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Note

Keys to gully formation processes on Mars: Relation to climate cycles and sources of meltwater

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ABSTRACT

Advances in dating gullies on Mars using superposition relationships and a stratigraphic marker horizon link gully chronostratigraphy to recent climate cycles. New observations of gully morphology show the close association of gully source regions, channels, and fan deposits with well-documented ice-rich latitude-dependent mantle deposits, the deposition of which is interpreted to be coincident with recent ice ages. On the basis of these close correlations, we interpret the formative processes for mid-latitude gullies to involve melting of these ice-rich mantling deposits and the generation of an aqueous phase leading to fluvial activity. Continued monitoring of gullies by spacecraft in the current "interglacial" climate period (~0.4 Ma to the present) will permit assessment of changing rates and styles of gully activity in the now largely depleted source areas.

1. Introduction

Originally discovered in images taken by the Mars Orbiter Camera, gullies on Mars were initially hypothesized to be the result of groundwater outbursts (Malin and Edgett, 2000). Additional hypotheses proposed alternative sources of water to carve gullies (e.g., ground ice; Costard et al., 2002; "pasted-on" terrain; Christensen, 2003), as well as entirely dry mechanisms for their formation (e.g., Shinbrot et al., 2004). The global distribution of gullies (Dickson et al., 2007; Dickson and Head, 2009), specific geologic studies (Christensen, 2003; Schon et al., 2009a; Levy et al., 2010; Morgan et al., 2010), terrestrial analog studies (Arfstrom and Hartmann, 2005; Head et al., 2007) and modeling efforts (Costard et al., 2002; Williams et al., 2009) favor variations of a meltwater scenario (e.g., Head et al., 2008) for the formation of gullies. New very high-resolution (sub-meter) image data from HiRISE provide striking details of gully characteristics and led McEwen et al. (2007) to report "evidence of fluvial modification of geologically recent mid-latitude gullies." With these studies supporting a prominent role for water in forming martian gullies, ongoing research efforts are focused on (1) constraining the timing of gully formation (Reiss et al., 2004, 2010; Malin et al., 2006; Schon et al., 2009a; Dundas et al., 2010), (2) investigating specific formation processes (e.g., Pelletier et al., 2008; Kolb et al., 2010a; Levy et al., 2010), (3) exploring linkages between gully processes and inferred climate cycles (Mustard et al., 2001; Head et al., 2003; Laskar et al., 2004; Schorghofer, 2007), and (4) determining candidate sources for meltwater (e.g., groundwater, ground ice, perennial ice, snow, and older glacial deposits) that may have been involved in fluvial activity (Head et al., 2003, 2007). Here we outline how new and recent observations address these questions by considering gullies in chronostratigraphic context and by demonstrating a close association between gully formation processes and meltwater derived from recent (<5 Ma) ice age deposits.

2. Dating gully formation

At the time of their discovery gullies were recognized as "geologically young" owing to a conspicuous absence of superposed impact craters or degraded morphologies (Malin and Edgett, 2000). Likewise, Malin and Edgett (2000) also describe in their report "other properties that similarly suggest relative youth, including superposition of aprons on eolian bedforms in Nirgal Vallis, superposition on polygonally patterned ground and the absence of rejuvenated polygons."

It was difficult to advance beyond this basis of gullies as "geologically young" because conventional techniques of calculating crater retention ages for planetary surfaces are not robust on the limited areas and high slopes of gully environments. Reiss et al. (2004) were the first to date gully development using a superposition relationship. Depositional fans from gullies in the pole-facing wall superpose the transverse dune population in Nirgal Vallis, which they report to have a crater retention age of 300,000 years to 1.4 Myr (Fig. 1). Reiss et al. (2004) concluded, "The last phase of more than 30°-obliquity at around 400,000 years [Laskar et al., 2004] correlates with the best fit model ages around 300,000 years for dune activity…Therefore gullies must have been formed after the last active phase of the dunes and are younger than 3 Myr, possibly less than 300,000 years."

In eastern Promethei Terra, Schon et al. (2009a) identified a well-developed gully system in a crater wall that they were able to date using a novel technique utilizing the emplacement of a secondary crater population as a chronostratigraphic marker. By identifying and dating the rayed source crater of these secondary craters (Fig. 1) Schon et al. (2009a) showed, "Multiple lobes that post-date the secondary crater population make the emplacement date [0.6–2.4 Ma; best fit: 1.25 Ma] of the secondary craters a robust maximum age for the youngest lobes of this fan, and therefore the most recent activity of the gully system." Schon et al. (2009a) concluded, "The presence of multiple superposing crater-free lobes [of the depositional fan] requires several episodes of gully activity postdating emplacement of the secondary craters. Therefore, the emplacement of the secondaries provides a firm maximum age on the most recent activity of this gully system" (Figs. 1 and 2).

The concurring observations of both Reiss et al. (2004) and Schon et al. (2009a) are interpreted similarly with respect to recent obliquity-driven (Laskar et al., 2004) climate cycles (Fig. 1) and can be linked to the climate conditions that are thought to have prevailed at that time. Specifically, on the basis of a wide variety of evidence, the period of enhanced obliquity from ~0.4 to 2.1 Ma (Fig. 1) has been interpreted to represent a "glacial" period or "ice age" during which ice-rich layers were deposited from about 30° north and south latitudes to the poles in the form of a many meters-thick mantle (e.g., Head et al., 2003; discussed further below). In the current period of lower amplitude obliquity variations (Fig. 1), the latitude-dependent mantle is undergoing degradation in lower latitude portions (~30–50°N and S

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