Recent climate cycles on Mars: Stratigraphic relationships between multiple generations of gullies and the latitude dependent mantle

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Abstract

Reconstructions of the orbital parameters of Mars spanning the last ~20 Myr, combined with global circulation models, predict multiple cycles of accumulation and degradation of an ice-rich mantle in the mid-latitudes, driven primarily by insolation at the poles during periods when obliquity was more than ten degrees greater than it is today (i.e., > ~35°). While evidence of an ice-rich “latitude dependent mantle” (LDM) consistent with these predictions is abundant, features indicative of cycles of emplacement and degradation of this unit are isolated and rare. In addition, fundamental physical properties of the LDM, such as paleo-thickness maxima, have not been determined. Gullies, which are sinuous channels found on steep slopes in mid- and high-latitudes, interact with the LDM and provide a stratigraphic feature useful for documenting both cyclical emplacement/removal and thickness estimates in past climate regimes. In the southern hemisphere, where gullies are most common, we present extensive evidence of (1) cyclical degradation and removal of gullies in the lower mid-latitudes (30–40°S), and (2) burial and exhumation of inverted gully channels in the transitional latitude band between dissected and preserved LDM (40–50°S), which can only be accounted for if an additional tens of meters of LDM were present at these locations during channel formation. These relationships support a model in which end-to-end gully evolution is controlled by the behavior of the LDM: at lower latitudes, gullies incise an ice-rich substrate and are removed when that ice becomes unstable, and at higher latitudes gullies are buried by successive emplacement of LDM where ice remains stable near the surface. Further, the presence of dormant buried gullies implies that present-day activity within gullies, likely to be controlled by the behavior of CO2 frost, is insufficient to explain the entire gully population, and that conditions conducive to increased gully activity preceded the most recent phase of LDM emplacement.

1. Introduction

Observations of the mid-latitudes from image (Soderblom et al., 1973; Squyres and Carr, 1986; Mustard et al., 2001; Head et al., 2003; Milliken et al., 2003), altimetry (Kreslavsky and Head, 1999, 2000; Neumann et al., 2003) and radar (Campbell et al., 2013) data all show that the texture of Mars is smoother at high-latitudes as compared to low-latitudes in both hemispheres. This softening of terrain has been attributed to the emplacement of a “latitude-dependent mantle” (LDM) that drapes much of the surface poleward of 30° (Head et al., 2003). The latitude-dependence of its distribution and evidence for its degradation in the lower mid-latitudes (30–45°; Mustard et al., 2001) suggest a role for the Amazonian climate in LDM evolution, and investigators have hypothesized that the LDM has a volatile component, likely to be water ice (Squyres and Carr, 1986; Mustard et al., 2001). Morphological evidence for ground ice extends to near-tropical latitudes where ice should not be stable near the surface today (Mellon and Jakosky, 1993; Schorghofer and Aharonson, 2005; Chamberlain and Boynton, 2007), which prompted Head et al. (2003) to argue that ice is transported from the poles to lower latitudes at high-obliquity, and back to the poles during low-obliquity conditions like today. This scenario is consistent with the high-amplitude oscillations in the orbital parameters of Mars over the last 20 Myr (Laskar et al., 2002, 2004).

A testable prediction of this model is that Mars should have undergone multiple cycles of emplacement and removal of LDM over the last several million years (Head et al., 2003). Evidence of this, however, has been relatively sparse. Schon et al. (2009a) documented localized examples of what they interpret to be layering in the LDM in the southern mid-latitudes, but their survey focused...
more on the emplacement phase of LDM as opposed to its degradation.

A major challenge in deciphering stratigraphy within the LDM is that Mars has very few contemporaneous landforms that can serve as effective stratigraphic markers. An intriguing exception, however, are gullies: relatively small steep-sloped drainage systems comprised of an alcove, channel and depositional apron in the mid-latitudes (Malin and Edgett, 2000), known to have formed in the last several million years (Reiss et al., 2004; Schon et al., 2009b) and undergoing modification today (Dini et al., 2010; Dundas et al., 2010, 2012, 2015; Raack et al., 2015). Due to their latitude dependent distribution (Malin and Edgett, 2000; Milliken et al., 2003) and orientation preferences as a function of latitude (Heldmann and Mellon, 2004; Balme et al., 2006; Dickson et al., 2007; Kneissl et al., 2010), gullies themselves are potential indicators of variable Late Amazonian climate conditions. Thus, a detailed assessment of the stratigraphic relationships between gullies and the LDM could reveal the surface record of the dramatic oscillations in Mars’ orbital parameters known to have occurred over the last 5 Myr (Laskar et al., 2002, 2004).

2. Association of gullies and LDM

Gullies form almost exclusively on pole-facing slopes in the lower mid-latitudes of each hemisphere (30°–45°) (Malin and Edgett, 2000; Heldmann and Mellon, 2004; Bridges and Lackner, 2006; Balme et al., 2006; Dickson et al., 2007; Heldmann et al., 2007; Kneissl et al., 2010; Harrison et al., 2014), and on all azimuths poleward of that (45° to ~80°) (Balme et al., 2006; Dickson and Head, 2009; Kneissl et al., 2010). This distribution correlates well with the global distribution of LDM, which is continuous at high latitudes (>45°; Kreslavsky and Head, 2000) and dissected at lower mid-latitudes (30°–45°; Mustard et al., 2001; Milliken et al., 2003; Head et al., 2003).

Slope measurements show that in the latitude bands where gullies are almost always pole-facing (30°–45°) (Heldmann and Mellon, 2004; Balme et al., 2006; Dickson and Head, 2009), pole-facing slopes are shallower than equator-facing slopes (Kreslavsky and Head, 2003; Conway and Mangold, 2013). Hyperspectral observations of seasonal CO₂ frost behavior on these slopes strongly indicates H₂O ice within the top tens of cm of the surface (Vincendon et al., 2010), showing that ice exists near the surface on Mars at all latitudes where gullies are found (<25° latitude and poleward) and on the pole-facing slopes where they most frequently occur.

The global correlation between gullies and LDM is matched by their direct association in high-resolution images. At several sites (Christensen, 2003; Head et al., 2008; Schon et al., 2009b; Raack et al., 2012), gullies have been shown to be eroding through smooth mantling deposits and not underlying bedrock, and channels associated with gullies that incise bedrock have not been explicitly documented since their discovery (Malin and Edgett, 2000). Gullies alcoves have formed in either bedrock or mantle, though alcoves in bedrock form independently at all latitudes on Mars and on airless bodies and are not diagnostic of the gully incision (Dickson and Head, 2009), and may only be modified by erosion due to gullies. Thus, the fate of gully channels and fans on Mars is likely to be controlled by the ice-rich mantling units that they generally incise in the mid-latitudes.

If the LDM provides an erodible layer for channel incision, then stratigraphic relationships between gullies and the LDM reflect the record of both features. A few localized examples of multiple episodes of gully activity have been reported (Dickson and Head, 2009; Schon et al., 2009b; Reiss et al., 2009; Morgan et al., 2010), but these relationships should be widespread if they reflect a global climate signal.

3. Stratigraphy of gullies and LDM

3.1. Fractured gully fans/channels

As part of a broader survey of larger ice-related features on Mars (Dickson et al., 2012), we identified a total of 1766 Context Camera (CTX; Malin et al., 2007) images between 20° and 80° in each hemisphere that imaged gullies. Of these, 479 had overlapping High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007a) images that were used to investigate the detailed stratigraphy between gullies and the mantle that they incise. Of specific interest were gullies with multiple fans that showed disparities in stages of degradation, as documented in the Newton crater region by Head et al. (2008) and in two southern hemisphere sites by Dickson and Head (2009) (see their Fig. 8). In this scenario, channelized gully fans lower in the stratigraphy are fractured, then those fractures and the fans themselves are cross-cut by younger gully channels that deposit fresh gully fan material, thus necessitating at least two separate gully-carving events.

One-hundred ninety-one HiRISE images, ~39.9% of all gully images from Dickson et al. (2012), show evidence for degraded fans lower in the gully stratigraphy (Fig. 1), with 160 of these occurring in the southern hemisphere where gullies are most common (Milliken et al., 2003). Fig. 2 provides an example of this stratigraphic relationship on a typical gullied crater wall in the southern mid-latitudes. In this example, young gullies occur on the pole-facing slope of an impact crater at 41.5°S, 202.3°E (Fig. 2b), and their channels incise the mantling unit that drapes the entire slope. The mantle is degraded lower on the slope, as it is cut by cross-slope troughs (Fig. 2a) that are similar in morphology to degraded mantle features observed elsewhere in the southern highlands (Head et al., 2008; Dickson and Head, 2009; Jawin et al., 2014). The troughs are characterized by chains of pits that coalesce (Fig. 2c). The pits, which range from ~1 m to ~4 m in depth (Fig. 2c), exhibit smooth floors, show no evidence for raised rims and, given their occurrence exclusively within a unit thought to be ice-rich (Mustard et al., 2001; Head et al., 2003), are likely to be related to the gradual sublimation of the LDM.

Other examples of this stratigraphic relationship (Figs. 3 and 4) reveal further evidence for the long-term evolution of gullies, as opposed to catastrophic initiation or limited lifetimes. A fundamental criterion for inclusion in this survey was that the lower fan material must be channelized, so as to avoid including talus piles that were emplaced via mass wasting events, which occurs at all latitudes and on airless bodies. Frequently, the fractured fan lower in the stratigraphy is associated with an abandoned channel (Figs. 3b, c, d, i and 4a, d, e, g). Fresh channels show evidence for smaller interior channels with terraces (Fig. 3c, f, and h), similar to features documented in gullies before (McEwen et al., 2007b; Schon and Head, 2009). The distribution of gullies that exhibit these types of stratigraphic relationships is similar to the overall distribution of all gullies in the southern hemisphere (Figs. 1 and 5). Fractured gullies are evenly distributed across the southern highlands (Fig. 1) with no obvious zones where gullies are common but cross-cut channels/fans are not, with the exception of polar latitudes where gullies are rare and degraded fans are absent. In a manner similar to the set of gullies as a whole, fractured gullies are most common in the lower mid-latitudes between 30° and 45°S (Fig. 5), a band known to be inhospitable to surface and near-surface ice under current climatic conditions (Mellon and Jakosky, 1993; Schorghofer and Aharonson, 2005; Chamberlain and Boynton, 2007) and which shows extensive evidence for dissection of the LDM (Mustard et al., 2001; Milliken et al., 2003; Head et al., 2003). This latitude band also marks the hemispheric transition
from smooth terrain at high latitudes (where ice is stable near the surface) to rough terrain at low latitudes (where ice is not stable) (Kreslavsky and Head, 2000). Thus, both the fractures within the LDM and the gullies themselves occur dominantly in regions where ice accumulation and preservation at or near the surface was enhanced during previous climate regimes (Madeleine et al., 2014).

If the majority of gully channels form within an ice-rich substrate that can be degraded gradually over time, could entire gully systems be removed? The LDM is interpreted to be a dust–ice mixture (Head et al., 2003), such that once the ice sublimes, the dust lag would lose coherence and be easily removed by eolian activity.

Fig. 6 shows a gullied crater wall in the southern mid-latitudes (39.9°S, 174.3°E) where a beheaded fan occurs at the lower portion of the mantled slope. The fan itself retains the proximal channel that fed it, but this channel terminates abruptly upslope such that there is little remaining record of the main gully channel and no preserved alcove. This beheaded fan system is perched above a layer of smooth mantling material that itself is well-incised by a suite of fresh gullies that are younger than this system. While the beheaded fan itself has withstood erosion, the broader layer within which the associated channel formed has been removed, which erased the majority of the channel and the entire alcove that comprised the rest of the original gully morphology.
There are two hypotheses that could explain this: (1) The fan is comprised of coarse material and is thus resistant to erosion, or (2) the fan is comprised of a larger volume of sediment compared to the ice-and-sediment material in the surrounding mantle, which would make the fan more difficult to completely erode from eolian redistribution following the sublimation of the ice-component of the surrounding mantle. Additionally, the lower slope upon which the fan is emplaced is likely to make it less susceptible to erosion from mass-wasting as compared to the sediment in the ice-rich mantle, which is emplaced on the steeper crater wall. Thus, while some gullies form on dunes and other unconsolidated erodible surfaces, the majority of mid-latitude gullies are associated with the ice-rich LDM, with their life cycle controlled by the stability of the ice within this surface layer.

3.2. Sinuous downslope ridges

A separate survey of the southern hemisphere using CTX imagery was conducted to determine the distribution of a previously unreported latitude–dependent feature, sinuous downslope ridges. All CTX images poleward of 20°S from the beginning of the mission through phase D06 (December, 2012), 19,198 images in total, were inspected for the presence of gullies and sinuous ridges frequently found in close proximity or along the same slopes as gullies (Figs. 7 and 8). In total, 3697 images contained evidence for gullies...
discernible at CTX resolution (very fine-scale channels only discernible in HiRISE or MOC were not documented in this survey), while 521 images showed evidence for downslope ridges. Many of these images contained overlapping coverage of the same features, so each image was rendered within ArcGIS to eliminate redundant observations and facilitate geospatial measurements.

These ridges range from relatively straight (e.g., Fig. 8a) to broadly sinuous (e.g., Fig. 7a). Like gullies, they almost always form in suites and frequently occur atop broader fan-shaped surfaces (e.g., Figs. 7c, g, h and 8d). Ridge crests range from sharp and fresh (e.g., Fig. 7i) to subdued and muted (e.g., Fig. 8e), with the latter cases most clearly showing increased levels of burial by subsequent smooth mantling material. Ridges are, on average, longer than gully channels (~1217 m vs. ~727 m), though this is likely to be due to measurement effects, as ridges frequently include material most likely to have originally been fan material (e.g., Figs. 7d, h and 8f, h, i), which was not included for the mapping of fresh gully channels. Longer ridges may also be preferentially preserved compared to smaller ridges, and are more likely to meet criteria for detection. Ridges branch (e.g., Fig. 7h) and terminate at the same point on the slope as the gully channels that they neighbor. At their upslope extent they are no longer expressed at the surface as they are buried by younger LDM.

The northernmost ridge was found at 33.03°S and there were no ridges mapped on the floors of Hellas or Argyre basins (Fig. 1). Unlike fresh gullies, which are most common between 30° and 40°S (Milliken et al., 2003), ridges dominantly occur between 40° and 50°S (Fig. 5). In this latitude band, ridges show a strong prefer-
Ridges and gullies are often found on the same slope (e.g., Figs. 7d, i and 8c, d, e, g, h, i), and the fresh gully channels are always stratigraphically younger than the sinuous ridges. In one location (Fig. 11), gully channels have exposed cross-sections of the LDM that drape the crater wall. The ridges are expressed as layers within the LDM stratigraphy (Fig. 11b). At all sites, the layers in the LDM are directly traceable to ridges expressed at the surface downslope (Fig. 11a). In Fig. 11b, several layers are exposed, and it is not clear whether each layer represents a new phase of LDM emplacement, or whether the gully channel is incising through a suite of ridges that were adjacent to each other. The former scenario would require several generations of LDM emplacement.
events along this slope. The latter scenario would require, at minimum, two: an initial phase that deposited the mantle material that served as the substrate for the ridge-forming event, and a subsequent layer that now superposes the ridges at higher slopes and embeds them at lower slopes.

Azimuths were measured for the four gully channels in Fig. 11a and for the ridges that occur along the same arc of the host crater wall. The ridges are oriented more towards north (by a mean value of 17.1°) than the channels, which themselves share the same orientation as a line drawn from the crater rim at this location to the center of the crater floor (Fig. 11). If the ridges represent previous generations of transport of material from upslope, then the local gradient at this location has changed significantly. Gully azimuth is dictated by the surface topography of the mantle and, as that mantle degrades, the local gradient begins to reflect the underlying host wall slope. Thus, the ridges observed at this location must have formed under conditions that permitted a significant increase in mantle accumulation along this slope, enough to change the local gradient such that the steepest slope was rotated ~17° to the north.

This is consistent with the formation mechanism of the ridges themselves. If the ridge crests represent the channel floors during older gully activity at these locations, then the height of the ridges reveals the minimum amount of mantle that must have been removed at this site. In order to quantify this loss, we used data from a stereo-derived digital elevation model (DEM) produced from images acquired by the HiRISE instrument. The DEM was produced using the NASA Ames Stereo Pipeline (ASP; Broxton and Edwards, 2008; Moratto et al., 2010). In order to ensure accurate topography, the HiRISE DEM initially produced was aligned in 3
dimensions to Mars Orbiter Laser Altimeter (MOLA; Smith et al., 2001) point-shot data using the NASA ASP iterative alignment technique described by Beyer et al. (2014); however, given the small spatial extent of the HiRISE DEM, and the comparatively low spatial coverage of MOLA point-shot data, we performed this alignment using a DEM produced from the High Resolution Stereo Camera (HRSC; Neukum et al., 2004; Jaumann et al., 2007; Gwinner et al., 2010) instrument aligned to MOLA point-shot data as an intermediary. The final HiRISE DEM over the sinuous ridges (Fig. 11) was used to calculate ridge heights of ~8 m above the present-day mantle surface and fresh gully channel depths of ~12 m (Fig. 12). If the channel depth for the older gully system was comparable to the depth of modern fresh gully channels, then an additional ~20 m of mantle must have been emplaced at this location when the older period of gully channel formation was ongoing. Combined with the mantle material that is still present, at least ~32 m of mantle material was emplaced at this location during peak accumulation conditions.

Ridges are likely to represent previous generations of gullies that are now being exhumed from an ice-rich mantling layer that is no longer stable within the southern mid-latitudes. Are there gullies that have not been exhumed but remain buried beneath layers of recent ice-rich mantling? Fig. 13 provides two examples of what appear to be this phenomenon. In Fig. 13a, a fresh, broad-alcove gully occurs adjacent to a muted alcove cut into the smooth mantle material that drapes the valley wall. The texture of the muted alcove and associated fan is identical to the surrounding wall material, suggesting that the gully system has been buried

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**Fig. 8.** Gallery of sinuous downslope ridges in the southern mid-latitudes, frequently found in association with fresh gullies. Ridges share the same morphologic and distribution properties of fresh gullies, though are concentrated in the 40–50°S latitude band. All images are exclusively from the HiRISE camera except where noted. (A) PSP_007239_1465 and ESP_011656_1465. (B) PSP_006952_1300. (C) PSP_005036_1425. (D) ESP_030766_1310. (E) ESP_030453_1310. (F) ESP_028677_1340. (G) ESP_020858_1425. (H) ESP_020605_1405. (I) ESP_020579_1445.
and is unlikely to be an erosional remnant. This fan material in this older system is (1) rougher than the neighboring fresh fan material, and (2) cross cut by cross-slope fractures within the mantling material, both of which indicate this fan is older than the most recent phase of mantle emplacement.

In Fig. 13b, two similar-sized gully systems occur adjacent to each other. The northern system has a fresh channel, hollow alcove and buried fan deposits, while the southern system shows only buried channel and fan deposits with a mantled alcove. The southern gully is dormant and has not hosted channel-carving activity since the most recent emplacement of mantling material on the crater wall. For this stratigraphy to be explained, (1) a layer of LDM must have been emplaced to allow for (2) an initial phase of gully activity that is now represented by two fans that consist of ridges protruding through a superposing smooth mantle; (3) this most recent mantle has filled in the alcove of the southern gully system, but has been eroded by (4) subsequent gully activity in the northern gully system.

4. Discussion

Based upon these observations, the fate of an individual gully in the southern hemisphere of Mars is observed to lie in a spectrum from (1) degradation and removal (orange arrows in Figs. 3, 4 and 6), to (2) burial (Fig. 13), to (3) inversion (Figs. 7–11). While several factors may influence the long-term evolution of any one gully, the dominant parameter that dictates the life-cycle of a gully is latitude: gullies in low-latitudes (< 40°S) are most likely to undergo long-term degradation and ultimate removal (Figs. 5 and 6), while gullies in the mid-latitudes (between 40°S and 50°S) go through multiple episodes of partial burial and inversion (Figs. 5, 11 and 13).

These spatial patterns are consistent with what is known about the stability of near-surface ice on Mars as a function of latitude (Mellon and Jakosky, 1993; Schorghofer and Aharonson, 2005; Chamberlain and Boynton, 2007) and corresponds to other geomorphological trends in the southern hemisphere regarding the
distribution and dissection of ice-rich mantling deposits (Kreslavsky and Head, 2000; Mustard et al., 2001; Milliken et al., 2003; Head et al., 2003). Thus, the gully life cycle is strongly controlled by the stability of the smooth mantling unit that they erode, which is known to be ice-rich (Head et al., 2003).

Based on our interpretation of sinuous downslope ridges as inverted gully channels, an additional tens of meters of mantling material must have been present in the past for channels to form at these locations. This is consistent with present-day conditions on Mars being less-conducive to the preservation of near-surface ice in the mid-latitudes than the geologically recent past. Head et al. (2003) presented evidence that Mars has been transporting H₂O from the mid-latitudes to the poles in each hemisphere for the last ~0.4 Myr, and this era was preceded by a high mean-obliquity era dating back to 2.1 Myr. Under these conditions, H₂O–ice is predicted to have accumulated in the mid-latitudes (Madeleine et al., 2014), which is where the best evidence for previous generations of thicker mantling material is found (Figs. 7, 8 and 11). The stratigraphy observed in degraded gully channels and fans (Figs. 2–4) and sinuous ridges (Figs. 7, 8 and 11) require that multiple episodes of both (1) mantle emplacement and (2) gully formation must have occurred across the entire southern mid-latitudes, which is consistent at the hemispheric scale with cyclical accumulation and degradation of ice-rich surface units controlled by astro-nomic forcing (Mustard et al., 2001; Laskar et al., 2002, 2004; Head et al., 2003). Deciphering stratigraphic relationships at higher fidelity than presented here, potentially revealing more than two cycles of LDM and gully activity, will be challenging given increasing degradation lower in the stratigraphy, though cross-sections of the LDM may be the most powerful tool for this analysis (Fig. 11).

We find it difficult, however, to explain why there would only be precisely two emplacement/removal events of the LDM and thus infer that these cycles have been occurring throughout the Late Amazonian.

These observations are broadly consistent with the hypothesis that the climate within which gullies form changes significantly over time, as does the surface being incised by the gullies themselves. Gullies that are buried (Fig. 13) cannot be explained by present day conditions. Thus, gully activity observed under present-day conditions that is associated with the behavior of CO₂ frost at the surface (Diniega et al., 2010; Dundas et al., 2010, 2012, 2015; Raack et al., 2015) does not explain gullies lower in the

Fig. 11. Equator-facing slope of a ~27 km impact crater in the southern mid-latitudes of Mars (48.7°S, 13.9°E) seen in HiRISE ESP_022841_1300. Gullies erode the mantled slope, exposing ridges within the cross-section of the mantle. Azimuth measurements were performed on the four fresh gully channels and the ridges that occur along the same arc of the crater wall, revealing a 17.1° disparity in mean azimuth between the two, suggesting a different surface gradient when the two features were formed. The compass rose is calibrated to the image’s orientation. (b) Inset showing the ridges (black arrows) exposed along the walls of the fresh gully channel. The ridges are separated in the stratigraphy by multiple layers of smooth mantle. Ridges exposed on the channel wall can be traced directly to ridges on the surface downslope.

Fig. 12. Profile of ridges and a gully channel from Fig. 11. DEM was generated using the NASA ASP (Broxton and Edwards, 2008; Moratto et al., 2010) from HiRISE orbits ESP_022841_1300 and ESP_022986_1300. The trend of the host slope has been removed to focus on the heights/depths of the ridges/channels. Each ridge is ~8 m above the surrounding smooth mantling material, providing a minimum thickness of material that must have been removed since the original channel that formed the ridge was active. Since adjacent gully channels are ~12 m in depth, it is likely that at least ~20 m of mantling material has been lost in this location since cessation of the older gully activity.
stratigraphy. One explanation could be that higher obliquity conditions yielded an amplified CO₂ cycle such that the processes observed today occurred in more locations. This dry flow explanation may not, however, account for the suite of channels that show sinuosity values in excess of what is measured for dry flows on Earth (Mangold et al., 2010) or gullies that initiate on slopes below the angle of repose (Dickson et al., 2007).

An explanation that is consistent with these properties is that some gullies are only active when liquid water is an erosive agent within the gully system, which is predicted to have occurred during high-obliquity excursion conditions (~35°) experienced within the last 1 Myr (Costard et al., 2002; Head et al., 2003; Williams et al., 2009b). This correlates with periods when GCMs predict net accumulation of LDM in the mid-latitudes where gullies are most commonly found (Madeleine et al., 2014). Increasingly sophisticated climate modeling may help clarify the relative importance of both CO₂ and H₂O cycling in the gully forming process.

5. Conclusions

The southern mid-latitudes of Mars have undergone multiple episodes of emplacement and removal of H₂O–ice in the last several million years, reflected by the stratigraphy of the LDM (Head et al., 2003; Schon et al., 2009a) and the gullies that incise it or are buried by it. While it has been known since their discovery that the distribution of gullies on Mars is latitude dependent (Malin and Edgett, 2000), higher resolution imaging data show that their evolution is dependent upon latitude, as well. These spatial patterns for gullies correspond globally with the predicted evolution of the LDM (Head et al., 2003), and the detailed stratigraphic relationships between them require successive phases of LDM emplacement, gully formation, and LDM removal. Contemporary Mars appears to be in the LDM removal phase in the mid-latitudes (30–45°), which contrasts relatively recent (~625 kyr) (Laskar et al., 2002) high-obliquity excursions when H₂O was stable at the surface in the mid-latitudes. Assessing the fate of this ice within the last ~600 kyr will help resolve the potential for liquid water at the surface of Mars in the Late Amazonian.

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