

## THE USE OF EQUILIBRIUM LANDFORMS TO IDENTIFY RECENT CLIMATE CHANGE ON MARS: INSIGHTS FROM FIELD STUDIES IN THE MCMURDO DRY VALLEYS OF ANTARCTICA.

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**Introduction:** The recognition of groups of terrestrial climate-related landforms has led to the definition of different morphogenetic regions [e.g., 1-2] which have been classified in terms of both mean annual temperature and precipitation. Marchant and Head (2007) [3] used this approach to classify the McMurdo Dry Valleys of Antarctica (ADV) into three separate microclimate zones based on groups of distinct equilibrium landforms which are in balance with local environmental conditions. Through the morphological mapping of the ADV, they were able to discern past and/or ongoing shifts in climate zonation from the identification of landforms that today appear in disequilibrium with local microclimate conditions [3]. The ADV are a hyperarid, cold polar desert in which sublimation exceeds precipitation [3] and has thus long been held to provide one of the closest terrestrial analogs for current Martian conditions [4-5]. Hence the methodology applied by [3] provides a framework from which to assess the climate history of Mars.

Here we report on our morphological investigations of an unnamed martian crater depression located at 40°S, 5°E. The site exhibits a multitude of ice-associated landforms of various scales and has a high degree of data coverage from all of the Mars orbital instruments. Hence, it is an excellent site in which to apply the methodology of [3] in order to gain insights into both the local and global climate histories of Mars. To aid our interpretation of the martian landforms, we draw upon fieldwork conducted in the ADV during the austral summers of 2006-7 and 2008-9.

**Antarctic Dry Valleys:** Fieldwork was carried out in the different microclimate zones in order to locate and identify landforms both active and relict that are morphologically similar to those in the Mars study site.

**Upland Stable Zone** [3]: In Beacon Valley, relatively small-scale glaciers form on steep walls as plateau ice collapses as shown in Fig. 1. Rock-fall debris is also supplied to the surface of the glacier from intervening cliffs. Ice-cored moraines fringe the present ice margin. Beyond these moraines are ice-cored lobes, which presumably represent downslope flow of older (distal) ice-cored moraines.

**Inland Mixed Zone** [3]: A 7+ km long debris-covered viscous-flow tongue occupies a major trough in the South Fork of Upper Wright Valley (Fig. 2). The snout of the tongue exhibits a convex up profile which levels off around ~20 m above the valley floor. The lack of a steep terminus and its convex-up cross sec-

tional profile argues that the lobe is currently inactive (i.e. it has experienced viscous relaxation [6]) Seismic surveys found no distinct evidence of concentrated ice, but instead suggest the interior consists of interstitial ice within pore spaces [6]. Shallow excavations throughout the surface of the tongue show that the top of the ice cement (ice table) occur at ~30 cm.

Gully systems are located along the warmer, southern wall of South Fork (i.e. where it receives more direct insolation, hence more melting). Several gullies exhibit fans that bury portions of the tongue itself, in a similar fashion to those of the martian tongue examined in the study area (see below and Fig. 2). Large-scale channel systems are also present along the center of the lobe.

**Mars: Moat Crater in Noachis Terra:** The martian study site, located in an 80-km wide degraded crater in Noachis Terra, reveals several landforms whose morphology and areal distribution closely match those described above for portions of the ADV. In detail, the martian site consists of deep valleys (>3 km) with steep walls (>30°) forming an annulus within the degraded crater. The formation of the valleys themselves has been attributed to the excavation of material that fills the crater basin [7]. A discrete stratigraphic layer is identifiable near the upper portions of the valley walls, as observed in MOC and HIRISE imagery and the THEMIS nighttime infrared data, where it appears relatively bright with a high thermal inertia. This layer appears to be actively breaking up, providing a source of scree and large boulders (> 5 meters) to the lower slopes. In some sections this cliffed layer forms an overhang, indicating that it is more resistant than lower portions of the slopes. The latitude dependent mantle [8] is present throughout the study region and appears as a distinct layer at the summit of the slopes, above the rock layer. The mantle layer has been directly measured to the order of tens of meters.

**Geomorphic Evidence for Water and Ice:** *Gullies*, which were first documented by [9] are present along almost every slope in the study area (Fig.2), though morphologic details vary with slope aspect [10].

*Lobate Debris Tongues (LDT)*, first identified by [11] are found emanating from many of the slopes and form distinct convex up snouts on the valley floors (Fig 2-3). They are distinguishable from Lobate debris aprons (LDA) found elsewhere on Mars [e.g. 12] in

that they are an order of magnitude smaller and do not have a 'brain terrain' texture along their surface.

**Small-Scale Geomorphic Evidence for Ice:** The rich coverage of high-resolution data sets (HRSC, MOC, CTX and HiRISE) for the study site has enabled the identification of small scale (i.e. ~ m sized) landforms. These include: *Polygons/patterned ground* and *Boulders surrounded by moats*, the latter of which could have formed by the sublimation of near surface ice due to the thermal inertia properties of the rock.

**Geomorphic Interpretation of Martian Deposits and Interpretation of Local Climate History:** The smallest-scale landforms on Mars superimpose the majority of surfaces in the study area, and thus are interpreted to be the youngest features [13]. The polygons and boulder moats may have formed in the most recent layers of ice-rich mantle, <1 Ma [8].

In a manner similar to the situation in the ADV, some of the gullies on slopes in Noachis Terra drain into, and appear to cut across LDT (Fig. 2). The occurrence of gully fans that in-fill and cut across troughs along the periphery of lobes argues that gullies are the youngest part of the system. Modeling has shown that these gullies are unlikely to be active now [10], with equator-facing gullies thought to have been last active prior to 2.5 Ma ago [10]; hence the LDT is likely >2.5 Ma. Elsewhere, other glacial features on Mars have been dated from a few million years [14] to hundreds of million of years [12]. The lack of any craters >100m on the surface of the LDT, and the general preservation of the LDT, suggest they are closer to the younger of these two ages.

The alpine glacial system in Beacon Valley (Fig. 1) may provide a reasonable analog for development of the Mars LDT. The plateau ice field in Beacon Valley, which represents the source for ice in the alpine glacier below (Fig. 1), might be a reasonable equivalent of the latitude dependent mantle. In addition, the LDT in Fig. 3 shows an arcuate ridge (3.d) that is similar in morphology and position to moraines surrounding glacial ice in Beacon (Fig. 1). On the basis of these morphologic comparisons, we interpret the arcuate ridge features as moraines, representing changes in the extent of the LDT.

**Conclusions:** Detailed mapping in the ADV yields terrestrial analogs for the origin of LDT in Noachis Terra (i.e., upper Beacon Valley; Fig. 1), and subsequent modification of LDT and gully incision (i.e., present-day South Fork, Wright Valley; Fig. 2). The morphologic change is best explained as a shift in martian climate, from one compatible with excess snowfall, and formation and calving of the latitude dependent mantle, to one incompatible with excess snowfall and glaciation, but rather consistent with minor snowmelt and gully formation. Available dating suggests

that the climate transition occurred sometime within the last few million years.

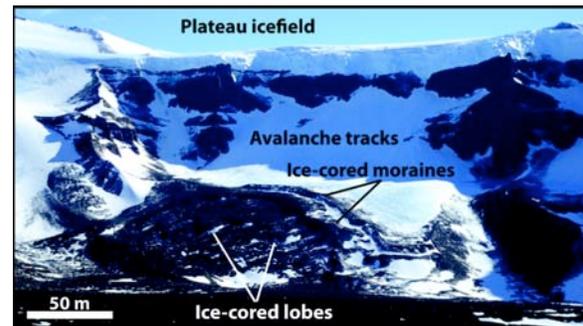


Fig 1. Alpine glacier, ice-cored moraines, and ice-cored lobes in upper Beacon Valley

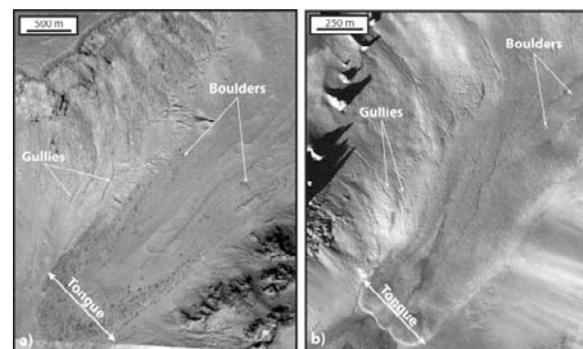


Fig 2. LDT on Mars (a) and ADV (b)

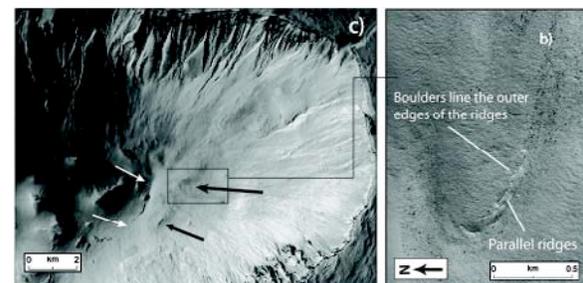


Fig 3. LDT in study area (c). Black arrows represent the inferred direction of flow. The white arrows highlight the terminus of the lobe. d) is a zoomed in perspective of the arcuate ridge on the surface of the LDT.

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