullies during 2009 and 2010 indicate that the gullies support sediment transport through wet debris flows, fluvial sedimentation and erosion, and dry granular flows, depending on sediment availability (spatially variable) and water availability (seasonally variable).

Direct insolation on the steep ice surface results in melt generation and runoff over the ice surface during the austral summer. Alcoves form in the ice during this insolation-driven melting, resulting in undercutting of the overlying sediments. Periodic collapse of the mantling sediments results in the introduction of sediment into the gully, which is transported downslope through sinuous channels to sand-dominated fans. Like many martian gully fans, these Garwood gully fans show evidence of fluvial reworking [12].

Garwood Valley gullies represent an extreme case of rapid landscape change in response to a strong disequilibrium between ground ice and surface temperature and humidity conditions. During peak summer, several cm (up to 10 cm) of ablation (backwasting) can occur per day in the gully alcoves as measured by a sonic ranger. Repeat LiDAR scans conducted in twice-yearly since November, 2009 provide a year-to-year measure of gully alcove erosion and fan aggradation volumes over annual timescales. Rapid ice removal, coupled with a limited sediment supply, may result in the eventual destruction of the Garwood buried ice gullies, leaving only modified, channel-less, remnant sediment fans as evidence of past activity. A LiDAR time-series of ice-based gully growth and decay can be found online at: http://web.pdx.edu/~pdx06058/cliff.gif The time-series shows a top-down view of gullies along the ice cluff (Fig. 1), with alcoves that grow, and back-waste to produce an alcove-free slope with fans at its base.

On shorter timescales, the cessation of flow during winter, coupled with erosive katabatic winds, was found to result in the geomorphic muting of gullies (driven primarily by dry debris avalanche emplacement) to the extent that they resembled ungullied slopes prior to flow reactivation (Fig. 2). A LiDAR time-series of gully decay by dry mass wasting can be found online at: http://web.pdx.edu/~pdx06058/gullies.gif . Notable lobes of dry gravel flows prominently overprint the fluvially-emplaced summer fan.

Conclusions. Garwood Valley, Antarctica, is a type locality for studying cold desert gully development in a buried ice substrate where ground-ice melt drives gully growth. It is also an ideal laboratory for studying dry mass-wasting processes that modify and degrade gullies. Gully alcove development can occur rapidly—on annual, or even seasonal timescales—when ice, rather than sediment or bedrock, is the primary eroded material. Ice melt and sublimation are the major drivers of alcove growth for gullies forming in buried ice substrates, rather than fluvial transport of sedimentary material. Removal and transport of overlying or englacial sediment results in the formation of well-preserved, fluvially modified fans, and fluvial-carved channels. Dry mass-wasting can modify gullies by transporting sediment through gully channels, or draping fan deposits, suggesting that both "wet" and a "dry" geomorphic agents can affect gullies in a single microclimatic zone.

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Fig. 1. Gullies forming in a buried ice substrate in Garwood Valley, McMurdo Dry Valleys, Antarctica. Note ~1.5 m tall surveying tripod to upper left for scale. Gullies consist of a recessed alcove (eroded from nearly pure glacier ice), sinuous channels, and sedimentary fans or aprons.

Fig. 2. (Above) Gullies forming as buried ice mobilizes overlying fluvio-deltaic sediments during January, 2010. (Below) The same hillslope in December, 2010, prior to the onset of summertime melting. Bright pixels are locations of outcropping buried glacier ice.