Unique chronostratigraphic marker in depositional fan stratigraphy on Mars: Evidence for ca. 1.25 Ma gully activity and surficial meltwater origin

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ABSTRACT

The origin of gullies on Mars is controversial (e.g., catastrophic groundwater release, debris flows, dry granular flows, or meltwater from surface ice and snow) and their ages are difficult to determine due to their small size. We describe a gully depositional fan that contains a unique chronostratigraphic marker (secondary crater clusters) between episodes of gully activity during fan development. This marker can be traced to its source, a 7-km-diameter rayed crater that we have dated as ca. 1.25 Ma. This age links gully activity to the emplacement of dust-ice mantling deposits interpreted to represent recent ice ages on Mars. This association, together with multiple episodes of depositional fan formation, favors an origin for these gullies from top-down melting of snow and ice during multiple favorable spin-axis and orbital variations. This melting mechanism is consistent with the occurrence of gullies in unique steep-sloped, poleward-facing insolation microenvironments that favor the melting of small amounts of surficial snow and ice.

INTRODUCTION

Martian gullies were defined by Malin and Edgett (2000) as geomorphic features having alcoves that taper into channels that continue downslope to triangular aprons of deposited material. They interpreted these features as consistent with fluvial erosion and proposed that groundwater release from confined aquifers was responsible for gully formation, a hypothesis further developed by Heldmann and Mellon (2004) and Heldmann et al. (2007). Many studies subsequent to Malin and Edgett (2000) have identified additional examples of gully morphology and have further characterized the geographic distribution of gullies in the middle and high latitudes of both hemispheres and their geologic settings on crater and valley walls, mesas, central peaks, and exterior crater rims (e.g., Balme et al., 2006; Dickson et al., 2007).

Since their discovery, a variety of formation hypotheses has been proposed to explain the diversity of gully observations. These hypotheses can be divided into three broad categories: entirely dry mechanisms (e.g., Treiman, 2003; Shinbrot et al., 2004), wet mechanisms invoking groundwater release (e.g., Malin and Edgett, 2000; Mellon and Phillips, 2001; Heldmann and Mellon, 2004), and wet mechanisms invoking surficial meltwater (e.g., Costard et al., 2002; Christensen, 2003; Head et al., 2008). It has been difficult to differentiate between these hypotheses and test their validity using past observations (e.g., Pelletier et al., 2008). Also uncertain is the age of Mars gullies and thus their specific link to recent climate history. Although they appear to have formed contemporaneously with latitude-dependent mantling deposits thought to have been emplaced during recent "ice ages" (e.g., Mustard et al., 2001; Head et al., 2003; Milliken et al., 2003; Reiss et al., 2004; Kostama et al., 2006), the area of individual gullies is too small to obtain reliable ages using crater size-frequency distributions.

In this study we document evidence of a gully system (Fig. 1) that contains secondary craters within its depositional fan that can be traced back to the primary crater, which can be reliably dated, thereby providing a chronostratigraphic marker for an intermediate stage of gully development. Stratigraphic relationships in the depositional fan of this gully system suggest (1) multiple episodes of alluvial fan-style deposition, (2) very recent depositional activity that is younger than a newly recognized rayed crater that is the source of the secondary craters, (3) temporal links to the recent climate history, and (4) surficial snowmelt as the most likely source of these multiple episodes of recent gully activity.

GULLY FAN STRATIGRAPHY

In eastern Promethei Terra (~35°S, 131°E), there is an ~5-km-diameter crater with a single well-developed gully system (Fig. 1) and several smaller gullies in its north-northeast wall. The smaller gullies lack discernible alcoves (i.e., they are channel fan assemblages), their incision is limited to the surficial mantling deposit (Mustard et al., 2001; Head et al., 2003; Milliken et al., 2003), and their fans clearly superpose the crater-fill floor material. In contrast, the large gully system (composed of a small western gully and larger eastern gully) shows evidence for incision into the crater wall and has multiple contributory subalcoves and channels (Fig. 1). The low-slope depositional fan associated with this gully system is significantly larger than the others and is bounded on its western margin by a small arcuate ridge. Depressions with similar bounding ridges are commonly observed in this latitude band (~30–50°S) in association with deeply incised gully alcoves that are interpreted as the accumulation zones for cirque-like glacial systems (Head et al., 2008). Therefore, the ridge is likely a moraine-like structure bounding a glacially-formed depression into which the fan is deposited, analogous to similar stratigraphic relations described by Hartmann et al. (2003), Berman et al. (2005), and Head et al. (2008).

The gully fan is composed of multiple lobes with distinct lobe contacts, incised channels, and channel fill deposits, all features similar to those observed in terrestrial alluvial fans, i.e., cone-shaped deposits of fluvially transported sediments that accumulate at distinct breaks in slope (Blissenbach, 1954; Blair and McPherson, 1994). Secondary craters (~1–25 m diameter) are pervasive in the vicinity of the gully, but only a portion of the fan has superposed secondaries, implying that at least some portions of the depositional fan were deposited both before and after the emplacement of the secondaries. The individual depositional lobes of the fan can be divided into two groups (Fig. 2): a lobe that predates the secondary crater population (1) and younger lobes (2–4), distinguished by stratigraphic contacts and crosscutting relationships, that are superposed on the lobe with secondary craters. These multiple lobes that postdate the secondary crater population make the emplacement date 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. We now

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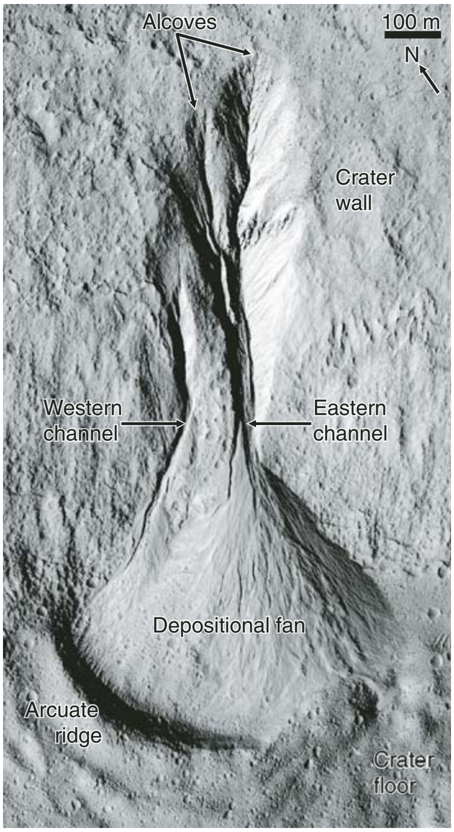

Figure 1. Eastern Promethei Terra crater wall gully system. Tiered alcoves contribute to eastern and western channels feeding the depositional fan complex. Distinct lobes provide evidence for multiple episodes of gully activity (HiRISE: PSP_002293_1450).

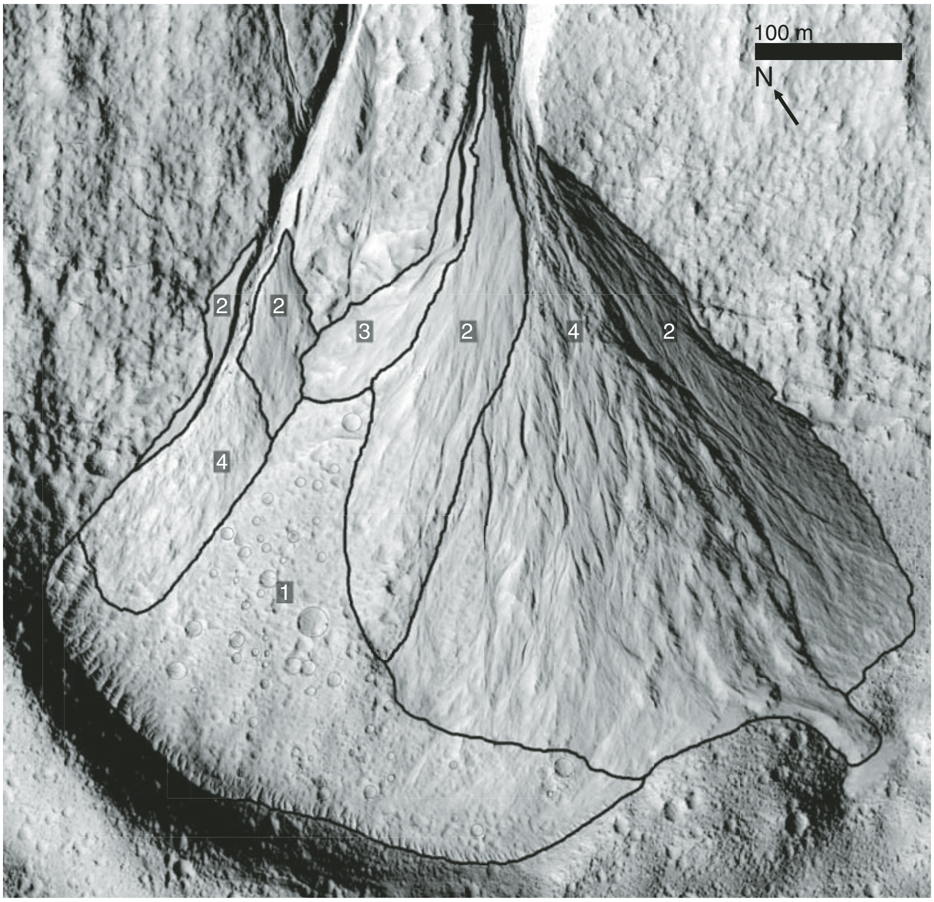

Figure 2. Sketch map of gully system depositional fan. The depositional fan is composed of six visible lobes. Lobe 1 is oldest visible lobe and retains dense population of secondary craters. Superposing uncratered lobes (2–4) postdate emplacement of secondary craters and require episodes of more recent gully activity (HiRISE: PSP_002293_1450).

explore the source of the secondary craters to assess the age of this chronostratigraphic marker in the history of gully activity.

NEARBY RAYED CRATER SOURCE OF SECONDARY CRATERS

Regional reconnaissance was undertaken to determine the origin of the secondary craters utilizing the orientation of the crater clusters and cluster patterns. This search led to the discovery of a previously unidentified rayed crater complex (Fig. 3A) consisting of two superposed very fresh craters, an ~18-km-diameter outer crater and an ~7-km-diameter inner crater located at ~35°7′S, 129°4′E, ~100 km southwest of the gully system. Distinctive rays are observed in THEMIS (Thermal Emission Imaging System) nighttime thermal infrared data (Fig. 3A), but are not observable as albedo contrasts in visible data, consistent with other identifications of young rayed craters on Mars (McEwen et al., 2005; Tornabene et al., 2006). This crater complex is also located in a similar thermophysical setting to previously identified rayed craters, i.e., intermediate albedo and thermal inertia, implying an intermediate dust cover (Mellon et al., 2000).

The morphology of these two impact craters that are candidates for the source of the secondary craters at the gully site reveals their relative states of degradation and modification, and thus which is the most likely candidate for the gully-related secondaries. Both the outer and inner craters have classically defined gullies, preferentially developed within their pole-facing walls. The inner crater gullies have branched subalcoves with intervening sharp spur-like ridges. The channel and alcove walls are smooth and are predominately unconsolidated sediment except where distinct bedrock outcrops occur. The equator-facing wall is a uniform slope of fine-grained material that has formed landslide deposits in several locations and is steeper (~29° versus ~20°) than the gully fans. Neither the inner crater gullies of the pole-facing wall nor the equator-facing wall are blanketed by latitude-dependent mantling deposits, suggesting that this crater is younger than the most recent episode of latitude-dependent ice-rich mantle deposition at this latitude (Head et al., 2003). The inner crater floor contains a small collection of dunes and landslide materials, but no sublimation features are observed that would indicate glacial modification (Kreslavsky and Head, 2006).

In contrast, morphological observations of the outer crater suggest that it predates deposition of latitude-dependent mantling deposits that would obscure fresh crater rays. Mantling deposits are observed on the rim and walls of the crater, while polygonally patterned ground, indicative of an icy substrate and extended thermal cycling, is observed in gully alcoves (Mangold, 2005; Levy et al., 2009). Furthermore, the outer crater also has a lower depth:diameter ratio (0.07) than the inner crater (0.12), and the walls of the outer crater are of lower slope and have greater asymmetry compared to the inner crater, indicative of more extensive modification (Garvin et al., 2003; Kreslavsky and Head, 2006). Mapping of the rays also shows that their radial distribution is focused within the inner crater, which is offset from the outer crater.

Therefore, we interpret the inner crater as the source of the rays and secondary craters of interest, and younger than the most recent episode of latitude-dependent mantling deposition at this low latitude. Our morphological observations suggest that the outer crater predates the end of an

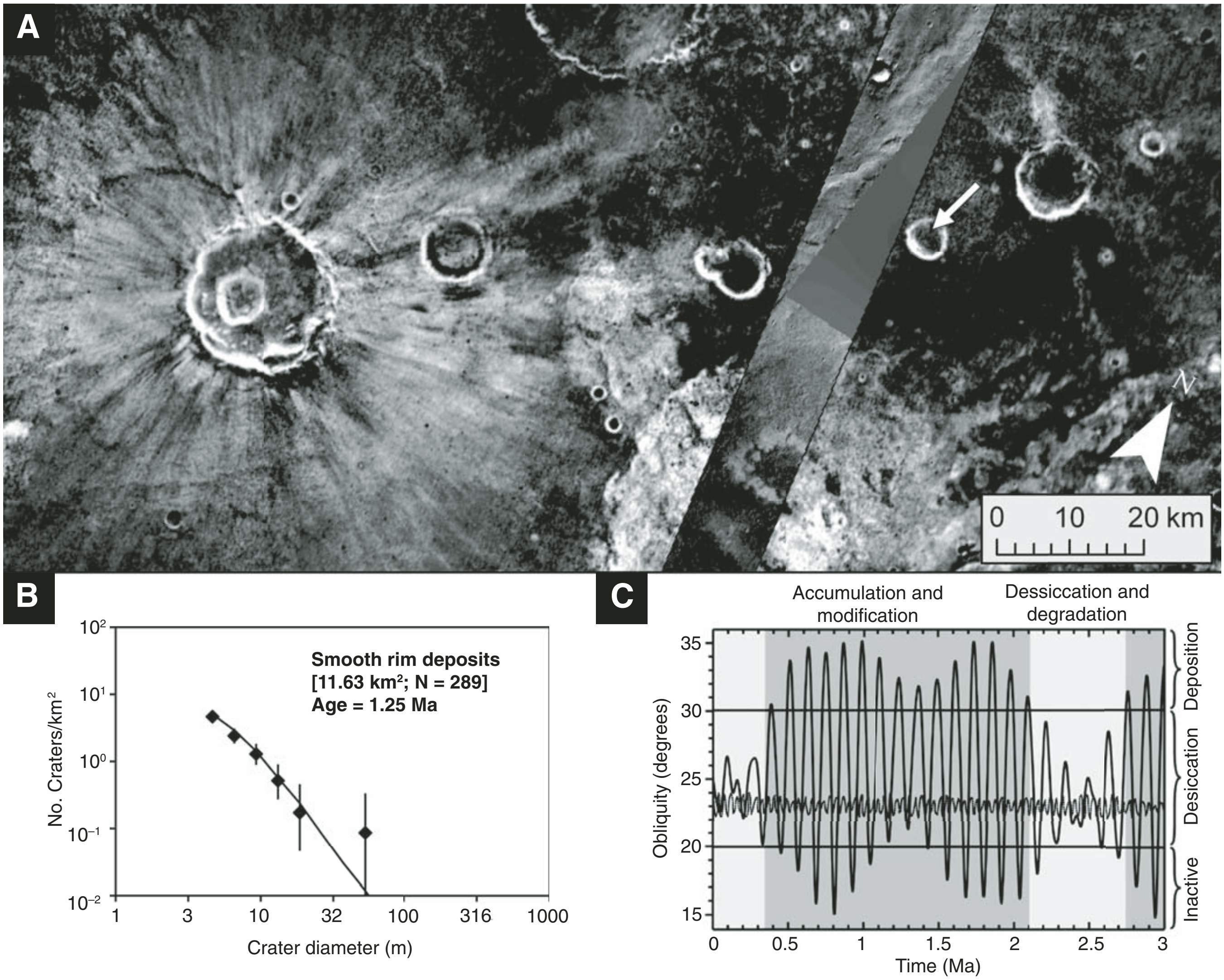

Figure 3. Eastern Promethei Terra (35°25′S, 130°25′E). A: THEMIS (Thermal Emission Imaging System) nighttime thermal infrared images show a pattern of fresh rays emanating from the ~7-km-diameter inner crater. The crater containing fan deposits (Figs. 1 and 2) is highlighted with white arrow. B: Crater counts displayed on incremental size-frequency plot of smooth near-rim deposits of the inner crater yield a crater retention age of ca. 1.25 Ma, placing formation of this crater in a period of obliquity-controlled mantle accumulation and modification. C: Mars obliquity variations (Laskar et al., 2002) over the past 3 Ma, with periods of mantle accumulation and modification (dark gray) and desiccation and degradation (light gray) indicated. Low-amplitude line between 22° and 24° is the obliquity range of Earth (after Head et al., 2003).

obliquity-controlled period of latitude-dependent mantle deposition, while the inner crater appears to postdate the most recent period of mantle deposition (Head et al., 2003). To test this proposition quantitatively, we performed crater counts on smooth near-rim units of the inner crater. These units north and south of the inner crater both yield crater retention ages of ca. 1.25 Ma (Fig. 3B), based upon isochrons of Hartmann (2005). Some uncertainty exists in the production rate of craters at this size range; however, recent recognition of small craters (Malin et al., 2006) has provided observational evidence that these inferred recent cratering rates on Mars are unlikely to be off by more than a factor of a few (Hartmann, 2007; Kreslavsky, 2007). Thus, including the inferred uncertainty in production rates, the age range for the chronostratigraphic marker is between 0.6 Ma and 2.4 Ma.

DISCUSSION AND CONCLUSIONS

This study has identified a gully system depositional fan in eastern Promethei Terra containing secondary craters that are chronostratigraphic markers in the deposition of the fan. Fan morphology indicates that multiple periods of activity were required for its construction and that the secondary craters were emplaced during an intermediate period in fan formation. The presence of multiple superposing crater-free lobes 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. Approximately 100 km to the southwest, a 7-km-diameter rayed crater was identified that is interpreted to be the source of the secondaries.

Impact crater size-frequency distributions (Fig. 3B) place this crater's formation in the waning stages of the most recent period of latitude-dependent mantle accumulation and modification (Fig. 3C) (Head et al., 2003). The higher-amplitude obliquity variations during this period favor both the deposition and top-down melting of ice-rich deposits amenable to gully formation (Costard et al., 2002; Head et al., 2003). These stratigraphic relationships imply that at least some gullies on Mars have been active in very recent periods of the Late Amazonian during recent ice ages (e.g., Head et al., 2003; Schorghofer, 2007).

The multiple episodes of gully-related depositional fan activity mapped in this study imply that these gullies are not catastrophic landforms that formed in single events (i.e., as one-time debris flows or outbursts of groundwater). The distinctive alluvial fan–style morphology, fluvial channel sedimentary structures, and alcove incision make dry mass-wasting processes implausible for the formation of the gully system. The multiple episodes of activity required by the fan stratigraphy documented here cast doubt on deep groundwater discharge scenarios that are less likely to generate episodic releases. Rather, small amounts of surficial meltwater derived from snow and ice accumulation are suggested by the insolation geometries of gully systems and can account most plausibly for multiple periods of recent activity required by these observations. Modeling by Williams et al. (2008) shows that martian snowpacks can reach melting temperatures under a variety of conditions and produce small amounts of meltwater. Freshly uncovered snowpacks under current conditions, snowpacks at higher obliquities, and windblown snow proposed by Head et al. (2008) to seasonally concentrate in gully channels, can all lead to small amounts of meltwater (e.g., Christensen, 2003). These multiple avenues of surficial meltwater generation and our stratigraphic observations place recent gully activity during the most recent deposition and modification of latitude-dependent ice-rich mantling deposits.

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