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Gully formation on Mars: Two recent phases of formation suggested by links between morphology, slope orientation and insolation history

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ABSTRACT

The unusual 80 km diameter Noachian-aged Asimov crater in Noachis Terra (46°S, 5°E) is characterized by extensive Noachian–Hesperian crater fill and a younger superposed annulus of valleys encircling the margins of the crater floor. These valleys provide an opportunity to study the relationships of gully geomorphology as a function of changing slope orientation relative to solar insolation. We found that the level of development of gullies was highly correlated with slope orientation and solar insolation. The largest and most complex gully systems, with the most well-developed fluvial landforms, are restricted to pole-facing slopes. In contrast, gullies on equator-facing slopes are smaller, more poorly developed and integrated, more highly degraded, and contain more impact craters. We used a 1D version of the Laboratoire de Météorologie Dynamique GCM, and slope geometries (orientation and angle), driven by predicted spin-axis/orbital parameter history, to assess the distribution and history of surface temperatures in these valleys during recent geological history. Surface temperatures on pole-facing slopes preferential for water ice accumulation and subsequent melting are predicted to occur as recently as 0.5–2.1 Ma, which is consistent with age estimates of gully activity elsewhere on Mars. In contrast, the 1D model predicts that water ice cannot accumulate on equator-facing slopes until obliquities exceed 45°, suggesting they are unlikely to have been active over the last 5 Ma. The correlation of the temperature predictions and the geological evidence for age differences suggests that there were two phases of gully formation in the last few million years: an older phase in which top-down melting occurred on equator-facing slopes and a younger more robust phase on pole-facing slopes. The similarities of small-scale fluvial erosion features seen in the gullies on Mars and those observed in gullies cut by seasonal and perennial snowmelt in the Antarctic Dry Valleys supports a top-down melting origin for these gullies on Mars.

1. Introduction

The discovery of gullies on Mars attracted significant attention because of the inferred role of liquid water in carving apparently modern landscapes (Malin and Edgett, 2000a). Gullies were initially interpreted to be the result of groundwater discharge (Malin and Edgett, 2000a; Heldmann and Mellon, 2004; Heldmann et al., 2005). Further analysis of the current metastability of liquid water on the surface of Mars generated alternative explanations, including atmospherically deposited sources of water (Costard et al., 2002; Hecht, 2002; Christensen, 2003; Dickson et al., 2007a; Head et al., 2008; Williams et al., 2009). Global surveys have demonstrated that gullies are limited to latitudes >30° (Malin and Edgett, 2000a) and that they have a preference for pole-facing orientations below about 45° latitude (Costard et al., 2002; Heldmann and Mellon, 2004; Dickson et al., 2007a; Dickson and Head, 2009).

Costard et al. (2002) used a one-dimensional version of the atmospheric Laboratoire de Météorologie Dynamique (LMD) GCM (Forget et al., 1999) to demonstrate that ice accumulation and near-surface melting of ground ice could account for this spatial distribution. Their mechanism involved the accumulation of near-surface water ice on pole-facing slopes and its preservation due to the low surface temperature maintained by a seasonal CO_2 frost cover. Springtime removal of the CO_2 frost, and the subsequent rapid heating of the underlying water ice, was invoked as a means of melting water ice, flow initiation, and subsequent gully formation.

Recent high-resolution studies of individual gully sites have revealed a wide range in gully morphology. Evidence for different forms of erosion are present, ranging from wet debris flows (e.g., Levy et al., 2010) to fluvial stream flow incision (e.g., McEwen et al., 2007; Head et al., 2008). The latter being associated with the occurrence of fine-scale channel forms such as streamlined islands, braiding and terraces (McEwen et al., 2007). This suggests that varying ratios of water and sediment have eroded gullies on

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