Gasa impact crater, Mars: Very young gullies formed from impact into latitude-dependent mantle and debris-covered glacier deposits?

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A B S T R A C T

The mode of formation of gullies on Mars, very young erosional–depositional landforms consisting of an alcove, channel, and fan, is one of the most enigmatic problems in martian geomorphology. Major questions center on their ages, geographic and stratigraphic associations, relation to recent ice ages, and, if formed by flowing water, the sources of the water to cause the observed erosion/deposition. Gasa (35.72°S, 129.45°E), a very fresh 7-km diameter impact crater and its environment, offer a unique opportunity to explore these questions. We show that Gasa crater formed during the most recent glacial epoch (2.1–0.4 Ma), producing secondary crater clusters on top of the latitude-dependent mantle (LDM), interpreted to be a layered ice-dust-rich deposit emplaced during this glacial epoch. High-resolution images of a pre-Gasa impact crater 100 km northeast of Gasa reveal that portions of the secondary-crater-covered LDM have been removed from pole-facing slopes in crater interiors near Gasa; gullies are preferentially located in these areas and channels feeding alcoves and fans can be seen to emerge from the eroding LDM layers to produce multiple generations of channel incision and fan lobes. We interpret these data to mean that these gullies formed extremely recently in the post-Gasa-impact time-period by melting of the ice-rich LDM. Stratigraphic and topographic relationships are interpreted to mean that under favorable illumination geometry (steep pole-facing slopes) and insolation conditions, melting of the debris-covered ice-rich mantle took place in multiple stages, most likely related to variations in spin-axis/orbital conditions. Closer to Gasa, in the interior of the ~18 km diameter LDM-covered host crater in which Gasa formed, the pole-facing slopes display two generations of gullies. Early, somewhat degraded gullies, have been modified by proximity to Gasa ejecta emplacement, and later, fresh appearing gullies are clearly superposed, cross-cut the earlier phase, and show multiple channels and fans, interpreted to be derived from continued melting of the LDM on steep pole-facing slopes. Thus, we conclude that melting of the ice-rich LDM is a major source of gully activity both pre-Gasa crater and post-Gasa crater formation. The lack of obscuration of Gasa secondary clusters formed on top of the LDM is interpreted to mean that the Gasa impact occurred following emplacement of the last significant LDM layers at these low latitudes, and thus near the end of the ice ages. This interpretation is corroborated by the lack of LDM within Gasa. However, Gasa crater contains a robustly developed set of gullies on its steep, pole-facing slopes, unlike other very young post-LDM craters in the region. How can the gullies inside Gasa form in the absence of an ice-rich LDM that is interpreted to be the source of water for the other adjacent and partly contemporaneous gullies? Analysis of the interior (floor and walls) of the host crater suggest that prior to the Gasa impact, the pole-facing walls and floor were occupied by remnant debris-covered glaciers formed earlier in the Amazonian, which are relatively common in crater interiors in this latitude band. We suggest that the Gasa impact cratering event penetrated into the southern portion of this debris-covered glacier, emplaced ejecta on top of the debris layer covering the ice, and caused extensive melting of the buried ice and flow of water and debris slurries on the host crater floor. Inside Gasa, the impact crater rim crest and wall intersected the debris-covered glacier deposits around the northern, pole-facing part of the Gasa interior. We interpret this exposure of ice-rich debris-covered glacial material in the crater wall to be the source of meltwater that formed the very well-developed gullies along the northern, pole-facing slopes of Gasa crater.

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1. Introduction

Martian gullies, defined by the presence of an alcove, channel, and fan, were discovered in the first meters-scale images of Mars (Malin and Edgett, 2000). While provocative, significant uncertainty surrounded their formation, history, and potential link to climate cycles. Some initial hypotheses for gully formation depended only on dry mass wasting and granular flows (Treiman, 2003; Shindrot et al., 2004) which would be largely climate agnostic, but most hypotheses imply that some form of aqueous fluidization mechanism is required. For example, wet gully formation scenarios that have been proposed include groundwater outbursts from shallow aquifers (Malin and Edgett, 2000; Heldmann and Mellon, 2004), deep groundwater outbursts (Mellon and Phillips, 2001), melting of shallow ground ice (Costard et al., 2002; Hartmann et al., 2003), melting of older snowpacks (Christensen, 2003), and similar melting of surficial snow and ice accumulations (Head et al., 2007, 2008; Dickson and Head, 2009; Williams et al., 2009).

While recent work strongly shows that mid-latitude gully formation required an aqueous phase (e.g., McEwen et al., 2007b), uncertainty is only now being resolved regarding the chronology of gully development, the timescale required for their formation, and variations in the style of sediment transport with time. These characteristics are crucial to evaluation of latest Amazonian climate and of gullies as a geomorphic process on Mars. Additionally, improved understanding of gully development will have important implications regarding the most recent occurrences of liquid water, which is of interest to the astrobiology research community (e.g., MEPAG, 2006; Space Studies Board, 2007).

Reiss et al. (2004) were the first to date gully deposition via superposition relationships in Nirgal Vallis. Schon et al. (2009a) showed concursus chronostriatigraphic data derived from a secondary crater population marker horizon indicating significant gully deposition post-dating ~1.25 Ma. These marker horizons suggest a direct link between gully formation and the degradation of surface ice and snow deposits related to latest Amazonian climate cycles (Schon and Head, 2011). Here we present a study of Gasa crater for which age constraints (Schon et al., 2009a) on the crater allow us to consider temporal aspects of the end-to-end process of gully development at this site. We suggest that impact into an ice-rich substrate may have contributed significantly to the development of gullies in Gasa crater. Gasa crater occurs within a larger 18-km diameter crater that hosts gullies and other geomorphic evidence of significant glacial ice accumulation. Nearby craters contain evidence of similar ice accumulations. The development of large gullies within youthful Gasa crater underscores the remarkable efficiency of gully formation as a geomorphic process.

2. Geologic setting

Gasa crater (35.72°S, 129.45°E) (Fig. 1) is a very fresh ~7-km diameter impact crater which occurs within the simple to complex crater transition on Mars (Pike, 1980; Garvin et al., 2003) with a sharp rim-crest, a well-defined flat floor, and no evidence of substantial infilling (depth-diameter ratio of 0.12). Gasa crater is located within an older ~18-km diameter crater in eastern Promethei Terra on Noachian cratered terrain (Fig. 1). The outer (un-named) host crater has muted topography, a low depth-diameter ratio (0.07), evidence of latitude-dependent mantling (e.g., Mustard et al., 2001; Kreslavsky and Head, 2002; Head et al., 2003), gullies, and polygonally patterned ground (e.g., Levy et al., 2009a) which are all evidence of extensive Amazonian modification (e.g., Kreslavsky and Head, 2006).

2.1. Crater rays

Radiating from Gasa crater are extensive ray patterns (Fig. 1A) visible in nighttime THEMIS infrared data (Schon et al., 2009a). The population of rayed craters, such as Gasa crater, on Mars is limited (Tornabene et al., 2006). Generally, the distinctiveness of crater rays arises from both compositional and maturity differences (e.g., Hawke et al., 2004). The thermophysical distinctiveness of martian rays (McEwen et al., 2005; Tornabene et al., 2006; Preblich et al., 2007) is attributable to thermal inertia (TI) differences with surrounding terrain (e.g., low TI rays). Hence, rays are most apparent in nighttime THEMIS IR data (Christensen et al., 2004). The distribution of identified rayed craters (Tornabene et al., 2006) suggests that the occurrence or persistence of rays is dependent on substrate. Intermediate to high background thermal inertia and intermediate albedo appear to be important criteria regarding the distinguishability of rays (see global maps of Mellon et al. (2000) and Putzig et al. (2005)). This is consistent with most of the Tornabene et al. (2006) detections occurring in volcanic terranes. Rays on Mars can be homogenized with the surrounding environment or obscured from view by multiple processes known to be active on the martian surface, including: glacial modification, dust deposition, eolian reworking, and volcanic flows. For example, rays from Zunil are conspicuously absent from the Medusae Fossae Formation (Preblich et al., 2007), which Kerber and Head (2010) have shown to have a complex history of erosion and reworking. Gasa crater is located farther poleward (35.7°S) than any rayed crater identified by Tornabene et al. (2006). The apparent dearth of rayed craters in the mid and high latitudes is consistent with recent resurfacing events in these regions due to emplacement of latitude-dependent mantling deposits (e.g., Head et al., 2003; Schon et al., 2011) discussed further below.

2.2. Crater age

The Gasa crater-forming impact event created a smooth near-rim ejecta deposit. This deposit is ideal for crater-retention age dating because of its smooth surface and gentle topography. Using HRSC data (McEwen et al., 2007a), 289 craters were identified on 11.63-km² of the smooth ejecta deposit with the largest crater 61 m in diameter (Schon et al., 2009a). Employing isochrons of Hartmann (2005), this crater size-frequency distribution implies a best-fit age of 1.25 Ma for the Gasa crater impact event (Fig. 2). While there is some uncertainty in the production rate of small craters, detections of recent small crater formation (e.g., Malin et al., 2006) suggest that inferred cratering rates are consistent with the observed cratering rate (Hartmann, 2007; Kreslavsky, 2007; Kennedy and Malin, 2009; Daubar et al., 2010). Therefore, we have confidence in an age range of 0.6–2.4 Ma for the formation of Gasa crater (Schon et al., 2009a), which is consistent with preservation of the rays (McEwen et al., 2005; Tornabene et al., 2006; Schon et al., 2011).

3. Ice-rich mantling deposits

Mars’ mid- to high-latitude (greater than ~30° North and South) latest Amazonian geomorphology is characterized by ice-related processes and landforms including a pervasive ice-rich mantling unit observed in the larger crater encompassing Gasa crater as well as on the surrounding terrain. The mantling unit, responsible in part for early observations of terrain softening (e.g., Squyres and Carr, 1986), was first identified in global maps of surface roughness (Kreslavsky and Head, 2000) derived from MOLA altimetry, which reveal topographic smoothing at high latitudes. The morphology and degradation characteristics of this ice-
Fig. 1. Context of Gasa crater. (A) THEMIS (Thermal Emission Imaging System) nighttime thermal infrared images show a prominent pattern of fresh rays that emanate from Gasa crater. (B) Gasa crater is offset on the floor of an un-named ~18-km diameter degraded crater. Portion of CTX: P08_004060_1440_XI_36S230W. Topographic profiles from the Mars Orbiter Laser Altimeter (MOLA) show the prominence of Gasa crater (A–A') within the host crater. Pole-facing slopes are shallower in both craters compared to equator-facing slopes. Profile B–B' of the host crater shows a gently poleward dipping crater interior that is characteristic of glacial deposits (Head et al., 2008).
rich unit have also been described from visual observations by Mustard et al., 2001; Kreslavsky and Head, 2002; Head et al., 2003; Milliken et al., 2003; Milliken and Mustard, 2003; Kostama et al., 2006; Morgenstern et al., 2007.

3.1. Ice content

While the process of vapor diffusion governs the stability of ground ice deposits (e.g., Mellon and Jakosky, 1995), geological evidence suggests that the ice-rich mantling unit is the result of atmospheric deposition rather than vapor diffusion into regolith pore space. Evidence for extensive atmospheric deposition of ice is provided by Gamma Ray Spectrometer / Neutron Spectrometer data which imply ice abundances that far exceed reasonable pore space volumes for regolith (Boynton et al., 2002; Feldman et al., 2002; Mitrofanov et al., 2002; Prettyman et al., 2004). Also supporting the depositional hypothesis, Levy et al. (2008) have documented observations of sublimation-type contraction crack polygons at the Phoenix lander site (68.22°N, 234.25°E), which they interpret to require a nearly pure ice substrate. Similarly, the Phoenix lander observed massive ice beneath a thin regolith cover at this location (Smith et al., 2009). Finally, repeated observations have identified new mid-latitude impact craters that expose a nearly pure ice substrate and this ice is observed to sublimate upon exposure (Byrne et al., 2009; Dundas and Byrne, 2010).

3.2. Depositional history

A theory of recent obliquity-driven “ice ages” was proposed by Head et al. (2003) that relates broad deposition of ice-rich mantling deposits to larger obliquity variations that occurred >400 ka (Fig. 3). The validity of this scenario is supported by global circulation model studies (Mischka et al., 2003; Levrard et al., 2004), models of ice stability (Schorghofer, 2007), and evidence of layers within the mid-latitude mantling unit (Schon et al., 2009b). This theory suggests that emplacement of the mantle was cyclical with depositional phases punctuated by periods of instability and degradation as expected from the obliquity record (Fig. 3).

3.3. Relative stratigraphic position

While the precise chronological history of mantle emplacement is not yet resolved, initial efforts to directly date its uppermost surface in the northern hemisphere by Kostama et al. (2006) suggest...
that crater retention age trends correlate with latitudinal variations in morphology. The highest latitudes (70–80°N) exhibit the youngest ages (~0.1 Ma), while lower latitude mantle terrains appear older, ~2 Ma (Kostama et al., 2006). Similar ages and trends are observed in the southern hemisphere (Kreslavsky et al., 2011; Schon et al., 2011). These trends are consistent with the preservation of rays from Gasa crater (Fig. 1A). The clear superposition of un-modified crater clusters and chains from Gasa crater on the latitude-dependent mantle (LDM) surface (Fig. 4) and the lack of morphological evidence for mantle deposition within Gasa crater (Fig. 1) show that Gasa crater post-dates LDM in the region. In contrast, latitude-dependent mantling is present on the walls of the host crater. For example, gully alcove walls within the host crater exhibit polygonal texture (Fig. 5) indicative of the ice-rich substrate (e.g., Mangold, 2005; Levy et al., 2009a). The position and development of these polygons imply that some alcove development preceded the most recent ice-rich mantle deposition at these locations. Polygons are also observed on crater wall mantle surfaces near gully alcoves (Fig. 6). Multiple episodes of gully activity also post-date the mantle as evidenced by un-mantled gully deposits with multiple fans (Fig. 6). Surficial channels of limited incision that are not associated with alcoves are also observed (Fig. 6) and provide evidence that melting of ice-rich LDM is sufficient for some gully activity (Schon and Head, 2011).

3.4. Ice-rich mantle and gullies within the host crater

Gasa crater is located within the 18-km diameter host crater (Fig. 1). This crater contains latitude-dependent mantling deposits, hosts pole-facing gullies, and has a significantly lower depth-diameter ratio (0.07) than Gasa crater (0.12). The pole-facing wall of the host crater is modified by a series of gullies. The largest gully alcoves have widths of approximately 400–500 m. Older fans are observed that are deformed by multiple closely spaced fractures parallel to the base of slope (e.g., Head et al., 2008), while stratigraphically younger fans are un-modified (Fig. 6). Younger fans are also located upslope and superpose previously eroded gully channels (Fig. 6). Alcoveless gullies (Fig. 6) similar to those described by Schon and Head (2011) and shown in Fig. 7 are also observed which are likely sourced directly from the mantle. The youngest activity is likely to be contemporaneous with similar activity that has been documented to post-date Gasa crater (Schon et al., 2009a; Schon and Head, 2011). Therefore, these observations support episodes of gully activity at this location that both predate (based on the presence of latitude-dependent mantling, which must predate Gasa, within a gully alcove, e.g. Fig. 5), as well as post-date Gasa crater.

4. Theories of gully formation

Melting of latitude-dependent mantling deposits has been proposed as a source of water for mid-latitude gullies (Head et al., 2003, 2008; Milliken et al., 2003; Blemaster and Lackner, 2006; Dickson and Head, 2009; Schon and Head, 2011). From a process standpoint, this scenario is comparable to previously proposed sources of meltwater including ground ice (Costard et al., 2002) and ancient snowpacks (Christensen, 2003), as well as similar scenarios (e.g., Levy et al., 2010; Lanza et al., 2010). It has also been proposed that gullies are late-stage features that develop during the wane and retreat of alpine-style glaciers (Arfstrom and Hartmann, 2005; Berman et al., 2005; Head et al., 2008). Evidence supporting this process model includes well-developed arcuate ridges interpreted as moraines below cirque-like alcoves that would have been ideal accumulation zones for glacial systems (Arfstrom and Hartmann, 2005; Berman et al., 2005, 2009; Head et al., 2008).

It is important to note that while these moraine features are prominently associated with some gullies, particularly in the east of Hellas region, they are not universally associated with mid-latitude gullies. In a recent study, Schon and Head (2011) documented small-scale surficial gullies whose incision is strictly limited to the mantling unit and which lack alcoves (Fig. 7). These gullies provide independent evidence that melting and degradation of ice-rich mantling deposits is an important source of meltwater, sufficient for gully formation in some instances. At this locality, approximately 100 km northeast of Gasa crater, Schon et al. (2009a) mapped multiple gully deposits that superpose secondary craters from Gasa crater. These stratigraphic relations indicate that mantle degradation and gully activity at the site (~35°S, 131°E) post-date the Gasa crater impact (Fig. 7).
Fig. 6. Host crater gullies. Older gullies fans associated with larger alcoves are modified by parallel fractures (e.g., Head et al., 2008). Younger fans are unmodified and overprint older gully channels. Polygonal terrain is observed on the latitude-dependent mantle that blankets the upper crater wall. Alcove-less surficial channels emerging from the latitude-dependent mantle extend for hundreds of meters and feed into larger gully drainages. These stratigraphic relationships suggest multiple generations of gully activity. The muted and degraded topography of the older gullies suggests that they predate the Gasa cratering event. Portion of HiRISE: PSP_005616_1440.
Fig. 7. Approximately 100 km northeast of Gasa crater, gully fans in a 5-km crater (A) post-date a dense population of Gasa secondary craters (eastern Promethei Terra, ~35°S, 131°E). The pole-facing wall (shown) is composed of degraded layers of ice-rich latitude-dependent mantling deposits. On the crater wall, post-Gasa degradation of the mantling unit has led to a partial to nearly complete removal of the secondary crater population and exposed prominent layers of the mantle. Small channels and gullies without alcoves emerge from the degraded mantle and are interpreted to have deposited fans during degradation and melting of the ice-rich mantling material. These fine-scale surficial gully features are highlighted with arrows in insets (B–D). These observations implicate meltwater from the degradation of latitude-dependent mantling in the process of gully formation. Portions of HiRISE PSP_002293_1450; from Schon and Head (2011).
Therefore, independent evidence exists for the development of gullies in association with two environments: (1) past glacial systems with commensurately large accumulations of ice during the late Amazonian (e.g., Berman et al., 2005; Head et al., 2008) and (2) from localized post-Gasa crater melting of latitude-dependent mantling deposits emplaced prior to Gasa (Schon and Head, 2011). Since these mantling deposits were emplaced pre-Gasa crater, how did the gullies within Gasa crater form? If water was involved, what was the source? The age, stratigraphic relationship with latitude-dependent mantling deposits, and geomorphic setting of Gasa crater enable us to consider these questions.

5. Gasa crater interior

The rim crest of Gasa crater is crisply defined, but asymmetric in form. The northern portion is deeply crenulated by gully alcoves while the southern extent is composed of linear to curvilinear segments (Fig. 8). The alcoves are neither symmetric nor uniform. The largest alcoves are located in the middle of the northern rim (pole-facing). Alcoves are progressively smaller both clockwise and counterclockwise from this orientation (Fig. 8). Individual alcoves are complex, often with multiple contributing sub-alcoves that have associated channels. Sharp divides between alcoves expose fractured rocky material. An orientation asymmetry is also observed within alcoves. For example, the primary orientation of the alcoves shown in Fig. 9 is toward the south-southwest. In these alcoves, substantially more sub-alcoves and channels are found on the pole-facing walls. The pole-facing walls of these alcoves also have more bedrock exposures (Fig. 9). In contrast, the equator-facing, un-crenulated southern rim and wall of the crater is characterized by narrow poorly-developed debris chutes and bedrock exposures.

![Fig. 8. Asymmetry of Gasa crater rim crenulation and wall morphology. The northern half of Gasa crater has a crenulated rim due to the development of significant gully alcoves. These alcoves are most well-developed in the central portion of pole-facing wall and become progressively smaller at offset orientations. Gully fans have coalesced to form a large pediment. These fans extend onto a hummocky crater floor texture (bottom center) that has been interpreted by Boyce et al. (2011) as resulting from rapid degassing of volatile-rich impact melt-bearing breccia immediately following the cratering event. Discontinuous channel segments are observed on the fans. The southern half of Gasa crater lacks gully alcoves and the rim is significantly less crenulated. In comparison to the gully fans and large sedimentary bajada developed in the north, talus cones and landslide deposits provide the only evidence of downslope movement on these equator-facing slopes. Portions of CTX: P08_004060_1440_XI_36S230W.](image)

![Fig. 9. Gully alcove asymmetry in Gasa crater. Gully alcoves can also contain microenvironments based on orientation-dependent asymmetry (e.g., Marchant and Head, 2007; Williams et al., 2009; Morgan et al., 2010). In this example, only pole-facing gully alcove walls (left) are incised by channels feeding the main gully channel. The preferential exposure of rocky material on the pole-facing walls also suggest that these surfaces have undergone more extensive erosion than their equator-facing counterparts (right). Gullies in the northern wall of Gasa (Fig. 8) that face south do not have this asymmetry in alcove-wall orientation (relative to the poles) or incision by sub-channels. Portion of HiRISE: PSP_005550_1440.](image)

![Fig. 10. Example of gully channel incision and deposition in Gasa crater. Gully channels in Gasa crater contain many examples of channels that have been cut off by further channel erosion and diversion (arrows). Lighter-toned younger fan deposits are visible at left. Portion of HiRISE: PSP_004060_1440.](image)
are comparatively sparse (Fig. 8). The debris chutes that have developed along the southern interior of Gasa crater are immature, i.e., shallow and narrow (Gutiérrez, 2005), compared to those observed in Zunil, a larger \((D = 10.4\ km)\) young rayed crater (McEwen et al., 2005), but are similar to those observed in the other rayed craters identified by Tornabene et al. (2006) such as Zumba.

**Fig. 11.** Example of gully fan deposition and terraces within gully channels in Gasa crater. Gully channels are observed eroding sediment previously transported and deposited by the gully. Terraces (arrows) are the result of further channel incision and are commonly observed in terrestrial braided stream environments (Ore, 1964). Portion of HiRISE: ESP_014081_1440.
events may have been lower energy. Portion of HiRISE: ESP_014081_1440.

5.1. Gully alcoves and channels

Within Gasa crater, distinct gully channels extend up into many sub-alcoves. Cutoffs between these tributary channels and main trunk channels indicate multiple flow events (Fig. 10). Multiple terraces are common in the channels (e.g., Schon and Head, 2009) as well as streamlined islands or longitudinal bars (Fig. 11). Some lower portions of the main channel regions (approximately 50–200 m in width) appear choked by sediment with discontinuous channel and bar features similar to braided stream environments (Fig. 12). The terrestrial conditions that give rise to braided stream morphologies, including high gradient, abundant sediment, and variable discharges (e.g., Leopold et al., 1964; Ore, 1964; Miall, 1978), are all likely to be applicable as well to the Gasa crater gullies. The sediment observed in the gullies appears uniform at HiRISE resolution (no coarse-grained lag deposits or sorting is observable), however meter-scale boulders are observed in the channels and on alcove slopes (including boulders with associated boulder tracks from recent downslope movement). Analysis of gully apex slopes (the gradient where deposition begins) in Gasa crater by Kolb et al. (2010) found ten gullies with apex slopes consistent with “wet or fluidized emplacement” (16.3–20.4°) and eleven gullies with steeper apex slopes (20.7–26.4°) consistent with dry granular flows. Amongst their five study crater locations, the gullies in Gasa crater were best preserved (Kolb et al., 2010), which is consistent with the youthful age of Gasa (Fig. 2). They concluded that gullies are likely to have formed in the geologically recent past via a wet/fluidization mechanism and that subsequent and any present activity is likely “dry post-gully modification” (Kolb et al., 2010). We interpret the recent observations of gully activity by Dundas et al. (2010) in Gasa crater as such dry modification, consistent with the interpretation of Dundas et al. (2010) that “none of these observations contradict the hypothesis that gullies are initiated by H2O snowmelt or that this process drives a significant fraction of gully erosion.” In contrast, recent observations of dune gullies have been interpreted to suggest that a seasonal CO2 frost process may be responsible for their formation and evolution under present climate conditions (Diniega et al., 2010). Present-day dune gully activity is consistent with observations of active sand transport in polar dunes that also removes dune gullies (Hansen et al., 2011).

5.2. Gully fans

Below the rocky outcrops of the alcove walls, many Gasa crater gullies exhibit sharply defined sedimentary interfluves (elevated ridges between channels of the same drainage network) (Figs. 8 and 12). These sediment masses are bounded by gully channel and fan deposits on their margins. Boulders are observed on their sides, but bedrock is not outcropping (Fig. 12). Most are located directly downslope (in the lee) of bedrock outcrops and have sharp ridges. These are evidence of the abundant sediment available for erosion and transport.

Adjacent to the sedimentary interfluves and extending downslope to the floor of the crater are the gully depositional fans. The fans have coalesced to form a large continuous sediment mass, similar to a bajada (a broad depositional deposit formed by the coalescing of alluvial fans) or pediment (veneer of eroded materials at the base of a mountain formed by scarp retreat) (Fig. 8), though individual fans and depositional lobes are still distinguishable (e.g., Fig. 11). Both small and large channel diversions are present on the fans. Discontinuous channel segments are also observed, notably on lower portions of the fans. Channels dissecting fan surfaces are predominantly linear, though some channels especially on eastern fans display modest sinuosity (Figs. 8 and 11A). Although the slopes are steeper, these characteristics are comparable to a terrestrial waterlaid alluvial fan (e.g., Blair, 2002). Recently, geomorphic changes such as the appearance of a bright gully deposit and transported boulders in channels have been reported by Dundas et al. (2010) in Gasa.

The toes of the fans impinge on multiple crater floor textures. In the northwestern floor of the crater, gully fans extend onto rocky crater floor material that we interpret as slumped deposits (Fig. 8). Along the northern margin, fan material extends onto a unique hummocky-textured floor morphology. Similar floor morphology was described by Tornabene et al. (2006) in other very young craters and has been interpreted as volatile-rich impact melt-bearing breccia (suevite) that degassed rapidly in the terminal phases of the impact event forming collapse pits (e.g., Tornabene et al., 2007a; Boyce et al., 2011; Osinski et al., 2011). Observations of this floor morphology in other young craters such as Corinoto crater
(Bray et al., 2009), Hale crater (Jones et al., 2011), Mojave crater (McEwen et al., 2007b), Tooting crater (Mouginis-Mark et al., 2007; Morris et al., 2010), and Zunil (McEwen et al., 2005; Hartmann et al., 2010) suggest that it is a relatively common feature of young craters on Mars. If Gasa crater and these gullies post-date the latitude-dependent mantle that is the source of gullies elsewhere in the area (Schon et al., 2009a; Schon and Head, 2011), what is the source of meltwater that might have produced the gullies inside Gasa crater?

6. Evidence of glacial ice in the host crater

The 18-km diameter host crater within which Gasa crater formed contains latitude-dependent mantling deposits, hosts

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![Fig. 13A](image-url) Debris flow deposits on the host crater floor (Fig. 1). Ponded materials and associated channels indicate flow over a distance of approximately 4 km. High-resolution topography data from HRSC and HiRISE digital terrain models show topographic control of the channels and ponded material indicating that these features are not the result of surging ejecta. Portions of CTX: P16_007396_1453_XL_345230W and HRSC: h6494.
many gullies, and has a significantly lower depth-diameter ratio (0.07) than Gasa crater (0.12). In this section we outline multiple lines of evidence suggesting that this crater hosted a significant glacial deposit that predated the Gasa crater impact. In our interpretation, the large gullies within Gasa formed in association with these ice deposits and the Gasa crater impact occurred into this

Fig. 13B. Channels are observed from the lower wall of the crater to ponded material in a topographic low near the Gasa rim crest. We interpret this feature to be the result of the Gasa impact event depositing hot ejecta on top of a debris-covered glacier on the northern crater floor, and melting glacial ice buried at shallow depth, forming a slurry that drained in directions related to local topography. Portion of HiRISE: PSP_009901_1440.
ice-rich glacial substrate, common at these latitudes (Head et al., 2008; Dickson et al., 2011). Additional geological evidence for this scenario is provided by the action of meltwater derived from glacial ice and fluidized ejecta created by the Gasa crater impact that flowed on the host crater floor and ponded in local topographic lows (Fig. 13A).

Fig. 13C. Ponded debris flow material exhibits surface fractures interpreted as resulting from desiccation and contraction. The texture is homogenous and smooth at HiRISE resolution. Portion of HiRISE: PSP_009901_1440.
Immediately north and northeast of the Gasa crater rim crest on the floor of the host crater ponded materials and associated channels are observed (Fig. 13). The ponds are sourced by channels that extend several kilometers from the lower crater wall (Fig. 13B). The channels are diverted around local topographic obstacles (Fig. 13B) and the ponds are observed where material pooled in local topographic lows (Fig. 13A). This topographic control of flow direction and evidence of flow back toward the Gasa crater rim, indicate that these deposits are not the result of surging ejecta from the Gasa crater impact. The ponded material (Figs. 13A–13C) has a texture that is smooth at HiRISE resolution in contrast to the pitted texture of graphic lows (Fig. 13A). This topographic control of flow direction and the ponds are observed where material pooled in local topographic lows, moving generally downslope toward Gasa crater, but apparently not breaching the topographic rim crest (Figs. 13A–13C). Subsequent desiccation of the slurry led to the formation of contraction cracks. These features provide evidence that Gasa crater impacted partly into an ice-rich substrate (e.g., Osinski, 2006; Senft and Stewart, 2008) that we interpret formed by glacial deposits concentrated on the floor at the base of the pole-facing host crater wall (e.g., Head et al., 2008; Berman et al., 2009; Dickson et al., 2011). Neither gullies nor similar ponded materials are found in the southern portion of the host crater (south of Gasa crater; Figs. 1 and 8), where topographic evidence (Figs. 1 and 13A) and the distribution and geometry of debris covered glaciers in nearby craters (Fig. 14) suggest that the pre-existing debris-covered glacier was thin to non-existent. In our interpretation, following the Gasa impact, melting of debris-covered glacial ice exposed in the Gasa crater wall stratigraphy would provide a source of water for gully activity within Gasa crater itself. The northern position of the glacial ice in the target area and within the host crater (Fig. 13A) is consistent with the occurrence of gullies only in the northern walls of Gasa (Fig. 8). This immediate source of ice in the upper crater wall stratigraphy, and its further exposure by melting and enhanced mass wasting, is interpreted to be one of the major reasons the alcoves, channels, fans and gully systems are so robustly developed in Gasa compared to other craters of similar age.

7. Glacial accumulations in craters

Are Amazonian glacial ice deposits likely to be present in craters in this latitude range? Amazonian glacial ice accumulations in craters have been interpreted from the presence of concentric crater fills (Levy et al., 2009c; Head et al., 2008; Dickson et al., 2011) as well as arcuate ridges interpreted as glacial moraines (Howard, 2003; Milliken et al., 2003; Arfstrom and Hartmann, 2005; Berman et al., 2005, 2009; Head et al., 2008; Pearce et al., 2011). While concentric crater fill may suggest relatively homogenous ice distribution, moraines indicate preferential ice accumulation on crater walls and glacial flow (e.g., Benn and Evans, 1998; Head et al., 2008; Dickson et al., 2011). Like gullies (Balme et al., 2006; Dickson et al., 2007) and viscous flow features (Milliken et al., 2003), these moraines and associated spatulate depressions are found preferential with pole-facing orientations in the southern hemisphere (Berman et al., 2005; Head et al., 2008). Interpretations of crater densities led Arfstrom and Hartmann (2005) to suggest that these features are no more than 10 Myr old and are most likely to have formed during a high obliquity phase that ended approximately 4 Ma. Subsequent deformation, flow, and sublimation are responsible for more recent surface alteration and possible removal of small craters (Arfstrom and Hartmann, 2005).

Berman et al. (2009) specifically investigated the eastern Hellas region, including Promethei Terra where Gasa crater is located. In that study they described commonly observed morphologies with pole-facing orientations indicative of ice accumulation and flow including lobate flows and arcuate ridges. Lobes were found to range in length from 1 km to 7 km with a mean length of 4.5 km (Berman et al., 2009). Arcuate ridges are found below gully alcoves and have similar widths (e.g., Berman et al., 2009). This spatial association has been interpreted as consistent with glaciers emanating from alcove cirques associated with gully formation during glacial retreat (Arfstrom and Hartmann, 2005; Berman et al., 2005, 2009; Head et al., 2008). In a stratigraphic analysis of recent crater
modification, Head et al. (2008) showed that gullies are younger and occur after such glacial deposits have lost ice. In these settings, ice preferentially accumulates on pole-facing walls sufficient to initiate ice flow and the development of debris covered glaciers. As climate conditions changed due to a general decrease in obliquity and the period of glaciation waned, these glacial systems lost ice via sublimation, particularly in their accumulation zones, exposing hollows and forming spatulate depressions (Head et al., 2008). Gullies are observed stratigraphically to post-date the loss of glacial ice; they occur in the regions that would have been accumulation zones for the glacial ice. Therefore, Head et al. (2008) suggest a genetic relationship based on ice accumulation in the shared source regions for the debris-covered glaciers and the later gullies. Gully activity led to the deposition of fans in the spatulate depressions. While stratigraphically older fans are deformed, younger fans are un-deformed (Head et al., 2008).

Consistent with these interpretations of glacial systems in Promethei Terra (e.g., Berman et al., 2009), the region east of Hellas is also identified in global climate modeling studies as a location of enhanced ice accumulation under past obliquity conditions (Forget et al., 2006; Madeleine et al., 2009) and contains many lobate debris aprons (Pierce and Crown, 2003). In craters neighboring Gasa crater, evidence of preferential glacial ice accumulation and flow is pervasive and therefore we would expect the host crater to have contained similar deposits. Observations from one of these neighboring craters provide additional detail regarding the comparable glacial ice accumulation that we interpret was present in the host crater at the time of the Gasa crater impact. Approximately 70 km north of Gasa crater is a 13.5-km diameter crater (Fig. 14). This crater has a mottled and lineated fill material similar to those described by Kreslavsky and Head (2006) in a study of glacially modified craters in the northern high-latitudes. Spatulate depressions bounded by moraine-like ridges are associated with the largest gully alcoves (Fig. 14). Linear ridges are parallel to the base of the pole-facing crater wall. We interpret these features to be the result of glacial accumulations concentrated on the pole-facing wall. Because gully fans deposit into the spatulate depressions, glaciacion preceded the most recent gully fan deposition here (Fig. 14), which is consistent with chronological interpretations in other studies (Arfstrom and Hartmann, 2005; Head et al., 2008; Berman et al., 2009). In summary, several lines of evidence support the presence of a debris-covered glacier deposit in the northern part of the host crater floor prior to the Gasa impact event.

8. Comparison with fresh crater Zumba

To consider the hypothesis that the gullies in Gasa crater result from impact into an ice-rich substrate we investigated the population of rayed craters identified by Tornabene et al. (2006) for a comparable impact. None of these craters contain gullies. While Gratteri (D = 6.9 km) and Tomini (D = 7.4 km) are most similar to Gasa crater in diameter, they are located at more equatorial latitudes where gullies are not found. Zumba crater (28.65S, 226.9E) is the most pole-ward rayed crater identified by Tornabene et al. (2006) and is located at a latitude near to where gullies are common. Zumba occurs in Daedalia Planum on a known substrate of Hesperian age lavas (Scott and Tanaka, 1986).

The rim of 2.6-km diameter Zumba crater is un-crenulated (Fig. 15A). Uniform debris chutes line the rim regardless of orientation. The crater wall has a uniform smooth texture of unconsolidated materials with no evidence of incision (Fig. 15A). Slumped materials are deposited on the crater floor, which has a pitted texture similar to Gasa and other young craters that is attributed to rapid degassing of volatile-rich impact melt-bearing breccia (e.g., Tornabene et al., 2007b). An extensive crater count of 46-km² of the ejecta deposit revealed 1197 superposed craters (Fig. 15B). Isochrons of Hartmann (2005) imply a best-fit age of 0.8 Ma for Zumba crater, consistent with a crater retention age of 0.2–0.8 Ma reported by Hartmann et al. (2010). Therefore, Zumba is similar in age to Gasa crater, but has very different morphology.
due to its impact into a uniform substrate (Fig. 15A) rather than the glaciated and brecciated crater interior environment that Gasa crater impacted (Figs. 1 and 13A–13C).

9. Chronological interpretation

Originally disparate individual observations can be assembled into a chronology (Fig. 16) that documents the history of gullies and the transitions in their activity. Previously, gullies were well known on older planetary surfaces, e.g., Dao Valles (Bleamaster and Crown, 2005) as well as in craters (e.g., Heldmann and Mellon, 2004; Balme et al., 2006; Dickson et al., 2007), but Gasa crater presents a compelling example of gullies also developing in an unambiguously very young location (Fig. 2). Chronological constraints require gully formation in the recent glacial/interglacial epoch (Schon et al., 2009a) and indicate that gullies can develop solely from degradation and melting of ice-age mantling deposits (Schon and Head, 2011).

The Eastern Promethei Terra region provides an opportunity to synthesize observations of multiple gullies, their geologic settings, and several temporal constraints to more fully understand the occurrence, ages, and formation processes of mid-latitude gullies. Principal geological events of interest (Fig. 16) were preceded by formation of the Noachian cratered terrain. Larger gullies of the Gasa host crater predate the Gasa impact and the emplacement of latitude dependent mantling deposits (Fig. 5). The glacial systems interpreted to be responsible for features such as arcuate and moraine-like ridges are most likely to date from a phase of higher mean obliquity, ~10–4 Ma (Arfstrom and Hartmann, 2005), though older glacial episodes elsewhere are also known (e.g., Head et al., 2005). Debris flow deposits (Figs. 13A–13C) induced by the Gasa impact provide geological evidence suggesting that the pole-facing crater wall and floor region of the host crater contained relict glacial deposits that pre-dated Gasa (Fig. 16).

Emplacement of hemispheric-scale ice-rich mantling deposits during the previous ice age (2.1–0.4 Ma) was cyclic and latitude-dependent (Fig. 3; Head et al., 2003). The youthfulness of high latitude mantling is known from the pervasiveness of un-modified polygonally patterned ground (Kreslavsky et al., 2011). Mid-latitude mantle surfaces are older and show more evidence of degradation than higher latitude mantling which was likely to have been emplaced more recently (Kostama et al., 2006). Secondary craters from the Gasa crater impact are superposed on the mantle surface (Fig. 4) and no mantling is observed within Gasa (e.g., Fig. 8). These observations require that the Gasa impact occurred subsequent to the most recent mantle deposition in this region. The size-frequency distribution of superposed craters (Fig. 2) suggests that the Gasa impact occurred between 2.4 Ma and 0.6 Ma with a best fit to Hartmann (2005) isochrons of 1.25 Ma. Together, the crater retention age and superposition relationship (secondary craters on the mantle; Fig. 4) indicate that the Gasa impact occurred during the waning of the most recent ice age on Mars.

Gullies are known to be active after the Gasa crater impact from gully fan deposition over Gasa secondary craters (Fig. 7; Schon et al., 2009a; Schon and Head, 2011) and the two generations of gullies in the host crater (Fig. 6). This is consistent with gully formation resulting from melting and degradation of latitude-dependent mantling deposits (Schon and Head, 2011). Thus, there were two ice-rich deposits in this region at the time of the Gasa impact, (1) regional near-surface ice deposits from the ice-age latitude-dependent mantle (e.g., Head et al., 2003), and (2) remnant glacial ice deposits in the interiors of some impact craters, such as the

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**Fig. 16.** Timeline of glacial and gully activity during the Latest Amazonian period of Mars history. Mantling deposits are interpreted to have been emplaced in a latitude-dependent manner during the previous period of enhanced obliquity (Head et al., 2003). The obliquity data are from Laskar et al. (2004). The Gasa impact event is constrained by its crater retention age (Fig. 2) and the relative stratigraphic position on the latitude-dependent mantle (Fig. 4). Timing of gully activity is known to stratigraphically post-date the Gasa impact event in this area (Schon et al., 2009a). Crater-wall glacial accumulations are suggested to date from a period of higher mean obliquity that ended approximately 5 Ma (Arfstrom and Hartmann, 2005).
host crater and others (Figs. 1, 13A–13C and 14) (e.g., Berman et al., 2005, 2009; Head et al., 2008; Dickson et al., 2011). In our interpretation, gully formation within the Gasa crater interior resulted from the impact disruption of these glacial ice deposits and their exposure in the pole-facing crater wall. Thus, ice-rich erodible substrate for gully activity was made available by the Gasa impact into the host crater interior target material (e.g., Senft and Stewart, 2008). abundant immediately post-Gasa debris flow features (Figs. 13A–13C) provide additional evidence suggesting that ice on the crater floor was melted and exposed by the impact. In our interpretation, gully evolution in Gasa (e.g., Kolb et al., 2010; Lanza et al., 2010; Okubo et al., 2011) was likely to have been limited by the ultimate quantity of meltwater generated from the glacial ice deposits. As this source of meltwater waned, steep slopes and abundant sediment remained available for dry mass wasting processes, consistent with our observations of fresh boulder tracks, the apex slope analysis of Kolb et al. (2010), and observations of gully activity by Dundas et al. (2010).

10. Conclusion

While our observations suggest that meltwater from the ice-rich LDM is the most common source of liquid for erosion and transport in gully systems, in our interpretation, formation of gullies in the late glacial period-aged Gasa crater occurred due to impact into a debris-covered glacial substrate that provided an additional source of meltwater for gullyforming. Gasa crater is the most poleward (35.7°) rayed crater identified to date on Mars, approximately seven degrees further south than Zumba (28.7° S), the most poleward rayed crater identified in the survey of Tornabene et al. (2006). Gasa crater has a crater retention age of ~1.25 Ma. The superposition of Gasa crater secondary crater chains on latitude-dependent mantling deposits in the region and the lack of mantling within Gasa crater show that Gasa crater post-dates the last episode of visible mantle deposition at this location. Because deposition of mantling deposits is interpreted to be coincident with obliquity excursions during Mars most recent ice age (Head et al., 2003), these relationships confirm the youthful age of Gasa crater.

Gasa crater proximal and distal stratigraphic relationships show that: (1) gully activity extends to extremely young ages, occurring at least as recently as 2.1–0.4 Ma, and perhaps even more recently, (2) gully activity is favored on steep, pole-facing slopes and involved multiple stages of development, (3) gully activity is very closely associated with erosion and degradation of the layered ice-rich LDM, (4) gullies commonly source in the ice-rich layers of the LDM, (5) close association of gullies with the ice-rich LDM layers implicates liquid water in their formation, (6) Gasa crater formed just after the last emplacement of the LDM at these latitudes, (7) robust gullies formed in Gasa despite the lack of emplaced and exposed LDM layers, (8) the source of meltwater for the anomalous gullies in the interior of Gasa can be related to the excavation and exposure of a debris-covered glacier on the floor of the parent crater in which Gasa formed. Thus, the Gasa crater example has provided new insights into the ages, geographic and stratigraphic associations, relation to recent ice ages, and the sources of water and associated climate conditions that led to gully formation.

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