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Martian gullies in the southern mid-latitudes of Mars: Evidence for climate-controlled formation of young fluvial features based upon local and global topography

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Abstract

A new survey of Mars Orbiter Camera (MOC) narrow-angle images of gullies in the 30°–45° S latitude band includes their distribution, morphology, local topographic setting, orientation, elevation, and slopes. These new data show that gully formation is favored over a specific range of conditions: elevation (−5000 to +3000 m), slope (>10°), and orientation (83.8% on pole-facing slopes). These data, and the frequent occurrence of gullies on isolated topographic highs, lead us to support the conclusion that climatic-related processes of volatile accumulation and melting driven by orbital variations are the most likely candidate for processes responsible for the geologically recent formation of martian gullies.

Keywords: Mars; Mars, surface; Mars, climate; Geological processes

1. Introduction

Recent detection of gullies in the mid/high-latitudes of each hemisphere of Mars (Malin and Edgett, 2000) has led to the hypothesis that liquid water, at optimum temperature/pressure conditions, has briefly existed in small amounts on the surface during the Late Amazonian. Gullies on Mars exhibit the same general morphology as their terrestrial analogs: a broad alcove at the top of a cliff face which narrows to form a channel that yields a depositional fan at the base of the slope. In almost all locations, gullies appear to be the youngest features in their vicinity: impact craters and other features are rarely seen superposing gullies, and depositional fans frequently overlie recently-formed structures such as small dune fields (Malin and Edgett, 2000; Heldmann and Mellon, 2004).

The global distribution of these features has been documented and a strong latitude dependence has been observed: gullies occur exclusively poleward of 30° in each hemisphere (Malin and Edgett, 2000; Christensen, 2003; Milliken et al., 2003; Heldmann and Mellon, 2004), with a larger concentration in the southern hemisphere. Attention has been given to compositions other than water for the carving agent [liquid CO_2 (Musselwhite et al., 2001); CO_2 frost (Ishii and Sasaki, 2004); brines (Lane et al., 2003); dry flows (Treiman, 2003)], and to the geological mechanisms necessary to create the observed features. Two end-member hypotheses have been proposed: release of subsurface volatiles under pressure (Malin and Edgett, 2000) and accumulation/melting of surface snowpacks (Hecht, 2002; Mangold et al., 2003; Hartmann et al., 2003), with several variants also suggested, including melting of near-surface ground ice (Costard et al., 2002; Mangold et al., 2003; Hartmann et al., 2003), geothermal activity (Gaidos, 2001; Mellon and Phillips, 2001), release of subsurface liquid CO_2 (Musselwhite et al., 2001), and dry granular flows (Treiman, 2003). While surveys of the entire southern hemisphere (Malin and Edgett, 2000; Milliken et al., 2003; Edgett et al., 2003; Heldmann and Mellon, 2004) have been undertaken to analyze these features, no global survey has been published that includes data obtained through the targeting efforts of the MOC team in 2000 and 2001. The survey of Heldmann and Mellon (2004) is through mission phase M18 (August, 2000), while the survey of Berman et al. (2005) is through E18 (July, 2002), but

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only covers the Phaethontis Quadrangle (MC-24). The limited focus of these surveys highlights the need for a more comprehensive survey of these features. These previous surveys have provided insight into morphology, distribution, slopes, and orientation of martian gullies, but little attention has been given to the immediate geological context within which gullies are found. We analyzed all of these properties, including geologic context, and use these data to evaluate the various hypotheses for gully formation on Mars. Coincident with our analysis, Balme et al. (2006) used MOC and High Resolution Stereo Camera (HRSC) data over the entire southern hemisphere to analyze the orientation and general distribution of gullies on Mars, including their frequent occurrence on isolated topographic highs. Our contribution complements their work; we assess gullies in the 30°–45° S latitude band, and focus on the role of topography in their formation. The Mars Orbiter Laser Altimeter (MOLA) gridded dataset has allowed us to determine the range of elevation at which these features are found, and analysis of MOLA point-to-point data provides us with the data necessary to determine the local slopes at which gullies can form on Mars. We also test the groundwater hypothesis by analyzing the local topography where gullies occur.

2. Testing hypotheses of formation

Most proposed models of gully formation explicitly or implicitly make predictions about the conditions necessary for formation. Here we review these to provide a basis for data collection and distinguishing among them with these new observations.

Models that invoke groundwater seepage (Malin and Edgett, 2000; Gaidos, 2001; Mellon and Phillips, 2001; Edgett et al., 2003; Heldmann and Mellon, 2004) all call upon either sufficient subsurface volume behind the gully for a confined aquifer that undergoes fluctuation in pressure or sufficient geothermal activity that would transport volatiles from depth to the surface, which would then be released through seeps. Additionally, a preference for gullies at lower elevations would be expected if groundwater were a primary agent for carving these channels, given the more likely availability of groundwater resources and higher atmospheric pressure conditions that would allow liquid water to be stable on the surface (Haberle et al., 2001; Hecht, 2002). These criteria allow us to make predictions with regard to the global and local distribution of gullies: Globally, we would expect to find gullies preferentially at low elevations, and, locally, we would not expect to find them on isolated topographic landforms such as central peaks, mesas, and raised crater rims. We would also expect that there would be no dependence on slope if gullies were formed from a subsurface source.

Snowmelt models (Christensen, 2003; Hecht, 2002) predict that gullies should occur in locations conducive to ice/frost accumulation, such as steep, shaded slopes in the mid/high latitudes in each hemisphere (Hecht, 2002), where ice would accumulate instead of sublimating. Snowmelt models also predict that an elevation dependence should be observed: since liquid water needs elevated atmospheric pressure to exist on the martian surface, gullies should not occur at higher elevations and more likely at lower elevations. Kossacki and Markiewicz (2004) also determined that the volume of water ice is dependent on water content in the atmosphere and local wind speeds. We would also expect to find gullies preferentially on steeper slopes that would provide the appropriate insolation conditions for the accumulation of snow (Hecht, 2002). Finally, the snowmelt model would predict that gullies should be found on a variety of landforms, including isolated topographic highs that would be unlikely candidates for groundwater accumulation, such as central peaks, dunes, raised crater rims, and small mesas.

Provided the contrasting physical processes that are required for these two hypotheses, these two end-members can be tested against each other by addressing the following fundamental questions: At what elevation range do gullies occur? On what range of slopes are they found? Do gullies occur on isolated topographic highs that might be insufficient to host an aquifer? We also use our data from this survey to perform our own orientation analysis, as previous studies have produced conflicting results (Malin and Edgett, 2000; Edgett et al., 2003; Heldmann and Mellon, 2004; Berman et al., 2005).

Our survey consists of all Mars Orbiter Camera (MOC) narrow-angle data obtained between 30° and 45° S, through relay phase R09 (September, 2003), which includes the portion of the mission that was dedicated to targeting of these features (2000–2001) (Edgett et al., 2003). We documented all examples of gullies within this latitude band, made measurements of the orientation and elevation of source alcoves, slopes of the surrounding terrain, and mapped a subset of examples of gullies found along the slopes of isolated surfaces, similar to the method employed by Balme et al. (2006). We now focus on the local and global topography and examine the nature of these data and several of these examples in detail and evaluate the contrasting formation hypotheses in the light of these new data.

3. Survey

Our survey consisted of all 5168 MOC narrow-angle images acquired from the beginning of the mission through relay phase R09 (September, 2003) within the 30°–45° S latitude band. This range was chosen for its high density of gullies based upon previous surveys (Malin and Edgett, 2000; Milliken et al., 2003; Heldmann and Mellon, 2004), and because it spans nearly the full spectrum of surface elevation on Mars, from the highest region of Thaumasia (∼8 km above datum), to the floor of Hellas basin (∼8 km below datum), providing the greatest possible sample of elevations on Mars. Our survey overlaps with the recently published survey of Balme et al. (2006), who analyzed the entire southern hemisphere with both MOC and HRSC data.

Individual gullies were mapped based upon having at least two of the three primary morphologic features outlined by Malin and Edgett (2000): alcoves, channels, and depositional fans. Since many gully channels are highly sinuous, orientation measurements were made based upon the initial orientation of the channel as it extends downslope from the base of the alcove, before being diverted by preexisting topography on the slope.

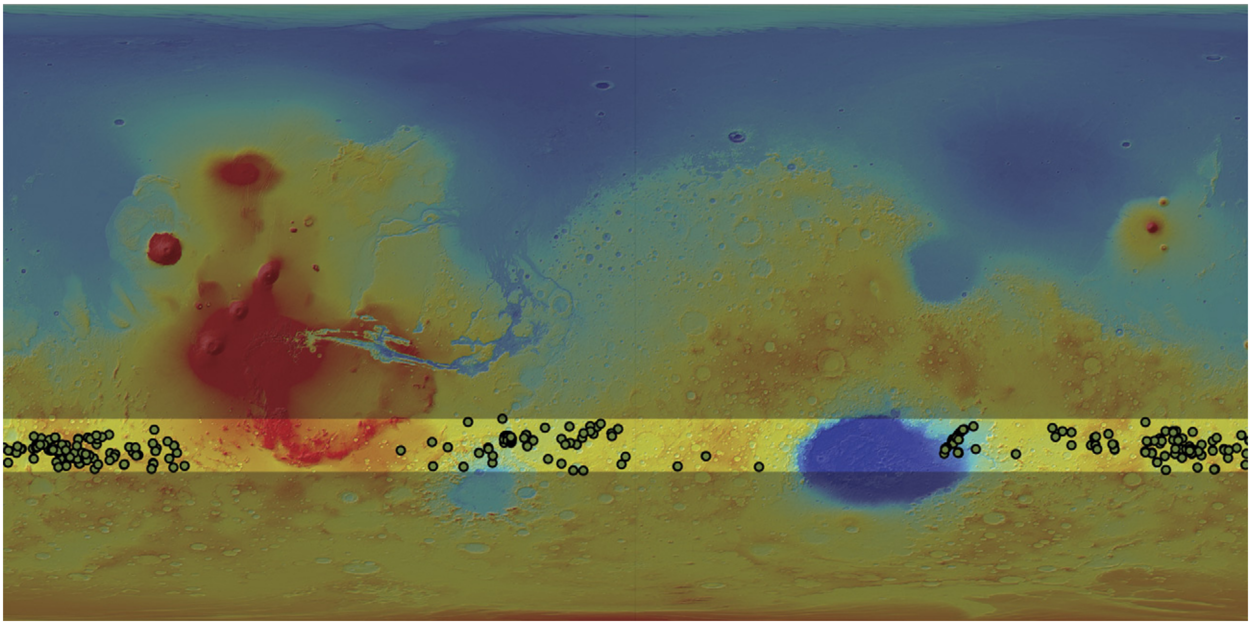

Fig. 1. Location of gully clusters within 30°–45° S.

All images that showed evidence for gully landforms were projected and mapped in GIS software to determine accurate orientation information and to eliminate redundant measurements of gullies that have been imaged multiple times. The images were also registered with MOLA data to obtain elevation information for the source alcoves of these gullies. Since elevation was being analyzed on a global scale (8 km above the datum to 8 km below), gridded MOLA data were sufficient for this portion of the analysis.

Gridded MOLA data, however, is of insufficient resolution to determine the slopes of gullies. Therefore, individual MOLA tracks were extracted at gully sites used to analyze the slopes upon which gullies are found within the 30°–45° S latitude band. MOLA tracks are ∼N–S trending, so only gullies with orientations within 30° of north or south were considered in the analysis. Gullies were grouped into clusters based upon proximity to each other on the same slope face. Once defined, each cluster was projected onto a MOLA gridded topography map to verify that registration with MOLA data was accurate. Clusters that were misregistered by over 1 km were not included in the analysis of individual MOLA tracks. Maximal slopes were then calculated from individual profiles that intersect that cluster and averaged together to determine the mean slope of the wall that hosts that cluster of gullies. Clusters that showed a wide variance in slope based upon comparison of multiple tracks were excluded from further analysis.

The MOLA data set, MOC wide-angle images and Themis Visible and IR data provided context data for the MOC narrow-angle images, which was necessary for determining the geological surroundings of the observed gullies. Gullies that were observed on the slopes of isolated elevated surfaces were segregated and further studied as a subset of the entire sample set of gullies. Features that were included in this subset were gullies found along the slopes of central peaks, small mesas, knobs, the crests of raised crater rims, and the exterior slopes of raised crater rims.

4. Results

Of the 5168 MOC narrow-angle images that were documented, 406 images (7.9%) showed clear evidence for gully landforms, with the distribution of features not being uniform (Fig. 1). The highest concentrations are found along the northern margin of Argyre basin (320° E, 35° S), northern Noachis Terra (20° E, 40° S), Terra Sirenum (185° E, 37° S), and along the walls of the Hellas outflow channels (90° E, 35° S) (Fig. 1). Of the 3154 gullies observed, 266 (8%) were found along the slopes of topographically isolated surfaces, as opposed to crater or valley walls. We now examine the entire population of these features in detail with regard to their distribution, global elevation, local slope, local geologic context, and orientation.

4.1. Global elevation

Image samples were analyzed over a range of 16 km (8 km above to as low as 8 km below the datum) (Fig. 2a). Gullies were found between −5177 and 3089 m (Fig. 2b), most commonly in typical southern highlands terrain, between 0 and 3 km elevation. This is consistent with the altimetry-frequency distribution of terrain within this latitude band (Fig. 2a). Most striking is the lack of gullies at both extremes of the elevation spectrum: no gullies are observed on Thaumasia (>3500 m) despite a heavily cratered surface yielding a high availability of slopes conducive to gully formation. There were also no gullies found on the floor of Hellas (<5500 m). Mean elevation for gullies within this latitude band is near the datum at ∼240 m.

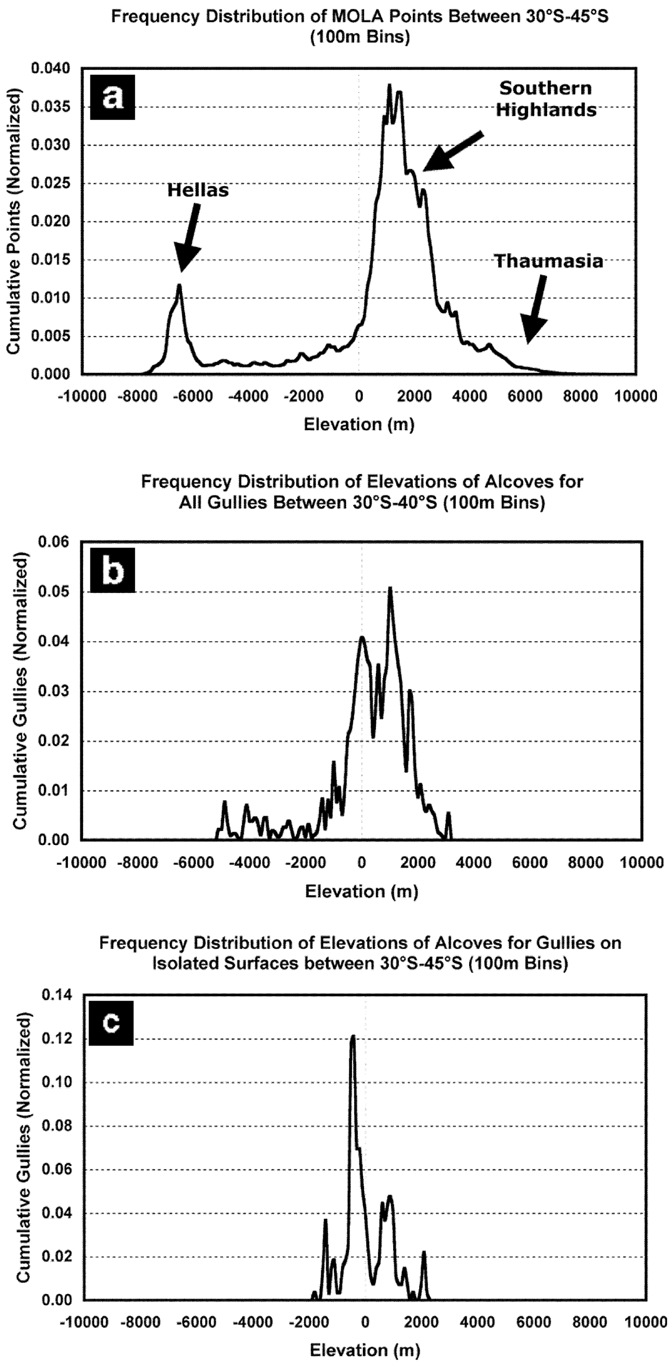

Fig. 2. (a) Frequency distribution of elevation based upon MOLA gridded data within the 30°–45° S latitude band. (b) Frequency distribution of alcove elevations for all gullies observed. (c) Frequency distribution of alcove elevations for gullies on isolated surfaces.

4.2. Local slopes

Our data show that gullies occur on steeper slopes than previously reported; 162 clusters were identified and their slopes were segregated into 2 degree bins (Fig. 5). While Heldmann and Mellon (2004) used gridded MOLA topography to calculate a mean slope of 21° between 30° and 72° S, we used MOLA track data to find that 87% of gully clusters in the 30°–45° S latitude band occur on slopes in excess of 21°. The mean slope is 26.5° while the median is 26.8°. The largest concentration of clusters are found on slopes between 24° and 30°, where 54.3% of gully clusters occur (Fig. 5). The discrepancy with the Heldmann and Mellon (2004) results can be due to the presence of high-latitude gullies in their survey; it is also probable that their use of gridded topography led to systematic underestimation of slopes. Our analysis did not show any correlation between gully slope and latitude or between gully slope and orientation.

4.3. Local geologic context

Of the 3154 gullies observed, 266 (8%) were found on the flanks of topographically isolated surfaces and mapped using GIS software. These gullies include those found on central peaks (Fig. 6), small mesas, knobs, dunes, the crests of raised crater rims (Figs. 7 and 8), and the outside slopes of raised crater rims (Figs. 7 and 8). With regard to distribution, these features are found in zones similar to those of traditional interior crater wall gullies (Fig. 1), with the highest concentrations being within the cratered terrain in northeastern Argyre basin (37° S, 323° E), the terrain within and around Newton Crater (40° S, 203° E), and the cratered highlands to the east of Argyre (40° S, 345° E). These results are consistent with regard to abundance and distribution to the recent findings of Balme et al. (2006), who found that ∼10% of gullies in the southern hemisphere are found on "knobs/hills."

Gullies on topographically isolated surfaces show the same range in morphology as traditional crater-wall gullies. Alcove widths range from <100 to ∼700 m, and there is no evidence observed that alcoves consistently emanate from beneath a distinct outcrop layer. Rather, these gullies most commonly form at different elevations along the same slope, even when layering is observed (Figs. 6a and 8). At MOC resolution, alcove walls show little evidence of degradation and appear fresh in all cases. All gullies on isolated surfaces exhibit well-defined channels that range from linear to highly sinuous, trending downslope for hundreds of meters. When depositional fans are visible within the MOC frame, they appear fresh and always superpose the surrounding terrain.

In a manner similar to traditional crater-wall gullies, these isolated gullies show a poleward trend in orientation. Of the 266 total gullies mapped, 204 (76.7%) are poleward-facing (Fig. 3b). "Average orientation" of this subset is 193°, slightly west of due south.

The elevation dependence for gullies on isolated surfaces is even more dramatic than that for traditional crater-wall gullies. Despite sampling from elevations as high as ∼8 km and as low as ~ -8 km (Fig. 2c), alcoves for gullies on isolated surfaces are only observed at elevations greater than -1822 m and less than 2156 m (Fig. 2c). The average elevation for gully alcoves on isolated surfaces is -33 m, slightly lower than the average elevation for all gullies (239 m).

4.4. Orientation

Gullies on all surfaces show a dominant poleward trend within the 30°–45° S latitude band. Of the 3154 total gullies

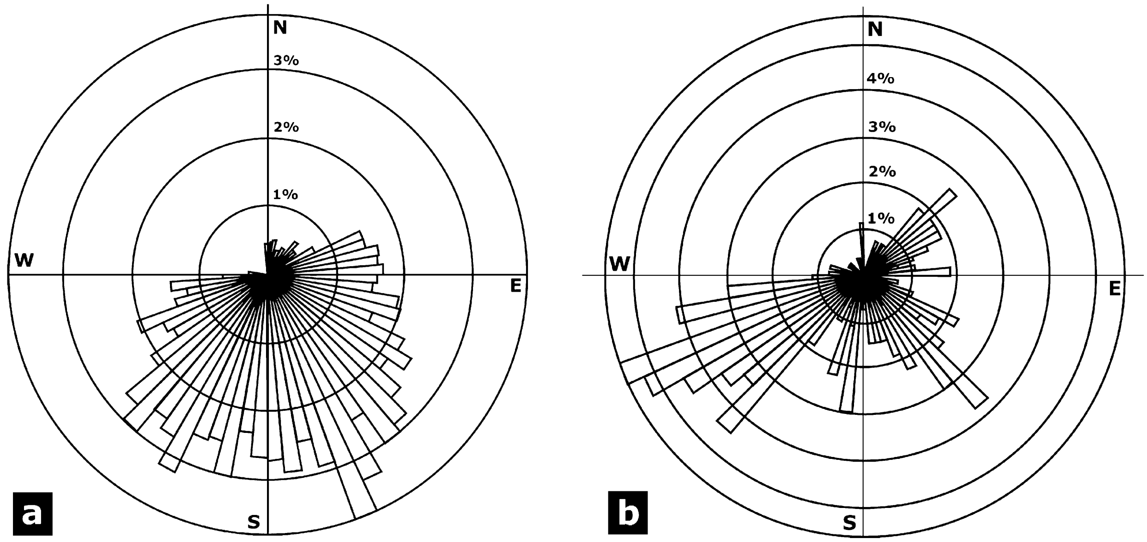

Fig. 3. (a) Rose diagram of gully orientation for all gullies in the 30°–45° S latitude band. (b) Rose diagram of gully orientation for gullies found along the slopes of topographically isolated surfaces in the 30°–45° S latitude band.

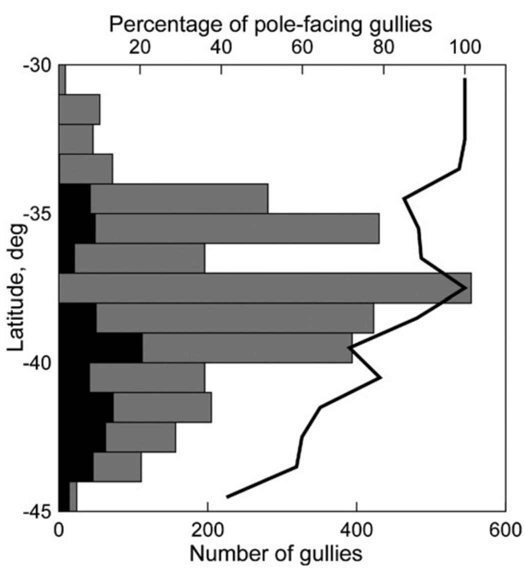

Fig. 4. Bar chart, frequency distribution of gullies as a function of latitude within 1 degree latitude bins. Black parts of bars correspond to the north- (equator-) facing slopes, gray parts denote south- (pole-) facing slopes. Line shows the percentage of gullies at pole-facing slopes.

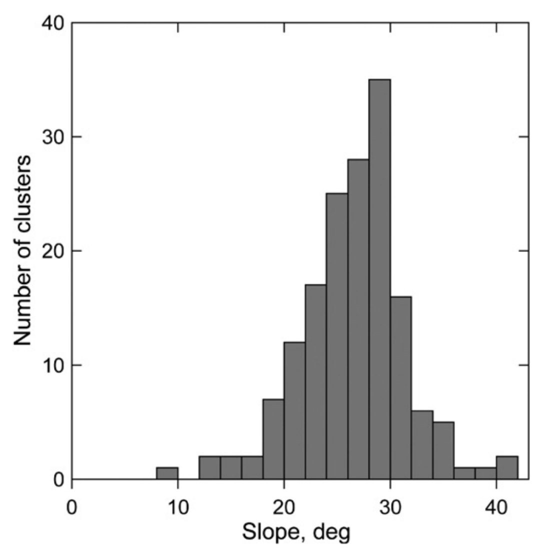

Fig. 5. Frequency distribution of gully clusters as a function of slope within 2° bins.

mapped, 2643 show a poleward trend (83.8%) (Fig. 3a), consistent with the results of Heldmann and Mellon (2004), Berman et al. (2005), and Balme et al. (2006). We calculated the azimuth of a vector sum of unit vectors directed along gullies; this azimuth, 166.5° characterizes an "average direction" of gullies. There also is a latitude dependence for orientation: the few gullies that are equator-facing are preferentially found at higher latitudes than those that are pole-facing (Fig. 4). Within the 30°–45° S latitude band, this trend is consistent with the observations of Heldmann and Mellon (2004), Berman et al. (2005), and Balme et al. (2006). According to those studies, the latitude dependence is even more accentuated at higher latitudes.

Issues of bias in data collection have also been taken into consideration. Heldmann and Mellon (2004) warned that targeting of poleward-facing slopes after the discovery of martian gullies and the illumination saturation of equatorward-facing slopes could result in an artificial preference for poleward-facing gullies. The frequent occurrence of equatorward-facing gullies at higher latitudes (Heldmann and Mellon, 2004; Berman et al., 2005; Balme et al., 2006), however, shows that these slopes have been imaged frequently in MOC data. Additionally, slope image saturation on equatorward-facing slopes is offset by poleward-facing slopes often being in complete shadow.

5. Discussion and interpretation

While it is important to remember that dry flows have the capacity to result in morphology similar to that of fluvial systems (Treiman, 2003; Shinbrot et al., 2004), the complete absence of gullies in the equatorial region of Mars, their frequent occurrence at slopes well below the angle of repose, and the consistently sinuous nature of the observed features suggests a strong fluvial component to their formation. Recent modeling (Haberle et al., 2001; Hecht, 2002) has shown that liquid water can exist on present-day Mars for brief periods at optimal locations. The source for this fluid, however, has been the focus of debate with regard to these features. Two end-member hypotheses have been proposed: release of subsurface volatiles under pressure (Malin and Edgett, 2000) and accumulation/melting of surface snowpacks (Christensen, 2003). We interpret the results of this study to support the hypothesis that formation of gullies within the 30°–45° S latitude band is related to snow and ice accumulation and melting due to climatic processes. Some variations on the snowmelt end-member hypothesis, such as contributions from melting ground ice (e.g., Costard et al., 2002; Mangold et al., 2003) may also play a role.

We have found 3154 gullies within 406 MOC narrow-angle images that include 266 that are found along the slopes of isolated topographic surfaces. For these latter examples, subsurface aquifers, a necessary ingredient in all groundwater models, are highly unlikely to exist due to volume constraints. Groundwater models call for an upper impermeable rock layer to serve as a cap to the water table (Malin and Edgett, 2000; Mellon and Phillips, 2001), so that groundwater emanates laterally through seeps when undergoing fluctuations in pressure. In addition to the documentation of gullies on dune faces that lack any rock layers (Reiss and Jaumann, 2003; Reiss et al., 2004; Dickson and Head, 2005), Treiman (2005) pointed out that the cratering event itself disrupts the immediate stratigraphy to such an extent that crater walls are poor locations for impermeable rock layers. Our documentation of gullies along the flanks of other topographically isolated slopes supports these findings.

For gullies on topographically isolated slopes, there is also no distribution correlation with features that might be candidates for geothermal activity, which would be expected for models that call upon volatiles being transported to the surface from depth. Rather, gullies on isolated slopes are found in the same regions as traditional crater/valley-wall gullies, only in smaller abundance, due to the lower availability of steep slopes. Another potential source of heat for crater-related gullies is the impact event itself, but recent modeling by Abramov and Kring (2005) indicates that 30 km diameter craters complete cooling cycles within 10^5 years, and even 180 km diameter craters finish cooling within 2×10^6 years. The relative youth of martian gullies (<10 myr) in comparison to their host craters make impact heating implausible for the melting of surface snowpacks.

The initial observation that families of gullies all emerge from beneath consistent layers (Malin and Edgett, 2000) has been used to argue for the groundwater hypothesis (Malin and Edgett, 2000; Mellon and Phillips, 2001; Edgett et al., 2003), but our updated survey of the southern mid-latitudes has found this scenario to be the exception rather than the rule. Within the subset of images of gullies on the slopes of isolated surfaces, nearly all adjacent alcoves emanate from different elevations (e.g., Fig. 6), even when layering is observed, and alcoves are frequently found at the crests of raised crater rims (Figs. 7, 8). Gully alcoves are often obscured by surface mantling units that

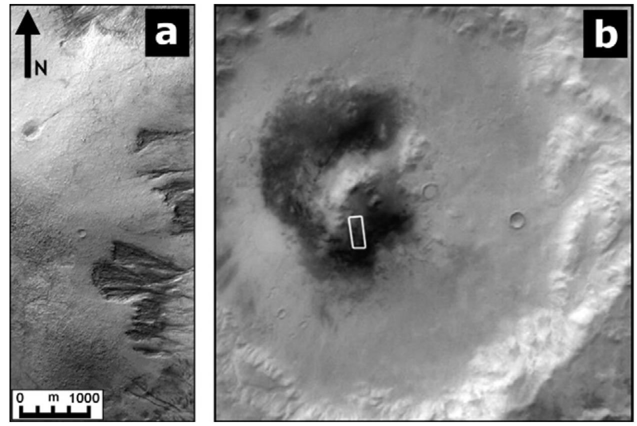

Fig. 6. (a) MOC narrow-angle image E1500539 showing gully alcoves incised into the central peak of Lohse crater. (b) MOC wide-angle image E1500540. White box represents location of (a).

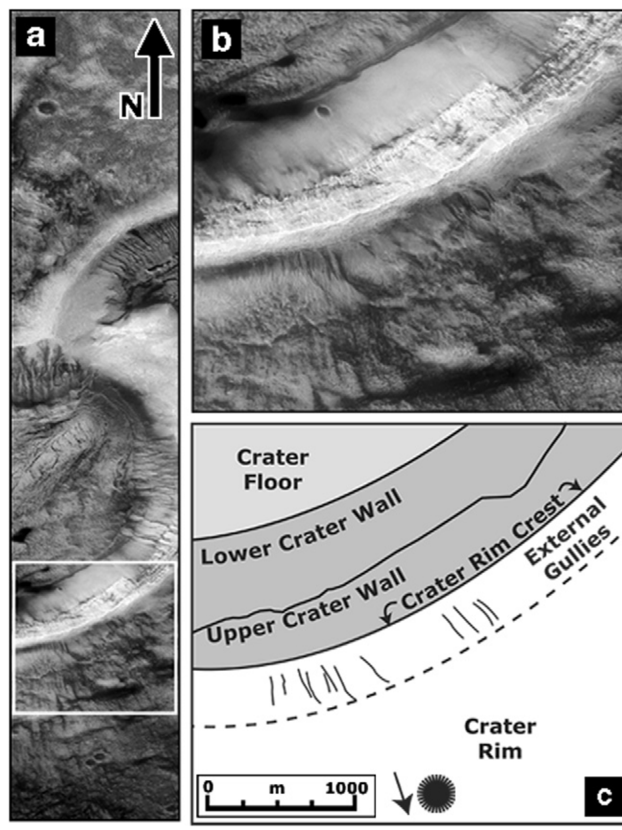

Fig. 7. (a) MOC narrow-angle image E1103663, showing context for (b). Notice gullies at the northern rim of the central crater, with alcoves found atop the crest of the crater rim. (b) Subframe of (a), showing gully landforms along the exterior of the crater rim. (c) Sketch map of landforms in (b).

are draped over the top of a cliff face, consistent with the observations of the gullies along the walls of the Hellas outflow channels (Bleamaster and Crown, 2005).

Our survey reveals that elevation conditions, both globally and locally, are critical to the formation of martian gullies. The majority of gullies are found within the cratered terrain that dominates the 30°–45° S latitude band, but no gullies of any kind were found within the craters on Thaumasia or on the floor

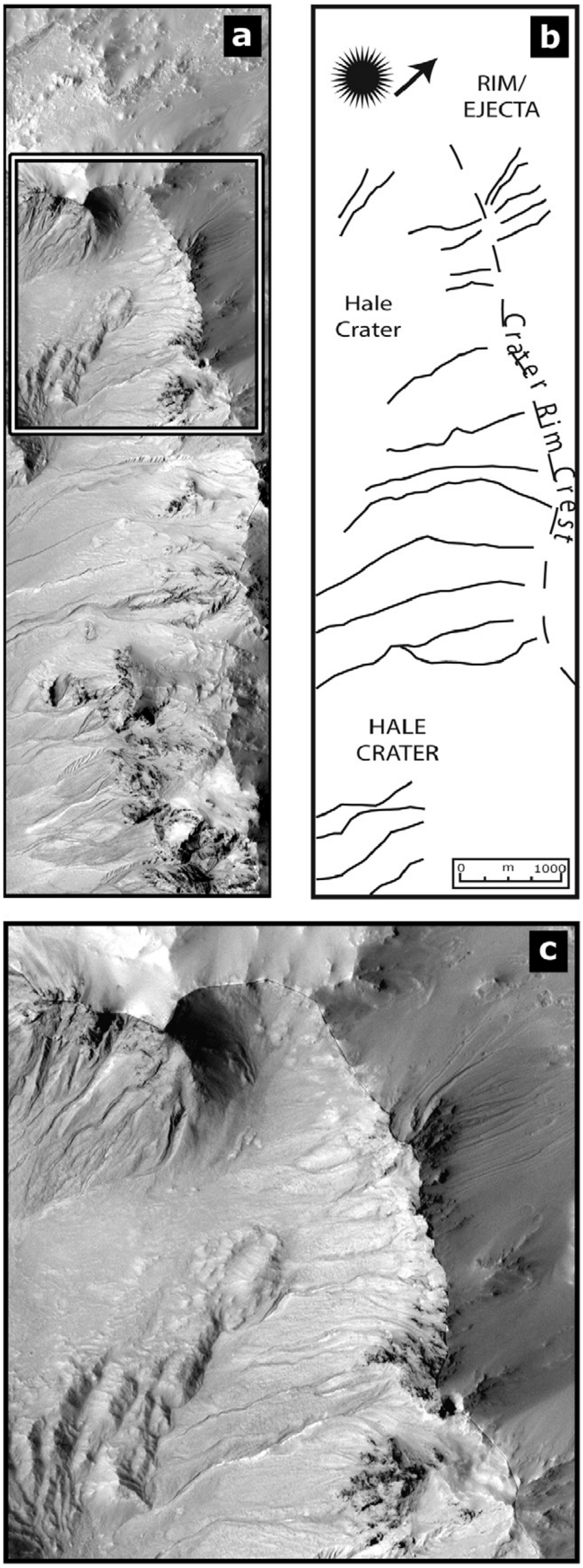

Fig. 8. (a) Subframe of MOC narrow-angle image R0702277, showing gullies on opposite sides of the northeastern rim of Hale Crater. Opposite sides of the crater rim were contrast stretched separately to highlight gullies. Box represents context for (c). (b) Sketch map for (a). (c) Subframe of (a), showing gullies incised into opposite sides of the same crater rim.

of Hellas basin (Fig. 1). While the paucity of gullies in Hellas is likely to be due to a lack of available steep slopes (Kreslavsky and Head, 2000; Neumann et al., 2003), the lack of gullies on Thaumasia is strongly consistent with the snowmelt model. Thaumasia is heavily cratered and has an abundance of high-slopes (Kreslavsky and Head, 2000) that would be conducive to gully formation based upon their distribution elsewhere in the 30°–45° N latitude band, but pressure at that altitude (>3 km above datum) would be low, causing ice to sublimate instead of accumulating, even at increased obliquity (Hecht, 2002).

Locally, the occurrence of gullies on steep slopes is another indicator of climate control for their distribution. Poleward-facing steep slopes such as the ones observed are ideal cold traps at mid-latitudes, as they shield direct sunlight and allow for ice to accumulate without sublimating (e.g., Hecht, 2002). The paucity of gully clusters on slopes less than 20° (8.6%) is consistent with the atmospheric deposition model: any surface snowpacks on low slopes are exposed to more sunlight and are more susceptible to sublimation, while those on high-slopes are protected by shade and are more likely to accumulate and subsequently melt. This preference for high-slopes and lack of mid-slopes should not be observed if subsurface aquifers were the source of the fluid.

The observed steep slopes also imply that less water is necessary to trigger downslope movement to carve gully channels. Of the 162 gully clusters in this survey that are aligned with MOLA tracks, 153 (94%) occur on slopes below the angle of repose (∼35°; Van Burkalow, 1945), meaning that dry processes alone (Treiman, 2003) are less likely to carve channels on these slopes. But the concentration of gullies between 20° and 30° slopes [76.5% (Fig. 5)] suggest that not as much liquid water would have been necessary to initiate flow. This suggests that the relative low-abundance of H_2O in the atmosphere could be a sufficient source to deposit the necessary water needed to melt and carve the observed channels as sediment-rich flows.

In addition to our topographic analysis, orientation conditions also suggest a climatic dependence for the formation of gullies on Mars. Malin and Edgett (2000) observed that gullies on Mars were oriented towards the poles in each hemisphere, but Edgett et al. (2003) revised that finding, concluding that there was no evidence for a preferred orientation direction. Their survey classified ∼10,000 observed gullies by hemisphere to show that there was no trend, but Heldmann and Mellon (2004) observed a latitude dependence to orientation: gullies within the 30°–44° S and 58°–72° S latitude bands were strongly oriented poleward, while gullies from 44°–58° S were oriented equatorward, which is consistent with the observations of Berman et al. (2005) in the Phaethontis Quadrangle (MC-24). Our updated survey shows a dominant poleward trend within the 30°–45° S latitude band for all gullies (Fig. 3a) and a similar trend for gullies on isolated surfaces (Fig. 3b), consistent with the analysis of Balme et al. (2006). This is consistent with the hypothesis that steep, shadowed crater walls in the mid/high-latitudes of Mars are effective cold traps where there is insufficient insolation to cause ice to sublimate, as would be expected on equator-facing slopes (Hecht, 2002). As previous studies have demonstrated (Costard et al., 2002), as the obliquity of Mars increases, atmospheric pressure will rise above the triple point of water at these locations, and the increased solar insolation on poleward facing slopes will result in melting of the accumulated ice instead of sublimation. The latitude-dependence observed by other workers (Heldmann and Mellon, 2004; Berman et al., 2005) is consistent with this model, as the lower temperatures at higher latitudes would lead to increased stability for snow on the surface.

Hecht (2002) made several predictions about the distribution of recent gullies on Mars if atmospheric deposition is the source of the carving agent. His work predicted that the key constraint to gully formation on Mars is not where ice would most likely melt, but where ice would most likely accumulate. Our observations are strongly consistent with this prediction and provide a framework to determine the ideal setting for gully location on Mars. The spatial and morphologic properties of a surface that are most conducive to gully formation are as follows:

1. Mid to high latitude. The thin martian atmosphere enhances sublimation on the surface of Mars as direct sunlight efficiently raises the temperature of exposed surface ice above the triple point (Hecht, 2002). Locations within $\sim 30°$ of the equator receive too much sunlight for ice to accumulate before melting/sublimation.
2. High slopes. MOLA track data show that gullies rarely form on surfaces less steep than 20° (8.6%). Steep slopes are more conducive to downslope flow and provide less exposure to direct sunlight, temperature increase, and resulting sublimation.
3. Low elevation. Surface observations suggest that increases in obliquity can increase the pressure on the surface enough so that snowpacks below 3 km elevation can melt, but any above 3 km remain as ice or sublimate.
4. Pole-facing slopes. In the 30°–45° S latitude band, exposure to solar insolation on equator-facing slopes results in rapid sublimation of atmospherically deposited snowpacks, yielding a dominant poleward trend.

Additionally, our study shows that gullies form on these slopes independent of their immediate geological surroundings. They form on topographically isolated features such as central peaks, mesas, raised crater rims, and dunes, where groundwater aquifers either cannot or are highly unlikely to exist.

Could gullies on topographically isolated slopes form by a different process than traditional crater-wall gullies? The general consistency between the two groups with regard to morphology, orientation, distribution, and source elevation, argues against this possibility. Given the climatic signatures (orientation, elevation, slope) and the geological context (on the flanks of isolated surfaces), atmospheric deposition of snowpacks and melting at high obliquity in the recent geologic past is the most favorable mechanism for the formation of gullies.

Acknowledgments

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