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Gully formation on Mars: Two recent phases of formation suggested by links between morphology, slope orientation and insolation history

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ABSTRACT

The unusual 80 km diameter Noachian-aged Asimov crater in Noachis Terra (46°S, 5°E) is characterized by extensive Noachian–Hesperian crater fill and a younger superposed annulus of valleys encircling the margins of the crater floor. These valleys provide an opportunity to study the relationships of gully geomorphology as a function of changing slope orientation relative to solar insolation. We found that the level of development of gullies was highly correlated with slope orientation and solar insolation. The largest and most complex gully systems, with the most well-developed fluvial landforms, are restricted to pole-facing slopes. In contrast, gullies on equator-facing slopes are smaller, more poorly developed and integrated, more highly degraded, and contain more impact craters. We used a 1D version of the Laboratoire de Météorologie Dynamique GCM, and slope geometries (orientation and angle), driven by predicted spin-axis/orbital parameter history, to assess the distribution and history of surface temperatures in these valleys during recent geological history. Surface temperatures on pole-facing slopes preferential for water ice accumulation and subsequent melting are predicted to occur as recently as 0.5–2.1 Ma, which is consistent with age estimates of gully activity elsewhere on Mars. In contrast, the 1D model predicts that water ice cannot accumulate on equator-facing slopes until obliquities exceed 45°, suggesting they are unlikely to have been active over the last 5 Ma. The correlation of the temperature predictions and the geological evidence for age differences suggests that there were two phases of gully formation in the last few million years: an older phase in which top-down melting occurred on equator-facing slopes and a younger more robust phase on pole-facing slopes. The similarities of small-scale fluvial erosion features seen in the gullies on Mars and those observed in gullies cut by seasonal and perennial snowmelt in the Antarctic Dry Valleys supports a top-down melting origin for these gullies on Mars.

1. Introduction

The discovery of gullies on Mars attracted significant attention because of the inferred role of liquid water in carving apparently modern landscapes (Malin and Edgett, 2000a). Gullies were initially interpreted to be the result of groundwater discharge (Malin and Edgett, 2000a; Heldmann and Mellon, 2004; Heldmann et al., 2005). Further analysis of the current metastability of liquid water on the surface of Mars generated alternative explanations, including atmospherically deposited sources of water (Costard et al., 2002; Hecht, 2002; Christensen, 2003; Dickson et al., 2007a; Head et al., 2008; Williams et al., 2009). Global surveys have demonstrated that gullies are limited to latitudes >30° (Malin and Edgett, 2000a) and that they have a preference for pole-facing orientations below about 45° latitude (Costard et al., 2002; Heldmann and Mellon, 2004; Dickson et al., 2007a; Dickson and Head, 2009).

Costard et al. (2002) used a one-dimensional version of the atmospheric Laboratoire de Météorologie Dynamique (LMD) GCM (Forget et al., 1999) to demonstrate that ice accumulation and near-surface melting of ground ice could account for this spatial distribution. Their mechanism involved the accumulation of near-surface water ice on pole-facing slopes and its preservation due to the low surface temperature maintained by a seasonal CO_2 frost cover. Springtime removal of the CO_2 frost, and the subsequent rapid heating of the underlying water ice, was invoked as a means of melting water ice, flow initiation, and subsequent gully formation.

Recent high-resolution studies of individual gully sites have revealed a wide range in gully morphology. Evidence for different forms of erosion are present, ranging from wet debris flows (e.g., Levy et al., 2010) to fluvial stream flow incision (e.g., McEwen et al., 2007; Head et al., 2008). The latter being associated with the occurrence of fine-scale channel forms such as streamlined islands, braiding and terraces (McEwen et al., 2007). This suggests that varying ratios of water and sediment have eroded gullies on

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Mars. Analysis of gullies in the Mars-like Antarctic Dry Valleys (ADV) (Marchant and Head, 2007) has shown that snowmelt from seasonal and perennial snow deposits can serve as a source for seasonal gully activity in a terrestrial hyper-arid polar desert setting (Dickson et al., 2007b; Head et al., 2007; Levy et al., 2007; Morgan et al., 2008). Recent modeling by Mischna et al. (2003) and Madeleine et al. (2009) has shown that snowfall on Mars is possible during periods of higher obliquity in the regions where gullies are located. Conditions favorable for the accumulation and preservation of snow and ice must be maintained long enough, prior to the onset of melting, in order for liquid water on Mars to carve the gullies (Hecht, 2002). The fluvial characteristics of martian gullies (McEwen et al., 2007), their distinctive latitude dependence (Malin and Edgett, 2000a), their close association with recent ice-rich mantles (Milliken et al., 2003; Head et al., 2003; Christensen, 2003) and lobate glacial-like lobes (Head et al., 2008), and evidence for snow and ice accumulation in current gully alcoves and channels (Head et al., 2008), all point to the potential role of top-down melting of accumulations of snow and ice as the source of water forming the gullies.

Recent Mars studies where gullies are found on slopes of all orientations have noted aspect-dependent variations in morphology related to slope orientation (Reiss et al., 2009). We test the viability of the top-down snowmelt model as an explanation for gully activity on Mars by investigating whether variations in insolation conditions favorable for the annual accumulation and subsequent melting of snow can account for aspect-dependant morphological differences observed in gullies. We apply the Costard et al. (2002) one-dimensional version of the LMD GCM (used to explain the global spatial distribution of gullies) to model the surface temperatures of a study area in Noachis Terra. We use site-specific topographic orientation and slope parameters as inputs for the model to assess the current distribution of surface temperatures. This was extended back in time through the application of the Laskar et al. (2004) simulations of the spin-axis/orbital history for Mars over the last 20 million years. We then assessed whether predicted variations in insolation-related surface temperatures could account for observed differences in gully morphology and the apparent ages of gully activity.

2. Terrestrial analog of gully formation: Antarctic Dry Valleys

In response to the evidence outlined above supporting the top-down melting of accumulations of snow and ice as the source of water that formed the martian gullies, this section discusses field observations of snowmelt as the source of gully activity in the hyper-arid polar deserts of the Antarctic Dry Valleys (Marchant and Head, 2007). Field research was conducted on gully systems within upper Wright Valley in the elevated extremes of the "inland mixed zone" (Marchant and Head, 2007). Gully systems ~0.5 to >1 km in length are carved into the southern slopes of the Asgard range and are comprised of the three morphological units used to define gullies on Mars (Alcove, channel and fan, see Fig. 1). The gradients of the Asgard slopes are ~35° which is consistent with martian gullies that are found on slopes in excess of 21° (Dickson et al., 2007a). Gully channels are ~2–6 m wide and up to 2 m deep.

In the Dry Valleys, precipitation occurs only as snow, and so the region provides an environment in which to study gully activity in the absence of erosion associated with rainfall. Annual precipitation consists of only a few centimeters (Bromley, 1985). Nevertheless, the wind redistributes and concentrates snow during the winter into seasonal and perennial snowpacks >30 cm thick within topographic hollows that include the gully alcoves and channels (Figs. 1 and 2) (Morgan et al., 2008; Dickson et al., 2007b; Head et al., 2007; Levy et al., 2007). Gully activity is initiated by the

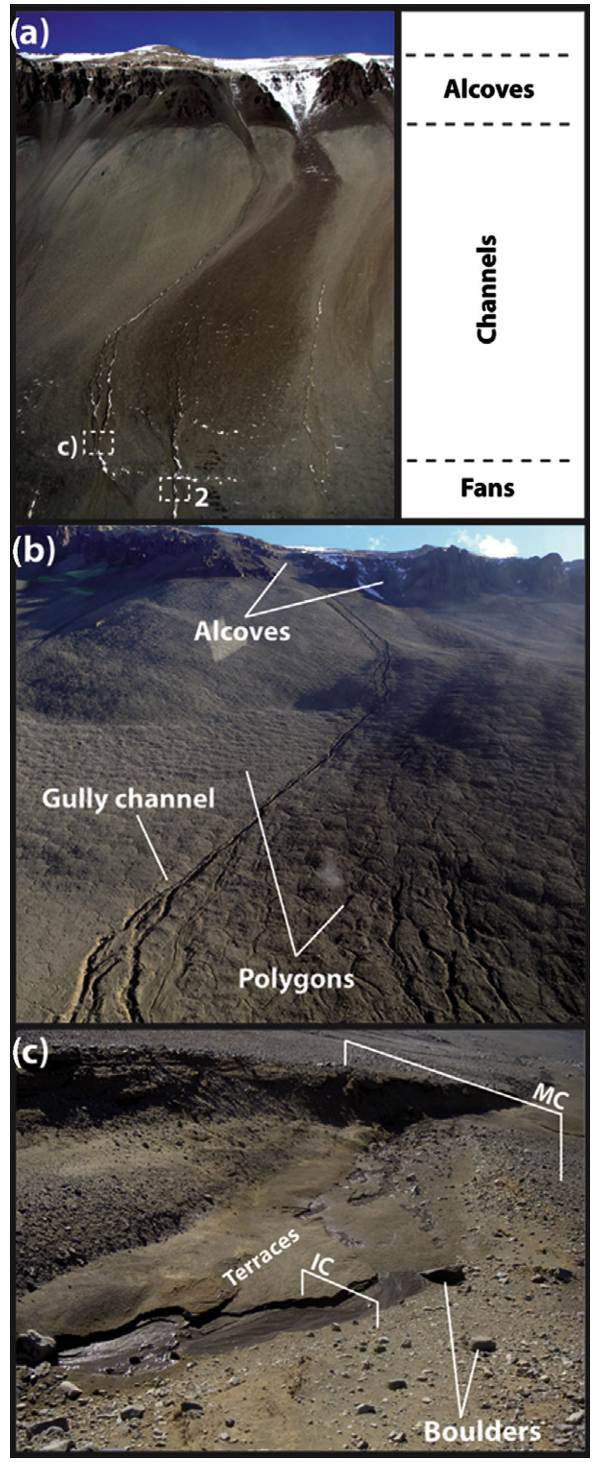

Fig. 1. Gully systems along the southern slopes of the Asgard range within upper Wright Valley of the Antarctic Dry Valleys. (a) Gully systems are comprised of the three morphological elements that define martian gullies: Alcoves, channels and fans. The difference in elevation between the alcoves and base of the fan is ~1 km. Wind blown snow can be seen within the channels of the gullies. The two boxes refer to images in (c) and Fig. 2. (b) Close-up view of the main channel and alcoves of the longest gully system in (a). Note the presence of thermal contraction crack polygons on the slopes that the gullies are carved into. (c) View of gully activity within the main channel (MC). Surface runoff due to snowmelt occurs during periods of peak insolation and carves smaller (~0.5 m) inner channels (IC) and terraces within the main gully channel. Images (a) and (b) where photographed from a helicopter, (c) was taken from the ground.

melting of these snowpacks in the spring by direct solar insolation, forming localized surface runoff and limited fluvial activity

Fig. 2. Dirt covered snowpacks within a gully channel in the Antarctic Dry Valleys, see Fig. 1a for context. During the winter, snow and fine sediments are redistributed by the wind and are concentrated within topographical hollows, including the gully channels. As the snow ablates the sediments are concentrated as a surface lag, significantly lowering the albedo of the snow and enhancing melting. This mechanism could occur on Mars as has been suggested by snowmelt models under martian conditions at high obliquity by Williams et al. (2009).

(Fig. 1c). Melting only occurs for a relatively short duration each day (maximum of 8 h) during periods of maximum insolation. As a consequence of ablation, the dust incorporated into the snowbanks during their formation becomes concentrated on the surface of the snow (Fig. 2) and further assists melting through the corresponding decrease in albedo. This processes is also considered important for snowmelt initiation on Mars (Williams et al., 2009). Gully activity ceased once all of the snow trapped within the channels had melted. During the 2006–2007 austral summer season this took approximately two weeks (Morgan et al., 2008; Dickson et al., 2007b; Levy et al., 2007).

3. Location and morphology of the gullies

The study site chosen for our investigation is within the 80 km diameter, Noachian-aged degraded Asimov crater located at 46°S, 5°E within Noachis Terra (Fig. 3). The floor of the crater is unusual in that it contains an annulus of deep valleys (~2 km maximum

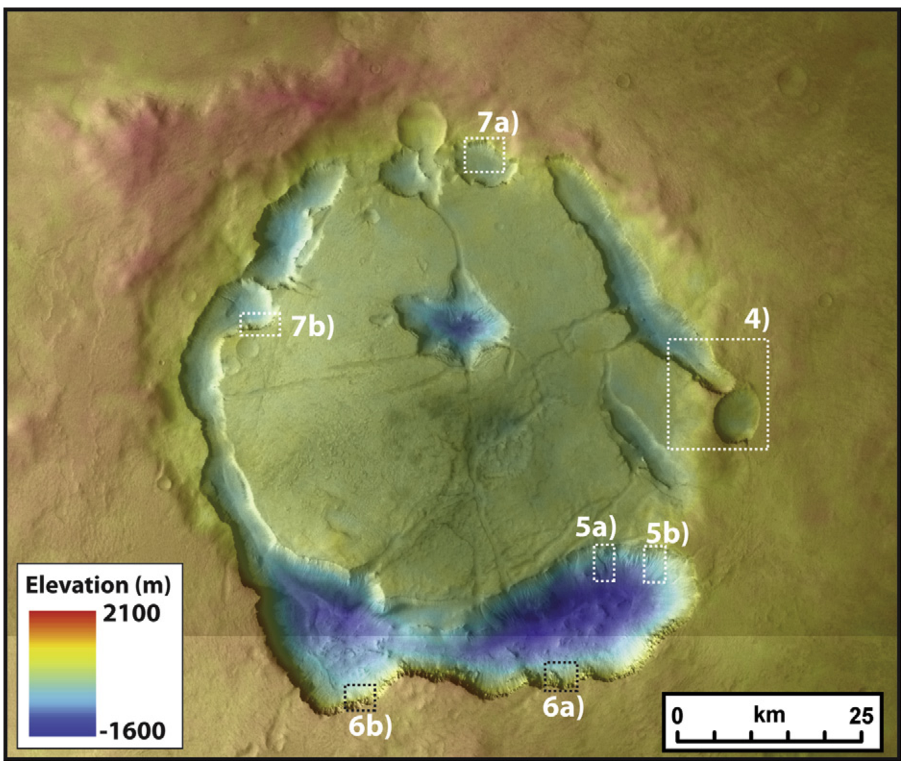

Fig. 3. Study region: Asimov crater, a moat crater in Noachis Terra. The boxes represent the location of the gullies in Figs. 4–7. HRSC orbit 1932_0000 (Image and DTM).

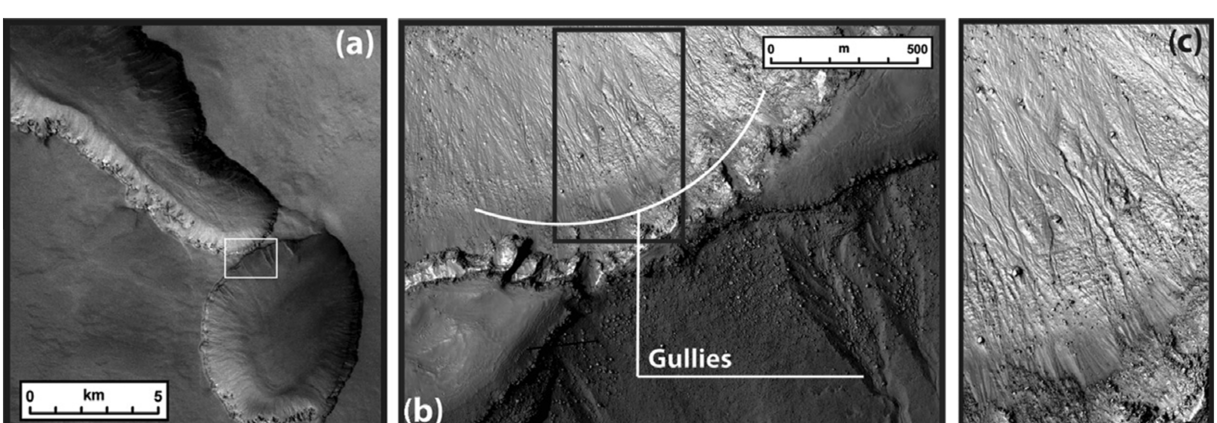

Fig. 4. Gullies located along the slopes of isolated ridges. This argues against a groundwater source for the gullies and instead supports a top-down source for gully activity.

depth) and an irregular central depression. Studies of this crater and similar examples suggest that the initially fresh crater was infilled with material and that the valleys were subsequently formed by the preferential removal of the crater fill along the interior walls of the crater (Schultz and Glicken, 1979; Malin and Edgett, 2000b). Gullies are located along every slope within the interior valleys and central depression, though their morphology varies significantly with slope orientation. Despite morphological variations, the gullies are all composed of the three basic morphologic units used to define martian gullies (alcove, channel and fan; Malin and Edgett, 2000a) and therefore, are considered to represent morphologic variations of a single landform type.

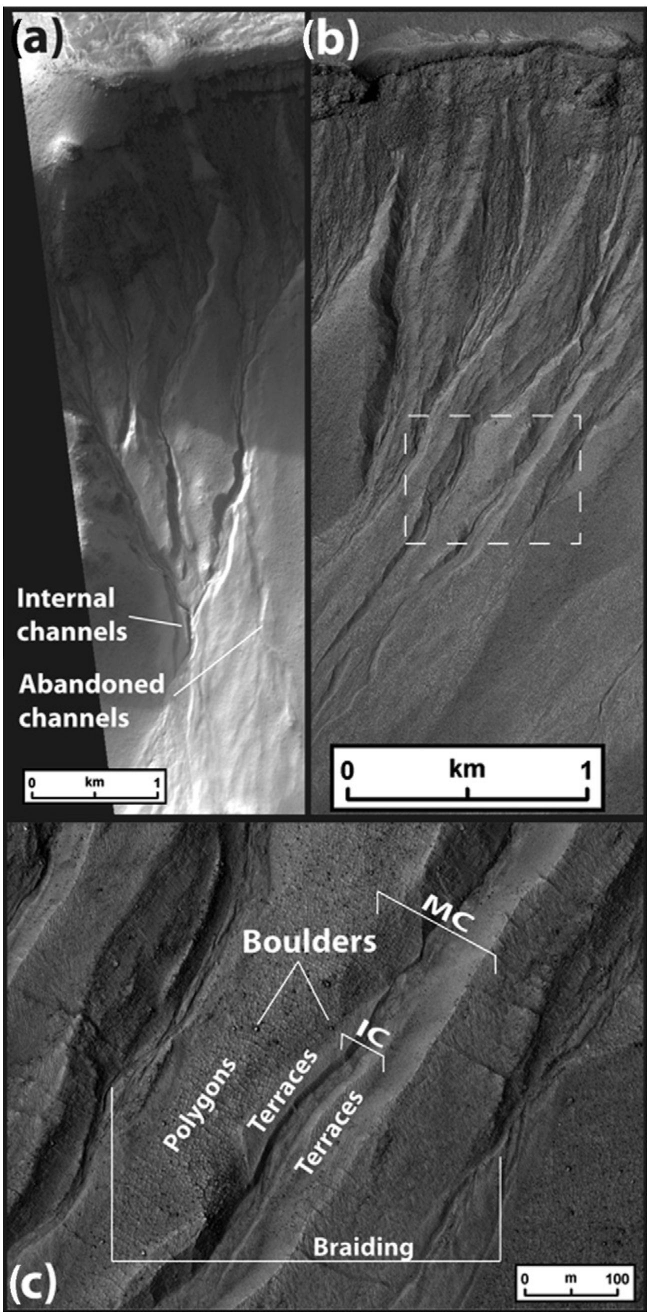

Fig. 5. High-resolution images of gullies on pole-facing slopes within the southernmost valley of Asimov crater. (a and b) These are the most complex and incised gullies found in the study area. (c) Close-up of box in (b) showing fine-scaled inner channel (IC) features suggestive of fluvial erosion within the main channels (MC). Compare this image with Fig. 1c from the Antarctic Dry Valleys, note the similarities in fluvial erosional features. Thermal contraction crack polygons can also be seen along the slopes the gullies are carved in. (a) MOC: E0301360, (b and c) HiRISE: PSP_004091_1325.

A thick, resistant, cliff forming rock unit displaying columnar jointing and interpreted to be a lava flow is present along the upper portions of the valley walls and provides a source of boulders to the slopes below. This lava flow largely caps the interior crater fill and likely formed prior to the valley formation as lava does not appear to have flowed into the valleys. Gullies on the crater fill side of the valley typically originate close to this layer, suggesting that there is a relationship between the two. This type of relationship has been interpreted as evidence for a groundwater source through the containment of a perched aquifer by the rock layer (Gulick et al., 2007). However, the occurrence of gullies along isolated ridges formed by the narrow divides between adjacent valley systems (Fig. 4) is inconsistent with the groundwater hypothesis for gully formation (as proposed by Malin and Edgett (2000a), Heldmann and Mellon (2004), Heldmann et al. (2005)) and instead supports gully activity resulting from an external water source. It also implies that variations in gully morphology were the result of external forcing and were not influenced by endogenic processes (such as the geothermal heating of ground ice) undetectable from the spacecraft data.

The largest and most complex gully forms are located on pole-facing (PF) slopes, and typically consist of multiple branching

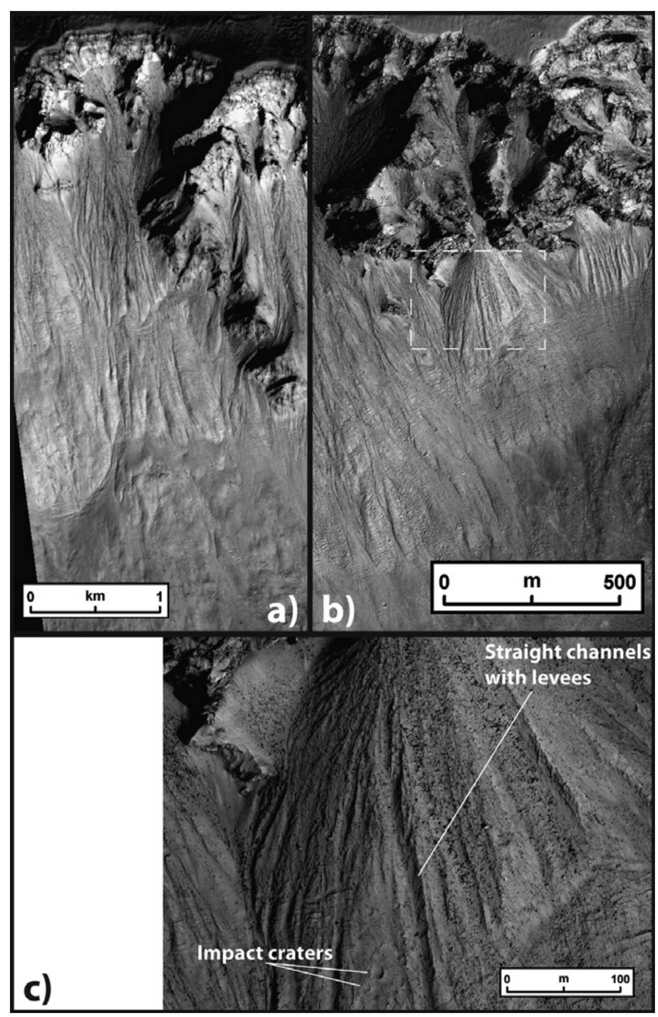

Fig. 6. High-resolution images of equator-facing gullies within the southernmost valley of Asimov crater; these represent the simplest of the gully types. (c) Close-up of box in (b) showing linear channels superimposed by impact craters, suggesting that the PF gullies have been active more recently than the EF gullies. (a) MOC: E1101724, (b and c) HiRISE: PSP_00 6926_1320.

tributaries that originate in alcoves at or near the base of the rock layer and merge together downslope to form single channels (~80 m wide) that open up into depositional fans (Fig. 5). Within the gully channels, smaller scale ~10 m wide internal channels are present, which at HiRISE resolution (sub-meter) can be seen to contain fine-scale fluvial-like features, including terraces and braided channels (Fig. 5c). These features are similar to those observed to form in the active gullies in the Antarctic Dry Valleys (compare Fig. 1c with Fig. 5c), and suggest that fluvial erosion was involved in the formation of the gullies (e.g. Morgan et al., 2008). Abandoned channels and distinctive fan stratigraphy (Fig. 5) suggest that multiple episodes of activity have been recorded in the gully morphology.

In contrast to the PF gullies, the gullies on equator-facing (EF) slopes have smaller, thinner (~20 m wide) channels that branch out from the apex of well-defined 200–500 m wide, cuspate alcoves that occur in the exposed rock layer at the summit of the slopes (Fig. 6). EF slopes are steeper than PF slopes, suggesting that the latter have experienced more erosion. Large amounts of debris (including 10 m diameter boulders) are visible within the alcoves and spread out down slope forming talus cones into which the gully channels are eroded. This suggests that dry mass-wasting processes in the form of rockfalls and debris slides may have accompanied gully activity along the EF slopes. Nevertheless, the prominence of the multiple channels that meander around topographic obstacles (Fig. 6a) argue for the involvement of a fluid agent. The occurrence of levees are similar to terrestrial debris flows that have been invoked to explain some martian gully formation (Costard et al., 2002; Hartmann et al., 2003; Levy et al., 2010). Together, these characteristics argue for the involvement of lower volumes of water in the erosion of the EF gullies relative to that involved in gullies on the PF slopes. It is likely that mass-wasting processes in addition to gully erosion also contributed to the shallower PF slopes we see at present. However, the difference in scale between the two gully types argues for the greater significance of PF gully erosion. Similar slope asymmetry is found within the ADV, with gentler slopes resulting from a greater availability of liquid water (Marchant and Head, 2007). This suggests that the same may hold true for Asimov. The east and west-facing gullies are morphologically similar to the PF gullies in terms of the level of incision, although they do not exhibit the same degree of complexity or finer-scale bedforms.

Pole-facing gullies appear fresher and more well-developed than equator-facing gullies (Fig. 5), suggesting that the PF gullies have been active more recently than the EF gullies. Determining an absolute age for the two gully systems using crater size–frequency distribution data is difficult due to the small sample areas involved; furthermore, the steep angles on which the gullies have formed (>15°) makes them prone to failure and thus degradation resulting in the loss of impact craters. Nevertheless, two equally sized survey areas corresponding to slopes only containing either PF or EF gullies were defined and a crater counting survey of all available MOC (22) and HiRISE (8) images was conducted. This revealed ~70 craters with a diameter >5 m (including six craters with a diameter of >100 m) are present on EF gullies in the EF survey area relative to only ~15 on the PF gullies in the PF survey area. Thus the PF gullies display a lower crater density than the EF gullies. This suggests that the EF facing gullies have not been active as recently as the PF and is therefore consistent with the morphological interpretation.

What are the causes of orientation-dependent differences in gully morphology? Examination of the circular valley systems shows that the aspect-dependence of gully morphology was maintained regardless of whether the gullies were eroded into the lava-capped crater fill material or the opposite valley side, along the interior of the Asimov crater walls (Figs. 5-7). The southern valley of Asimov is the widest and deepest (>2 km relative to ~500 m for the north valleys) and so it has the largest scale and number of gullies along its walls. However, the same gully asymmetry consisting of multiple tributary fed PF gullies relative to the more linear channels and cuspate alcoves of the EF gullies is still maintained in the northern valleys (Fig. 7). This suggests that insolation (through its effect on the stability of a surficial water source), not slope composition, was the critical factor in the development of gullies of different morphology.

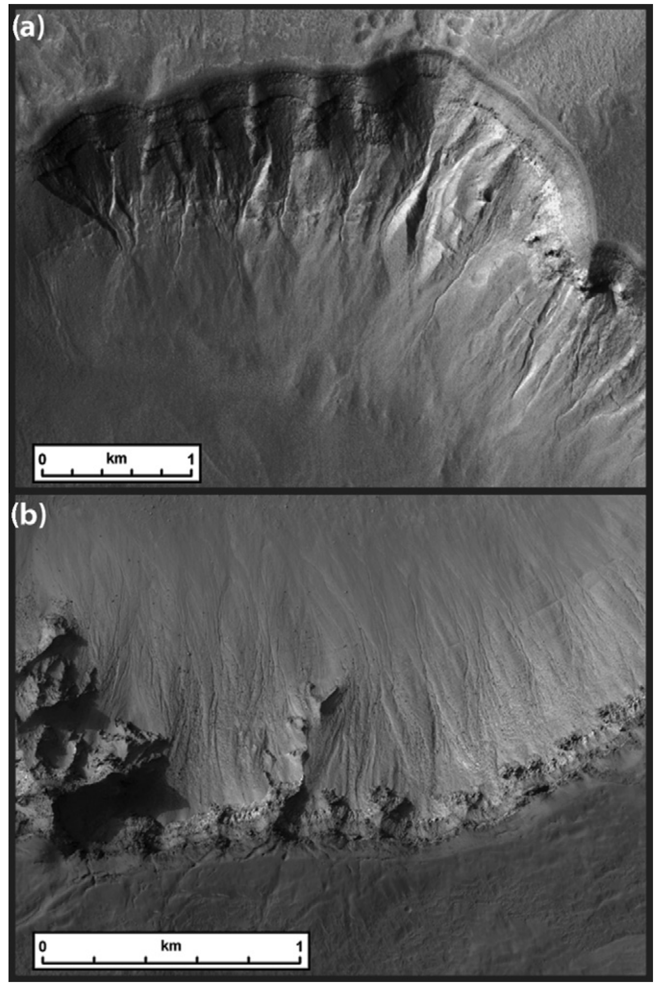

Fig. 7. Examples of PF (a) and EF (b) gullies within the northern valleys of Asimov. Note that the same gully morphology asymmetry is preserved between the two gully types as is seen in the southern valley (Figs. 5 and 6) despite the fact the slope composition has switched. (a) PF gullies consist of multiple branching tributaries as noted in Fig. 5 except that these gullies are carved into the crater wall instead of the interior crater fill material. (b) EF gullies displaying cuspate alcoves and linear channels. Compare with Fig. 6, except these gullies are eroded into interior fill material instead of the crater wall. (a) CTX: P05_003102_1327 and (b) HiRISE: PSP_002179_1330.

4. Model results and geologic interpretation

In order to investigate the differential insolation conditions related to aspect we employed the one-dimensional version of the LMD GCM developed by Costard et al. (2002). Within the model the diurnal and seasonal surface temperatures are derived from the balance between the radiative and turbulent fluxes, thermal conduction into the regolith and CO_2 condensation and sublimation. Insolation is a function of obliquity, orbit eccentricity and longitude of perihelion. Therefore, in order to investigate the potential for melting to occur in the past, Laskar et al. (2004) simulation of Mars orbital dynamics can be used to provide the inputs for these

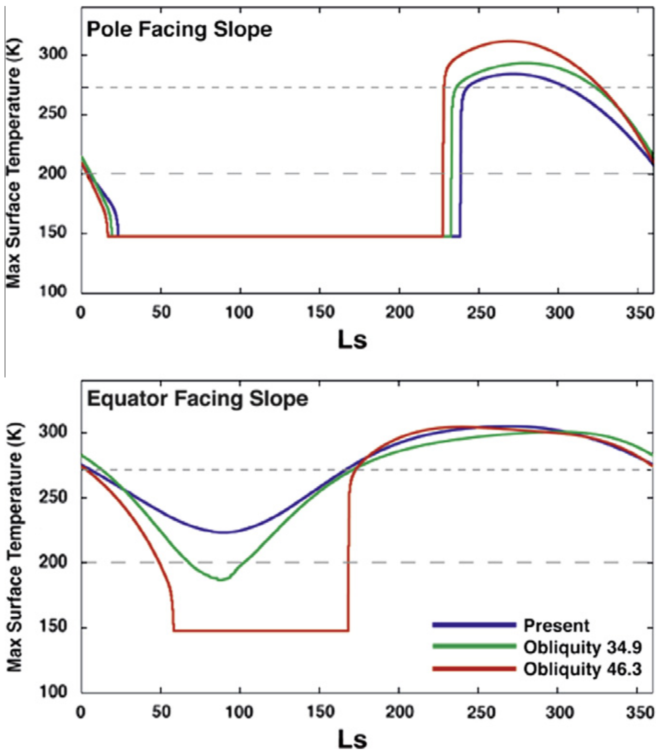

Fig. 8. Maximum daily surface temperatures (K) over a year at 46°S for a 25° polar facing slope and a 25° equator-facing slope under present conditions, and under the conditions dictated by the orbital parameters (obliquity, eccentricity and longitude of perihelion) predicted by Laskar et al. (2004) for 868 ka (obliquity 34.9°) and for 9.1 Ma (obliquity 46.3°).

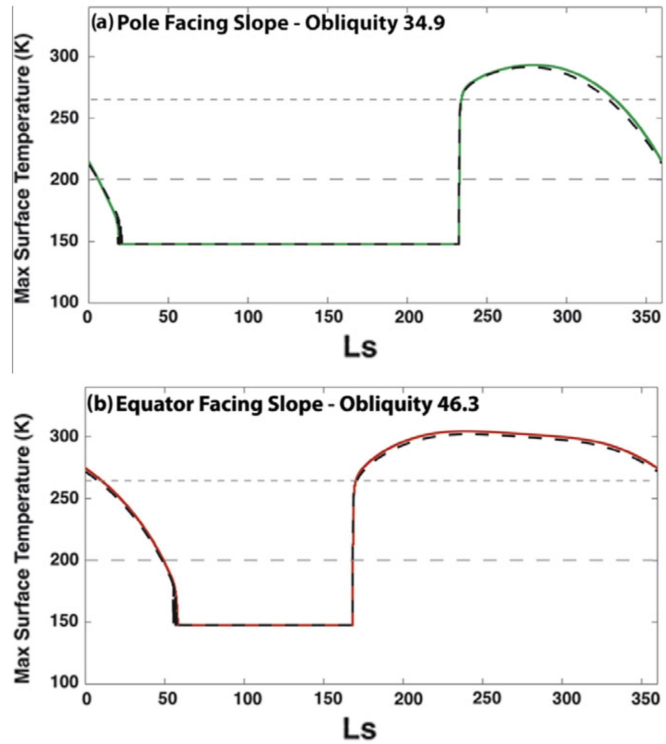

Fig. 9. Maximum daily surface and subsurface (~1 cm depth) temperatures (K) over a year at 46°S for: a 25° polar facing slope under the conditions dictated by the orbital parameters for 868 ka (obliquity 34.9°) and a 25° equator-facing slope under the conditions dictated by the orbital parameters for 9.1 Ma (obliquity 46.3°). Both the surface and subsurface maximum daily temperatures exceed the melting point of water during the late spring. The subsurface temperature profile was calculated based on thermal properties for a windblown martian snowpack (heat capacity = 2200 J K^{-1}, conductivity = 0.11 W m^{-1} K^{-1}, thermal inertia = 313 J m^{-2} $s^{-1/2}$ K^{-1}, snow density = 400 kg m^{-3}).

three parameters. Through this method we can pin point specific points in Mars history of interest. We used the 1D model to compare the maximum daily surface temperatures at the study site under three different scenarios: (1) present insolation conditions, (2) maximum insolation conditions during the most recent period of ~35° peak obliquity values (868 ka), and (3) maximum insolation conditions during the most recent period of ~ 45° peak obliquity values (9.11 Ma). We assessed the results in terms of conditions that might permit the accumulation, and subsequent melting, of snow and ice (Figs. 8 and 9).

The input parameters chosen for the model are provided in Table 1. In regards to surface temperatures the values of thermal inertia and surface albedo are of the most significance. In the regions where snow accumulation was assessed to be possible, we assumed that the surface of the slopes were covered in a thin layer (~1 cm) of snow, and our model parameters were chosen accordingly. In response to our Antarctic observations (Fig. 2) and the modeling results of Williams et al. (2009), which both describe the formation of a surficial lag of dust on ablating snowpacks, an albedo of 0.15 was chosen. With regards to thermal inertia, a value of 313 SI was chosen to reflect that of terrestrial measurements of wind-hardened snow.

4.1. Pole-facing gullies

Our simulations demonstrate that for the majority of the year the PF slope temperatures at all obliquities are constrained by the frost point of CO_2 (as was highlighted by Costard et al., 2002) and thus remains at ~150 K (Fig. 8). As this temperature is below the frost point of H_2O, the PF slopes will also be favorable environments for the accumulation of snow and ice, provided that there is a source of snow. Under current conditions snowfall is unlikely to occur, although seasonal ice accumulations have been reported in

Table 1
Model parameters used in the study.

Parameter			Value
H_2O snow albedo			0.15
H_2O snow thermal inertia			313 SI
H_2O snow emissivity			0.95
CO_2 albedo (when present)			0.5
CO_2 emissivity			0.9
Time at which models were run	Present	868 ka	9.112 Ma
Obliquity	25.2	34.94	46.27
Eccentricity	0.0934	0.0558	0.0844
Longitude of perihelion	251	289.2	245.6

this latitude range (Schorghofer and Edgett, 2006; Head et al., 2008). During periods of higher obliquity, greater amounts of snow and ice may have been deposited as a result of the increased sublimation of the residual summer cap (e.g., Mischna et al., 2003; Madeleine et al., 2009). Snow and ice deposits could have been built up on the PF slopes through the winter by the redistribution of snow by the winds in a similar manner to that observed in gullies in the Antarctic Dry Valleys (Figs. 1 and 2) (e.g. Morgan et al., 2008). During the martian spring, the rapid removal of the CO_2 frost cover permits enhanced heating of the surface. The exposure of any H_2O snow deposits accumulated during the winter would prevent this temperature increase from immediately reaching the H_2O melt point due to the relatively high albedo of snow (0.4, for slightly dusty snow: Williams et al., 2008). However, modeling by Williams et al. (2009) and our Antarctic fieldwork (Fig. 2) has demonstrated that due to the expected dust content of snow on Mars, the initial effects of sublimation would lead to the generation of a surface lag and thus reduce the albedo sufficiently (0.13, albedo of dust layer; Williams et al., 2008) to permit melting to occur (Fig. 8). In addition to this, localized dust storms generated by the high thermal gradient between the receding CO_2 frost cover and the exposed ground could deposit a thin layer of dust over exposed snowpacks. Fig. 9 shows the evolution of the daily maximum temperature profile at ~1 cm depth using the assumed thermal properties for a martian windblown snowbank during obliquity of 34.9°. As is the case with the surface (Fig. 8), temperatures do rise above the melting point at this depth. Williams et al. (2009) has shown that the melting of small dusty snowpacks ~1 cm thick can generate 1 mm of runoff/m^2. This volume of snowcover over an average PF alcove (~2 km^2) could generate a maximum 2000 m^3 of runoff, enough to fill a 200 m long section of inner channel (10 m × 1 m; Fig. 5c) to bankfull conditions (assuming no losses to infiltration, evaporation and freezing). This level of activity would require repeated cycles of accumulation and melting to generate the ~2 km channels and is consistent with geomorphic evidence for multiple episodes of activity (such as abandoned channels, see Fig. 5).

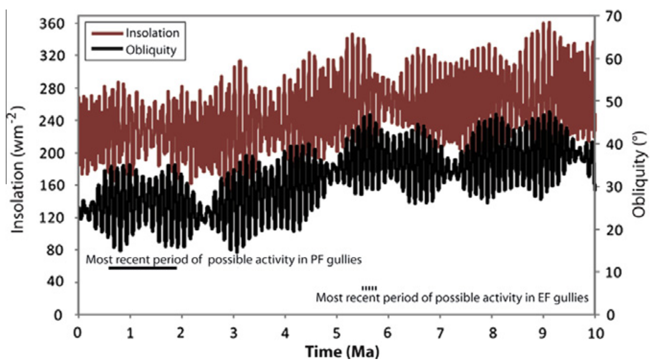

Fig. 10. Obliquity and insolation values for 46°S simulated by Laskar et al. (2004). The potential periods of the most recent gully activity for PF and EF slopes are plotted based on the results of the model and the morphologic investigation.

4.2. Equator-facing gullies

The model results for the equator-facing slopes (Fig. 8) are significantly different than the pole-facing slope results. On EF slopes, gully activity is only likely to have taken place during periods when obliquities are ~45°, despite conditions favorable for melting during all obliquities. For obliquities below 45° the winter (L_s 90–180°) surface temperatures do not become sufficiently cold for CO_2 frost to be deposited (Fig. 8). The absence of CO_2 ice prevents any trapping of wind-blown water snow. In addition to this the surface temperatures warm gradually to the melting point of H_2O during the spring and thus are unfavorable for the formation of meltwater (Hecht, 2002; Costard et al., 2002). At obliquities ~45° the annual surface and subsurface (at ~1 cm depth with the snowpack) temperature regime is similar to the PF slopes (Figs. 8 and 9), and CO_2 condensation can occur. However, the potential accumulation period (L_s 70–190°) is close to half the length that is experienced during the same period on the PF slopes (L_s 20–250°), and as a consequence the gullies may have had less time to accumulate snow (and thus have a lower potential supply of meltwater).

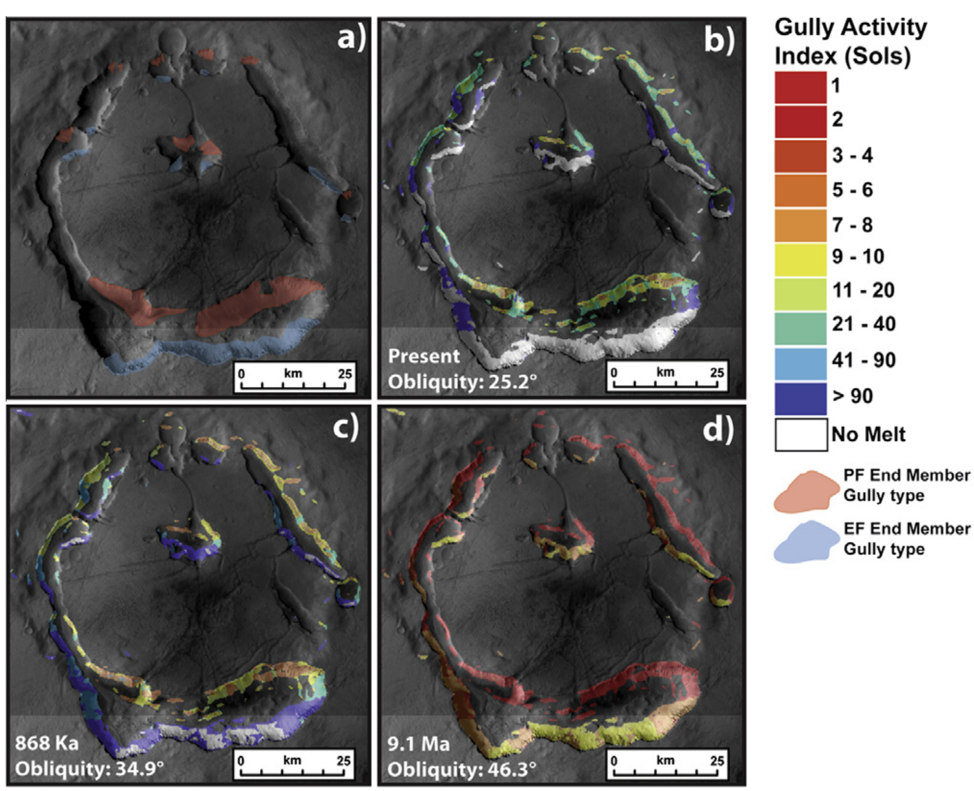

Fig. 11. (a) The location of the two morphologic gully end member types. Pole-facing gullies (PF) are highlighted in red and equator-facing gullies (EF) are in blue. Panels b–d show the spatial representation of the model results based on the aspect and slope values for the study site derived from a 200 m/pixel HRSC DTM. The value represented on the maps is the length of time (in sols) taken for the spring maximum surface temperatures to rise from 150 K (frost point of CO_2) to the melting point of water. No activity corresponds to conditions where either the temperature never becomes cold enough for CO_2 frost to form or the melt point is never achieved. Hence, the lower the number the larger the potential for gully activity to occur in the year from a combination of snow deposits being stable long enough to accumulate sufficient volumes and then being able to melt rapidly. (b) The present. (c) 868 ka (obliquity 34.9°). (d) 9.1 Ma (obliquity 46.3°). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.3. History of gully activity

It has long been established that obliquity is the most influential of the three climate drivers (e.g. Kieffer and Zent, 1992) and thus our results suggest that gully activity along PF slopes would have been favored during phases of peak obliquity $\geqslant 35°$. This occurred most recently in the period between ~0.5 and 2.1 Ma (Fig. 10). This period is consistent with age estimates of gully activity elsewhere on Mars (Reiss et al., 2004; Schon et al., 2009). In comparison, the model results suggest that the EF gullies were only active prior to 5 Ma when the obliquity cycles would peak to $\geqslant 45°$ (Fig. 10). Hence the most recent phase of EF gully activity occurred at an earlier period than was experienced by the PF gullies. This is consistent with the higher number of superimposed craters and a more degraded appearance of EF gullies relative to PF gullies. Even during 5–10 Ma, obliquities of 45° were only achieved for 20 kyr during each ~110 kyr obliquity cycle relative to the 70 kyr spent at obliquities >35° during the same time period. Hence the limited accumulation period and lower frequency of activity may account for the vast difference in gully morphology between the EF and PF slopes and the associated lower EF slope erosion rates would explain the steeper EF slopes relative to the PF slopes. Due to the lesser but still significant influence of eccentricity (wavelength ~2 Ma) on insolation, not all of the periods of high obliquity will correspond to the same amount of insolation (Fig. 10) (see also, Kreslavsky et al., 2008). Therefore, gully activity is expected to vary in response to this over the last 20 Ma.

4.4. Spatial representation of the model results

Fig. 11a shows the spatial distribution of the polar facing and equator-facing gullies that display the most prominent differences in the geomorphological characteristics that were described above. The two end member gully types were mapped based on the following morphological characteristics: PF end member gullies (highlighted in red in Fig. 11a) were defined by broad alcoves that contain multiple tributaries that coalesce to form single large sinuous channels. EF gullies (highlighted in blue in Fig. 11a) were defined by linear channels that originate from the base of well-defined cuspate alcoves that occur in the rock unit. The difference in valley depth (Fig. 3) appears to have had a limiting affect on both gully types. Hence, the two end members were not defined by specific scale ranges as both groups were affected by the lengths of the slopes they were on. The gullies on slopes not highlighted in Fig. 11a consisted of morphologic characteristics representative of both end member types. Fig. 11b–d shows the model results based on the aspect and slope values for the study site derived from a 200 m/pixel HRSC Digital Elevation Model. The value represented on the maps is the time taken for the temperature to increase from 150 K to the melting point. Hence, the smaller the value the higher the potential for gully activity to have occurred (assuming that a dust layer is produced over the snowpacks to reduce the albedo sufficiently). Larger time periods will increase the effect of loss through sublimation, reducing the volume of the snowpack, possibly to the point at which it is completely removed before melting could occur. Regions of no activity (such as EF slopes at obliquities <45°) correspond to conditions where either the temperature never become cold enough for CO_2 frost to form or the melt point is never achieved. The model results show good agreement with the map of gully morphology (Fig. 11a). In addition to representing the spatial distribution of the extreme insolation environments experienced by EF and PF slopes, Fig. 11 also provides an insight into gully formation at other orientations. Gullies on east- and west-facing slopes experience gully activity index values between those of the PF and EF slopes, which is consistent with the gullies on these slopes consisting of morphologies between the two end members.

5. Summary and conclusions

The top-down melting model of gully formation presented here is consistent with the morphological variations displayed in the study area and provides a potential timeframe for gully activity over the last 10 Ma which may yield an insight into morphologic variations observed elsewhere on Mars. Furthermore, continued high-resolution modeling will help to elucidate the more detailed processes that operate in this environment on Mars, such as those seen in the Antarctic Dry Valleys (ADV). For example, wind on Mars may be a means of concentrating precipitation into snowpacks in a manner similar to that seen in the ADV (e.g., Morgan et al., 2008; Dickson et al., 2007b; Head et al., 2007; Levy et al., 2007). Furthermore, more work needs to be done in comparing the way in which snow, dust, and other sediment accumulates and melts in the ADV so that models of accumulation and melting on Mars (e.g., Williams et al., 2008, 2009) optimize their geological realism. Additionally, katabatic winds, which are particularly developed over both martian and Antarctic slopes, yield competing effects on the stability of ice. On the one hand, slope winds are known to contribute to the transport and formation of snowpacks. On the other hand, katabatic flow results in a warmer atmosphere above the slope by adiabatic compression (Nylen et al., 2004; Marchant and Head, 2007; Spiga and Forget, 2009), which might favor melting. Further modeling would also address the influence of atmospheric circulation over complex terrains on the formation of clouds and on the precipitation budget. Integration of these comparative terrestrial and martian analysis will provide new insights into recent water-related processes on Mars.

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