Formation of gullies on Mars: Link to recent climate history and insolation microenvironments implicate surface water flow origin

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Features seen in portions of a typical midlatitude Martian impact crater show that gully formation follows a geologically recent period of midlatitude glaciation. Geological evidence indicates that, in the relatively recent past, sufficient snow and ice accumulated on the pole-facing crater wall to cause glacial flow and filling of the crater floor with debris-covered glaciers. As glaciation waned, debris-covered glaciers ceased flowing, accumulation zones lost ice, and newly exposed wall alcoves continued as the location for limited snow/frost deposition, entrapment, and preservation. Analysis of the insolation geometry of this pole-facing crater wall, and similar occurrences in other craters at these latitudes on Mars, shows that they are uniquely favored for accumulation of snow and ice, and a relatively more rapid exposure to warmer summer temperatures. We show that, after the last glaciation, melting of residual snow and ice in alcoves could have formed the fluvial channels and sedimentary fans of the gullies. Recent modeling shows that top-down melting can occur in these microenvironments under conditions similar to those currently observed on Mars, if small amounts of snow or frost accumulate in alcoves and channels. Accumulation and melting is even more favored in the somewhat wetter, relatively recent geological past of Mars, after the period of active glaciation.

craters | erosion | glaciation | fluvial | snow

In the current atmospheric environment of Mars, liquid water is either unstable or is metastable for areas and seasons where atmospheric pressure exceeds the water triple-point pressure, and water quickly freezes and/or sublimates (1). Thus, it came as a major surprise when Malin and Edgett (2, 3) reported the discovery, in high-resolution images (Figs. 1 and 2), of a class of young features apparently carved by running water. Termed gullies, these features consist of an alcove, a channel, and a fan (Fig. 2 *Left*). Restricted mostly to middle and a few high-latitude locations, gullies were interpreted by Malin and Edgett (2, 3) to have originated through processes related to groundwater discharge. The potential presence of liquid water on the surface of Mars currently, or in the very recent geological past, when liquid water was thought to be unstable (1), generated a host of alternative non-water-related explanations for the gullies, including liquid CO_2 (4), CO_2 frost (5), and brines (6). Geological mechanisms proposed to create the observed features can be divided into three types of hypotheses: (*i*) bottom-up liquid sources, such as the release of subsurface groundwater (2, 7–9) or subsurface liquid CO_2 (4), perhaps aided by geothermal activity (10, 11); (*ii*) top-down water sources, such as the accumulation and melting of preexisting surface snowpacks (12), recently deposited snow and frost (13, 14), or melting of near-surface ground ice (15); and (*iii*) dry granular flow (16). The discussion has been intensified by the recent report of changes in a few gullies in the past decade, interpreted to mean that the gullies are not only active in the recent geological past (2, 3, 7–9, 14, 15), but that some are still active today (17). In this contribution, we examine the geological setting of gullies to provide a context and framework of information in which their origin might be better understood. Assessment of the stratigraphic relationships in a crater interior typical of many gully occurrences provides evidence that gully formation is linked to glaciation and to geologically recent climate change that provided conditions for snow/ice accumulation and top-down melting.

The distribution of gullies shows a latitudinal dependence on Mars, exclusively poleward of 30° in each hemisphere (2, 14) with a distinct concentration in the 30–50° latitude bands (e.g., 2, 7, 8, 14, 18). A significant number of gullies form on impact crater interior walls (19, 20). For this reason, we chose to analyze in detail the geology of a crater interior at ≈40°S latitude (Fig. 2), the most common latitude for gully occurrences (14), to assess geomorphic features and stratigraphic relationships associated with gullies. Features that we observe in this crater are typical for craters in this latitude zone (14, 20).

Observations

High-resolution image and altimetry data (MOC, CTX, HiRISE, and MOLA) are available for analysis of morphological details and stratigraphic relationships (Fig. 1) of a 10.5-km-diameter crater (Fig. 1) within the much larger Newton Crater on Mars in the southern midlatitudes (204.7°E, 40.1°S). The crater displays well developed gullies (Figs. 1 and 2*A*) and a very asymmetric wall and floor topography, with the north wall and crater floor sloping shallowly (≈5°) toward the steep southern wall (≈20–34°) (Fig. 1*C*). Inspection of the crater floor morphology illustrates the reasons for this asymmetry. Multiple lobate depressions along the base of the northern wall are directly upslope of multiple parallel lobate flow textures on the northern part of the floor; these in turn merge and converge in the central part of the crater toward two major southern floor lobes. The southern part of the crater floor appears broadly lobate and the two lobes clearly embay topographic features that are part of the southern wall and floor (Fig. 1*A* and *B*). The floor and wall morphology and asymmetry, the stratigraphic embayment relationships, the density of superposed small craters (much sparser on the lobes than on the crater rim), all suggest that these deposits are part of a geologically relatively recent phase of modification of the crater.

The characteristics of the surface morphology and the array of geomorphic features implicate snow and ice in the crater modification. The surface texture of the floor lobes is very similar to that of midlatitude lobate debris aprons, lineated valley fill, and concentric crater fill, all interpreted to involve a significant amount of ice in their formation (21–26). The slopes and surface

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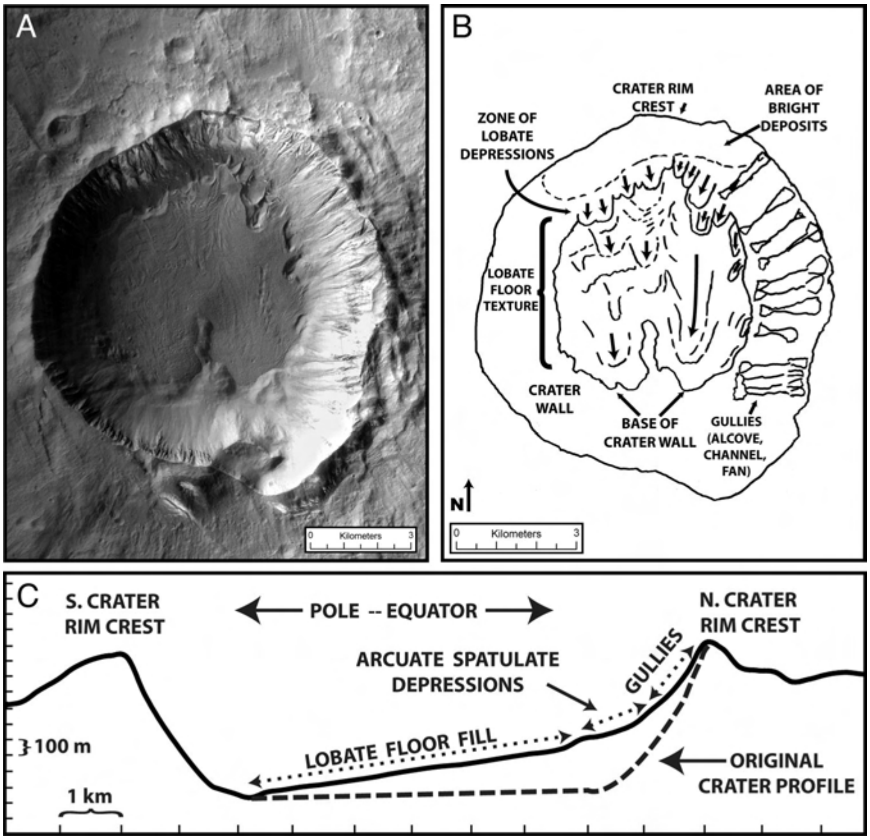

Fig. 1. Impact crater (10.6 km diameter) in eastern Newton crater (204.7°E, 40.1°S). (*A*) CTX image p02_001842_1397_xi_40S155W. North is at the top. (*B*) Sketch map showing main geological features and structures. In the geologically recent past, snow and ice accumulation on the pole-facing crater wall (top) was sufficient to form debris-covered glaciers that descended down the crater wall and out onto and across the crater floor, filling the floor with ice-rich debris lobes (see profile). Subsequently, climate conditions caused cessation of glacial flow and sublimation of the proximal ice with less debris cover, beheading the glaciers and leaving elongate depressions with moraines along the base of the wall (see Fig. 3*A*). The continuing climate trend caused melting of some of the remaining ice and snow, forming the gullies (alcoves, channels, and fans) that incise and are superposed on the polygons and glacial lobes. (*C*) Asymmetrical crater profile on the crater floor shows that the crater has been modified from its initial fresh-crater morphology (dashed line). The northern crater wall is shallower than the southern wall, and the floor is asymmetrical, tilting from part way up the northern crater wall to the base of the southern wall. This post-crater-formation modification is interpreted to be due to glacial processes in recent geological history. Portion of MOLA profile 15161.

morphology are very similar to deposits at the dichotomy boundary interpreted to be debris-covered glaciers in valley systems (21–23). Recent analyses of SHARAD radar data show evidence that these deposits are indeed predominantly ice (27, 28). Lobe-shaped spatulate depressions along the northern base of the crater wall (Fig. 3 *A* and *B*) are similar to remnant features interpreted to be due to flow of glacial ice in other craters at this latitude (18–20, 22, 23, 29). Furthermore, a change in climate between the time that the broad floor lobes were emplaced and today is indicated by the fact that the multiple lobe-shaped spatulate features at the northern base head from depressions. This is interpreted to mean that previously existing snow and glacial ice have sublimated, leaving hollows and thus beheading remnant glacier ice protected from sublimation by an extensive debris cover out on the crater floor (e.g., 29).

Further evidence for climate change is seen from superposition relationships at high resolution along the northern crater wall (Fig. 3 *A* and *B*). Within the lobate depressions, ample evidence is seen for moraine formation and the downwasting and loss of glacial ice. Inside a broad arcuate wall-facing depression at the northern edge of the floor, a distinctive morainal ridge surrounds a hummocky inner deposit interpreted to be sublimation till remaining from the sublimation and downwasting of relatively pure proximal ice containing some debris. The edges of two lobes are observed in the northern part of the image (left center of Fig. 3 *A* and *B*), interpreted to mark the further retreat and temporal stabilization of the position of the active glaciers.

High-resolution image data show that gullies are superposed on, and postdate, the geologically recent period of active ice lobe formation (Fig. 3 *B*–*D*). The crater interior maps (Figs. 2*B* and 3*B*) show that gullies, consisting of alcoves, channels, and fans (Fig. 1*A*), occur in the regions that would have been the accumulation zones for ice flowing into the lobate spatulate depressions. Superposition relationships show that the gully distal fans embay the base of the slope and the lobate spatulate depressions, indicating a younger age (Fig. 3 *B*–*D*). Furthermore, if accumulation and flow of glacial ice had postdated the gullies, the process would likely have covered or destroyed the fine texture currently displayed by the gullies (Fig. 3 *C* and *D*).

Numerous gullies are observed along the crater wall above the lobate spatulate depressions (Figs. 1–3) and show the classic gully morphology. Broad alcoves high on the crater wall contain channels in their interiors that exit the alcoves, extend downslope, and terminate in a distal fan along the base of the wall slope, commonly in the interiors of the lobate spatulate depressions (Figs. 1*A* and 3 *A* and *B*). The very close stratigraphic relationships between the gullies and the lobate spatulate depressions (Fig. 3 *A* and *B*) strongly suggest a genetic relationship related to the glaciation that marks the modification of the crater floor; these two features share the same source regions (the ice accumulation zone for the spatulate depression and the source area for the gully), suggesting that both may be related to ice accumulation.

Interpretation and Discussion

We interpret the sequence of events on the floor and wall as follows: (*i*) the accumulation of snow and ice on the northern wall to sufficient thickness to cause flow and formation of debris-covered glaciers to produce the major floor lobes; (*ii*) climate change causing a decrease in snow and ice accumulation on the crater walls resulting in sublimation of ice lobes, ultimately leaving the beheaded lobate spatulate depressions; and (*iii*) the formation of gullies on the crater walls, and distal fans in the empty spatulate depressions.

There is clear evidence that activity in the gully fans was episodic (Fig. 3 *B*–*D*). Early distal fans are deformed by a pervasive series of closely spaced fractures that are generally parallel to the base of the slope. Later fans are clearly super-

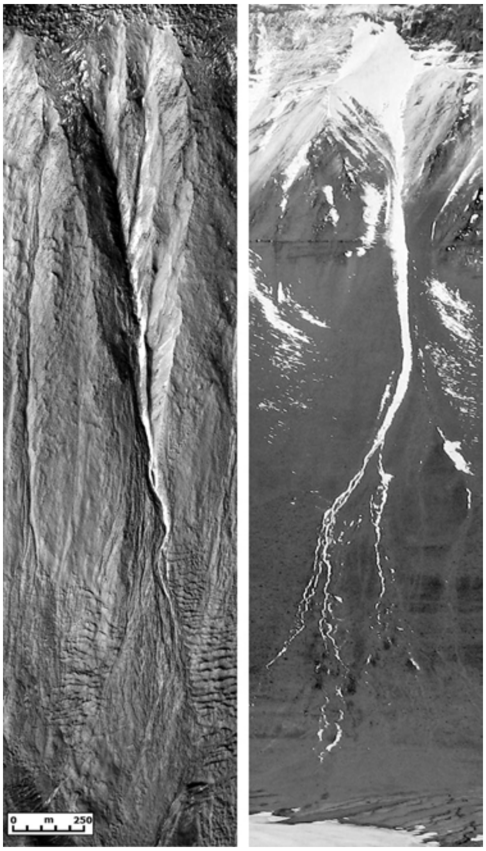

Fig. 2. Gullies, consisting of alcoves, channels, and fans. (*Left*) Gully on the interior crater wall; see Fig. 1 for context. (*Right*) Gully on the wall of Wright Valley, McMurdo Dry Valleys, Antarctica. Note windblown seasonal snow captured in alcove and channels, and preferentially protected from insolation heating. This snow melts as a result of peak daytime insolation during the height of austral summer, and water flows down the gullies causing erosion and redeposition of sediment into the fan (13, 29).

posed on both the earlier fans, and on their deformed bases (Fig. 3 *C* and *D*). The most recent fans consist of braided distributary channels on the fan surface and distal channel deposits. Evidence for episodic activity is also seen in the alcoves and channels. Alcoves host multiple channels that cross-cut, converge, and erode (Figs. 2 *Left* and 3 *A–D*). Sources of the flowing material are broadly distributed within the alcoves. We find no evidence for localized groundwater sources in the form of rock outcrop seeps or spring-like point sources. Rather, the sources are widely distributed in the alcoves themselves, with flow becoming channelized and then concentrated into broader channels downslope, ultimately leading to a dominant channel. Detailed mapping of individual channels (Figs. 2 *Left* and 3) shows evidence for downcutting, multiple channel generations, channel switching, meandering, cutoffs, teardrop-shaped islands, and other evidence of fluvial flow systems (see also ref. 30).

What is the origin of the material causing the gully erosion? Previous hypotheses have suggested an origin from bottom-up groundwater sources (2, 3, 7–9, 11), avalanches and debris flows (16), or top-down melting of ground ice (15), snow (13, 14), or snowpack (12). We interpret the trends in the stratigraphic relationships in the crater to mean that climatic conditions changed from those favoring significant glaciation in the geologically recent past, to those favoring progressively less snow and frost accumulation, ultimately leading to conditions in which there was patchy seasonal snow and ice on the northern crater walls. Such accumulation would concentrate snow and ice specifically in the topographic traps of the alcoves, where shielding would further favor perennial ice retention. For example, a long-term climatic drying trend might cause such an evolution in glaciation and ice retention, with the later phases conducive to seasonal heating and melting of snow/ice accumulated in the alcoves to cause water flow and formation of gully channels and fans.

The stratigraphic relationships in the gully fans suggest that early fans were deformed at the base and later ones were not. Gullies in the Mars-like Antarctic Dry Valleys (Fig. 2 *Right*) show evidence of deformation of their fans by the effects of channel meltwater soaking into the fans, wetting the sediment at the top of the ice table, and causing slumping and faulting as wet debris slides downslope along the top of the ice table (31). We interpret the deformation in the fans on Mars to be caused by similar mechanisms. The lack of deformation on the younger superposed fans (Fig. 3 *C* and *D*) could be due either to (*i*) formation in a slightly dryer climate, and thus a period of less meltwater, or (*ii*) the fans are so recent that deformation has not yet taken place.

What are the causes of the observed trends? The latitude dependence of gully occurrences and the similarity of their occurrences with those of glacial-like viscous flow features here and elsewhere on Mars (18, 20, 22), strongly suggest a link to climate change and variations in the astronomical parameters that drive climate change (e.g., spin axis obliquity and orbit eccentricity) (32).

Glaciers and ice sheets form wherever annual solid H_2O accumulation (frost and snow deposition) exceeds potential ice loss (melting and sublimation). On Mars, the year-average temperature is everywhere below the freezing point of water; however, the present climate is very dry, and ice bodies exposed at the surface are stable and in climatic equilibrium only in the coldest polar areas. For higher values of spin-axis obliquity, compared with the present epoch, the year-average insolation of the polar areas is somewhat greater, and the summertime insolation is much greater. Thus, higher obliquity causes higher seasonal mobility of H_2O and a generally wetter climate. Global climate models predict redistribution of surface solid H_2O in high obliquity epochs (33–35, and references therein). For wetter climate conditions, pole-facing slopes at midlatitudes are very favorable locations for ice accumulation (1, 15, 36). The main reason for this is the nature of the seasonal insolation cycle for such slopes (Fig. 4). The year-average insolation on the pole-facing slopes is lower than on any other slopes or horizontal surfaces at midlatitudes. Even more importantly, in the autumn these slopes get little, if any, insolation and become cold first, whereas in the spring they remain cold much longer than other surfaces (Fig. 4). This leads to greater amounts of accumulation of seasonal CO_2 frost on these slopes and hence to longer periods of preservation of seasonal solid CO_2 deposits. As a result, in the late spring and/or early summer, when the atmosphere in a given hemisphere begins to get warmer and wetter, the pole-facing slopes remain cold and act as an effective trap for atmospheric H_2O. A similar slope effect is observed on the Earth, but it is much more significant on Mars because of (*i*) the weaker thermal coupling between the thin atmosphere and the surface, and hence the greater role of direct insolation; (*ii*) the higher obliquity on Mars in the past; and (*iii*) the presence of seasonal solid CO_2 deposits. In addition to this specific insolation regime, the presence of steep slopes, as on the Earth, may enhance precipitation from upwelling air masses and provide topographic traps for windblown snow (29), thus further increasing deposition. Therefore, pole-facing slopes at midlatitudes are the most probable locations for snow and frost accumulation, and hence for glacier formation under wetter climate conditions.

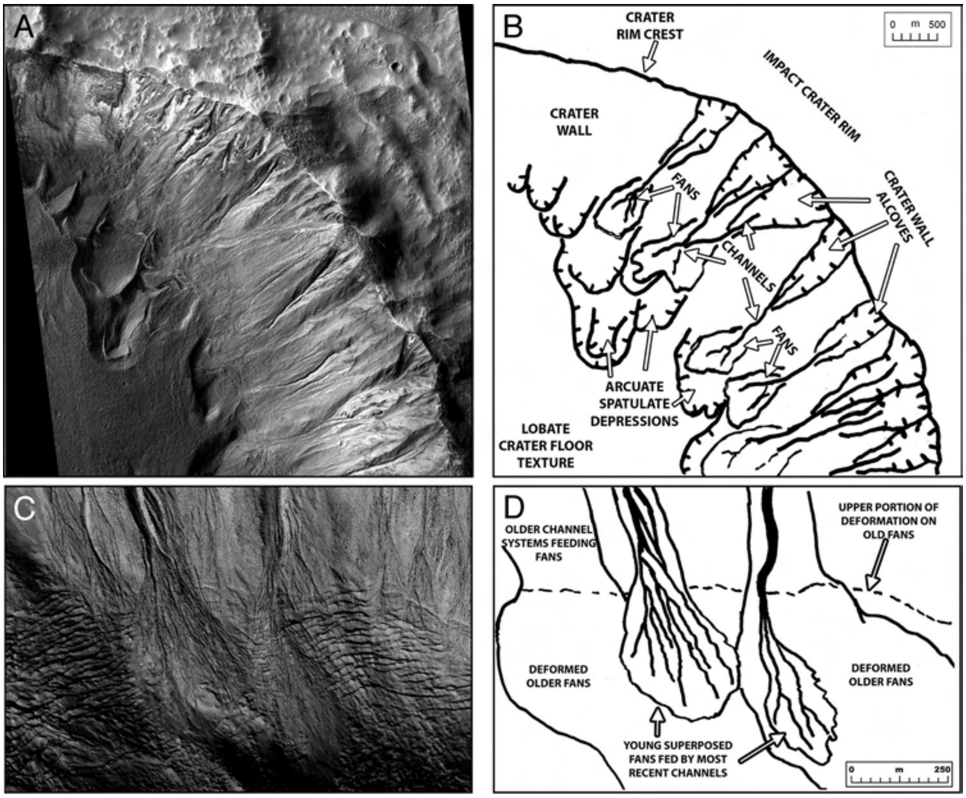

Fig. 3. Detailed relationships of the geomorphic features in the interior of the crater. (*A* and *B*) Image and sketch map of lobate depressions along the base of the northern crater wall and gullies forming on the upper wall and emplacing fans in the central parts of the arcuate spatulate depressions. The arcuate depressions are interpreted to be the beheaded remnants of lobate glaciers that extended downslope from an accumulation zone on the crater wall (top and right) and contributed to the debris-covered lobate deposit on the crater floor (bottom left) (see Fig. 1). The arcuate ridges marking the boundaries are interpreted as moraines formed while the glacier stabilized. The gullies, consisting of alcoves in the upper walls, channels, and basal fans, clearly superpose and fill the empty spatulate depressions. (*C* and *D*) Deformed gully channel and fan deposits forming fractures and terraces near the base of the slope along the eastern and northeastern wall of the crater. Note the stratigraphic relationships between the fractures and terraces and the gully deposits (channels and fans). The most recent channels and fans clearly postdate the fractures. Older channels and fans are clearly cut by the fractures. These relationships suggest a continuing geomorphic response to changing climate conditions, with basal slope deformation (likely involving sliding and deformation of fan sediments dampened by fluvial activity in the gully) in earlier periods of gully formation, but not in later periods. Portions of HiRISE image PSP-001842_1395.

Recent calculations of the spin/orbit parameters of Mars for the past 20 million years (32) show that obliquity has been oscillating with a changing amplitude (up to ±10°) around a mean value that has decreased from ≈35° 10–20 Ma ago to ≈25° for the past ≈3 Ma. We associate the observed waning of glacial activity with this general decrease in obliquity (37, 38). We interpret gullies to have formed in the waning stages of this trend, when the net accumulation/potential loss balance was close to zero or negative, but the climate was still wet enough for significant seasonal accumulation of H_2O frost and snow in the same favorable locations, on the pole-facing slopes (Fig. 4). Unlike the year-average insolation, the summertime insolation for such slopes is not significantly lower than for horizontal surfaces and slopes of other orientations (Fig. 4), and under some conditions is even higher (15). This means that seasonal or minor perennial patches of frost, snow, and ice in gully alcoves could seasonally melt and form fluvial channels and fans (13).

Could such activity be taking place in gullies in similar settings at these latitudes today or in the very recent past? Three conditions must be met to provide liquid water for forming gullies: (*i*) There needs to be a source of water (snow or frost), (*ii*) temperatures must be high enough to cause melting of the snow or frost, and (*iii*) atmospheric pressures must be above the water triple-point pressure. First, we have shown here (Figs. 2 and 3) that pole-facing crater walls at this latitude have been an accumulation zone for water ice during the geologically recent period of glaciation, and are highly likely to continue to be favored sites for accumulation afterward. Present-day seasonal accumulation of H_2O frost is indeed observable both at the Viking Lander 2 site (39, 40), and globally (41), but thicknesses are small. It has been shown on Earth, however, that even in cold hyperarid areas with very low net snow accumulation (e.g., the Antarctic Dry Valleys) windblown snow is preferentially trapped and preserved in topographic lows (such as alcoves and gully channels) until peak summer seasonal insolation induces melting (13, 29). Second, recent improved numerical snowpack mass and energy models treat the rates of sublimation and melting that snowpack (located at 33°S on a poleward-facing slope) undergoes during diurnal variations in insolation (42). This treatment shows that snowpack interior temperatures do reach the melting point for most of the parameter settings, and thus could form liquid water, if the atmospheric pressure is only slightly higher than the triple point pressure. Other estimates (36) gave qualitatively the same results. In this model (42), current formation of gullies by melting of snow would require the deposition of only a few centimeters of snow each year so that snow could then be melted in the spring or summer. Third, analysis of both surface pressures and temperatures on present-day Mars show that (if sufficient sources of water were available) liquid water would be metastable in several areas over ≈29% of the surface of Mars in the present climate system for several tens of sols each year (43, 44). The lack of evidence for liquid water in many of these areas

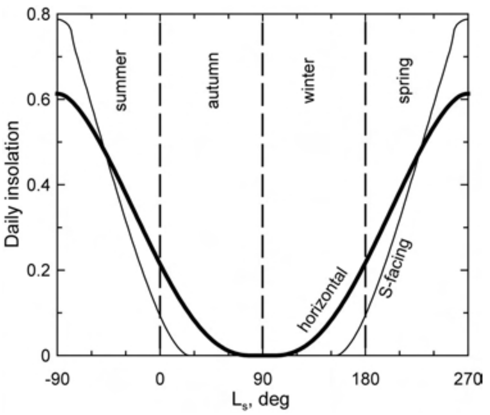

Fig. 4. Seasonal evolution of daily insolation at the location of the crater in Fig. 2 for a horizontal surface (thick line) and for 25°-steep south-facing slope (thin line). Calculations performed for spin/orbit configuration 5.30 Ma ago, when obliquity was higher, 43°. The season is quantified as solar longitude L_s. Insolation is given in ''solar constant'' units: a surface normally illuminated by the Sun at a distance equal to the semimajor axis of Martian orbit during the whole day receives insolation equal to unity. Note that during southern spring, the inclined surface does not see the sun for a much longer period than the horizontal surface, permitting continuous cold temperatures and enhanced CO_2 and H_2O accumulation. Furthermore, as southern summer approaches, the peak insolation for the inclined pole-facing slope is higher, favoring the melting of the accumulated snow and ice.

of predicted stability is attributed to the lack of sources of water when conditions for melting are met.

In the specific case of the gullies treated here (Figs. 1–3), knowledge of the current atmospheric pressure on Mars indicates that the water triple-point pressure is not exceeded. Thus, in the current climate, snow or ice exposed at the surface at this site would sublimate when heated, not melt. However, a minor climate shift toward a slightly higher atmospheric pressure and somewhat larger localized seasonal H_2O accumulation could create conditions for limited meltwater production. This scenario could readily occur in the very recent past, within the present spin/eccentricity configuration, a few hundreds or thousands of years ago, for example, if the perennial CO_2 deposit was absent at the south polar region (45).

Even more likely conditions for gully formation occurred slightly earlier, but still in the very recent geological past, when the climate was significantly wetter than now because of higher polar insolation under somewhat different spin and orbit configurations (33–35). Gullies in the Mars-like Antarctic environment (Fig. 2 *Right*) have water sources from perennial snow banks in alcoves, and from windblown snow that accumulates in the channels themselves (13) (Fig. 1*B*). These gullies display spasmodic activity from melting of such snow deposits induced by peak daytime temperatures in austral summer. Similar processes could also readily occur in these areas of Mars in the geologically recent past (Figs. 1–3).

Do these interpretations apply to gully occurrences that do not occur on pole-facing slopes or are not associated with glacial-like deposits? In the southern hemisphere, 83.8% of the gullies are on pole-facing slopes (14). In the northern hemisphere, where there are many fewer craters and the topography is generally much smoother, gullies are much less abundant and show both pole-facing and equator-facing orientations (46), and latitudinal trends are observed in the presence of ice-rich mantles and gully morphological development and preservation. These trends have also been interpreted (46) in the context of a model for gully formation involving obliquity driven water-rich deposit formation, melting, and desiccation. Furthermore, several workers have shown the close areal correlation and temporal relationship between gullies and glacial-like viscous flow features (18, 38), further supporting the availability of meltwater as a mechanism in gully formation. Finally, the relationships between the very well developed glacial-like features and gullies documented here are testimony to end-member environments in which conditions were such that the accumulation of ice initiated prolonged glacial flow. A wide range of conditions could have existed in which seasonal accumulation of snow and ice would be sufficient to allow melting and form gullies, but the annual balance was not sufficient to initiate glaciation.

Summary and Conclusions

Gullies on Mars occur in specific microenvironments at midlatitudes, and their origin has been controversial. We use the geological record of a crater interior microenvironment typical of the midlatitudes to show that formation of gullies follows a geologically recent period of midlatitude glaciation. The evidence indicates that, in the recent past, sufficient snow and ice accumulated on the northern pole-facing wall of a 10.5-km-diameter midlatitude (40.1°S) impact crater to cause ice flow and an overriding of the crater floor with debris-covered glaciers. As the period of glaciation waned, debris-covered glaciers ceased flowing and lost ice in accumulation zones where ice was exposed directly to the atmosphere (leaving spatulate depressions). After this period, exposed alcoves became the locus of more limited snow/frost deposition, entrapment, and preservation. Stratigraphic relationships show that gully channels and fans are the youngest geomorphic feature, and that they formed in the postglacially exposed crater wall topography. Stratigraphic relationships between gully deposits show that periods of gully fan formation were separated by active slope failure of the fan; the most recent gully fans are not deformed.

These relationships demonstrate an intimate link between geologically recent glaciation and gully formation, with gully formation representing the continuation of a postglacial trend. These relationships, together with models for preferential accumulation, heating, and melting of snow and ice in these environments, demonstrate that liquid water, derived from melting of surface snow and frost, is a plausible mechanism for the formation of gullies. Snow and ice deposits, accumulating in protected alcoves, undergo melting, erode channels, and deposit sedimentary fans.

This top-down melting origin for gullies on Mars is further strengthened by analogous relationships to the Mars-like Antarctic Dry Valleys, where perennial snowpack and seasonal windblown snow trapped in alcoves and gullies (compare Fig. 2 *Left* and *Right*) melt to form channels and fans (13, 29). The specific latitudinal distribution on Mars, combined with the episodic nature of fan formation, implicate astronomical parameters linked to climate change as the cause of gully formation. In the past 20 million years, Mars was characterized by obliquity excursions up to twice its current mean value, decreasing with time to the values observed in the very recent past. Higher obliquities led to more water in the atmosphere in the midlatitudes and deposition of snow and ice, particularly in the favored and shielded microenvironments such as pole-facing crater interiors at these latitudes. The more recent trend toward lower obliquity led to midlatitude conditions conducive to melting of late-stage snow and ice accumulations, and to a transition to the current cold hyperarid desert conditions. Conditions very similar to those at present on Mars favor the occurrence of top-down melting in specific microenvironments, in particular, those in which windblown snow accumulates in alcoves and channels (13, 29) (Fig. 2). Accumulation and melting would be even more favored in the somewhat wetter relatively recent geological past of Mars.

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