The formation and evolution of youthful gullies on Mars: Gullies as the late-stage phase of Mars' most recent ice age

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ABSTRACT

Gullies are extremely young erosional/depositional systems on Mars that have been carved by an agent that was likely to have been comprised in part by liquid water [Malin, M.C., Edgett, K.S., 2000. Evidence for recent groundwater seepage and surface runoff on Mars. Science 288, 2330–2335; McEwen, A.S. et al., 2007. A closer look at water-related geologic activity on Mars. Science 317, 1706–1709]. The strong latitude and orientation dependencies that have been documented for gullies require (1) a volatile near the surface, and (2) that insolation is an important factor for forming gullies. These constraints have led to two categories of interpretations for the source of the volatiles: (1) liquid water at depth beneath the melting isotherm that erupts suddenly (“groundwater”), and (2) ice at the surface or within the uppermost layer of soil that melts during optimal insolation conditions (“surface/near-surface melting”). In this contribution we synthesize global, hemispheric, regional and local studies of gullies across Mars and outline the criteria that must be met by any successful explanation for the formation of gullies. We further document trends in both hemispheres that emphasize the importance of top-down melting of recent ice-rich deposits and the cold-trapping of atmospherically-derived H2O frost/snow as important components in the formation of gullies. This provides context for the incorporation of high-resolution multi-spectral and hyper-spectral data from the Mars Reconnaissance Orbiter that show that (1) cold-trapping of seasonal H2O frost occurs at the alcove/channel-level on contemporary Mars; (2) gullies are episodically active systems; (3) gullies preferentially form in the presence of deposits plausibly interpreted as remnants of the Late Amazonian emplacement of ice-rich material; and (4) gully channels frequently emanate from the crest of alcoves instead of the base, showing that alcove generation is not necessarily a product of undermining and collapse at these locations, a prediction of the groundwater model. We interpret these various lines of evidence to mean that the majority of gullies on Mars are explained by the episodic melting of atmospherically emplaced snow/ice under spin-axis/orbital conditions characteristic of the last several Myr.

1. Introduction

The Amazonian period of Mars has generally been characterized as having climatic conditions similar to those observed today: Mars has been a low-temperature, low-pressure, hyperarid environment dominated by eolian activity since the Hesperian, over 3 Gyr ago (Carr, 1996; Golombek et al., 2006; Marchant and Head, 2007). While this impression is likely accurate for globally averaged conditions over time, the discovery of extremely young gullies in middle/high-latitudes provides compelling evidence that conditions were adequate at certain locations at certain times for short-duration surficial flow of liquid water within the last several million years (Malin and Edgett, 2000). While other channel-carving agents have been proposed (Musselwhite et al., 2001; Treiman, 2003; Shinbrot et al., 2004), liquid water is most consistent with the resultant morphology of gully landforms (Malin and Edgett, 2000; McEwen et al., 2007) (Fig. 1). Dry flows on steep slopes on Mars have been observed for decades at all latitudes, but latitude-dependent gullies bear little resemblance to these features (Fig. 2; equator-facing slope in Fig. 1a) (Malin and Edgett, 2000). While dry granular flows are capable of producing channels on extremely steep slopes (Shinbrot et al., 2004), the fine-scale braided channels, streamlined islands on channel floors, meanders, and terraces documented by HiRISE data provide morphologies that on Earth are only observed in the presence of liquid water (McEwen et al., 2007; Schon and Head, 2009). The occurrence of gullies only at mid- and high-latitudes (Malin and Edgett, 2000; Milliken et al., 2003) and on slopes below the angle of repose (Heldmann and Mellon, 2004; Dickson et al., 2007a; Heldmann et al., 2007) further implicate liquid water as a channel-carving agent.

Malin and Edgett (2000) noted and documented that (1) average conditions are below the triple-point where most gullies occur, (2) gullies are found mostly on cold, poleward-facing slopes, (3)
gullies are broadly clustered in certain regions (Newton crater, Dao Vallis, etc.), and (4) many gullies appear to emerge from distinct layers of bedrock. These properties were used to argue that gullies most likely formed from the sudden outburst of water from a shallow aquifer a few hundred meters beneath the surface, erupting explosively along crater/valley walls, entraining debris while carving sinuous channels and producing depositional aprons, and ceasing when water within the system is exhausted. The poleward orientation of most gullies suggested that insolation is a pivotal component to gully formation (Malin and Edgett, 2000), and Mellon and Phillips (2001) used this to formulate a conceptual model for gully initiation in which a water-rich soil layer (found at depth beneath a thick layer of unconsolidated regolith) is maintained in the liquid state by average geothermal heating and is confined by aquicludes on all sides except the slope face, where it is bounded by a layer of ground ice. Spin-axis/orbital parameter induced insolation perturbations would initiate freezing cycles within the aquifer, expanding the reservoir and generating outbursts at the slope face.

As more Mars Orbiter Camera (MOC) data were acquired and Mars Odyssey (MO) entered its primary mission, a suite of alternative hypotheses emerged that still involved liquid water eroding gullies, but focused on the plausibility of insolation driving melting of atmospherically-emplaced water ice. These include melting of: (1) surface snowpacks (Lee et al., 2001; Head et al., 2008); (2) ground ice in the top meter of the soil (distinct from groundwater found hundreds of meters beneath the surface) (Costard et al., 2002; Gilmore and Phillips, 2002); (3) accumulated frost deposits in cold-traps on present-day Mars (Hecht, 2002); and (4) snow-rich dusty mantling deposits (Christensen, 2003).

Taken together, the interpretations for gully formation involving liquid water can be subdivided into two hypotheses: (1) groundwater models and (2) surface/near-surface melting models. Each model calls upon the same driver for the initiation of flow within a gully system: spin-axis/orbital excursions that change the state of water either at or below the surface. Yet the models make different predictions with regard to the global distribution of gullies and the detailed morphology of gullies and their environments.

Several workers have attempted to test these models by mapping the global (Milliken et al., 2003), hemispheric (Heldmann and Mellon, 2004; Balme et al., 2006; Bridges and Lackner, 2006; Heldmann et al., 2007), and regional (Berman et al., 2005; Dickson et al., 2007a) distribution of gullies using a variety of data sets. Despite the range of instruments and the range of observers, these surveys have yielded consistent results that show that gullies follow regular patterns with regard to their areal and altitudinal distribution. This implies that there are key environmental factors in the formation of gullies and that detailed studies of particular gully systems (Head et al., 2008; Schon et al., 2009) could provide important insight into the formation of gullies as a whole.

Gullies have formed in the very latest of the Amazonian (Malin and Edgett, 2000; Reiss et al., 2004; Schon et al., 2009). Recent independent work with data acquired since the discovery of gullies has shown that the climate observed today may not be representative of the martian climate at other times in the Late Amazonian. Recent modeling of spin-axis orbital variation history has shown that the present obliquity of Mars (25.19°) is low compared to its maximum value within the last 5 Myr (>35°), and that the eccentricity of the martian orbit has ranged from ~0.0 to ~0.12 in the same timeframe (Laskar et al., 2004). Multiple workers have argued that this variability in spin-axis/orbital parameters is recorded on the surface of Mars in ice-related units emplaced in the last several hundred million years (Head and Marchant, 2003, 2008; Pierce and Crown, 2003; Head et al., 2005, 2006a,b;...
Li et al., 2005; Forget et al., 2006; Dickson et al., 2008; Holt et al., 2008; Plaut et al., 2009) and at a smaller scale during the last ~5 Myr (Mustard et al., 2001; Head et al., 2003; Milliken et al., 2003; Hartmann et al., 2003; Arfstrom and Hartmann, 2005), when gullies are likely to have been active (Malin and Edgett, 2000; Reiss et al., 2004; Schon et al., 2009). Deposits interpreted to have formed as a result of Late-Amazonian ice-related processes have been observed at all latitudes on Mars, arguing for cyclical transport of water from high-latitudes to low-latitudes with increases in obliquity (Head et al., 2003, 2005; Head and Marchant, 2003, 2008; Mischna et al., 2003; Mischna and Richardson, 2005; Forget et al., 2006), and from low-latitudes to high-latitudes when

![Fig. 2. Alcoves without gullies in the equatorial regions (A, C, E) and alcoves with gullies in the mid-latitude regions (B, D, F; see Fig. 3). In these equatorial instances (A, C, E), alcoves are generated by mass wasting of loose material at the crest of steep slopes. Under appropriate climatic conditions, such alcoves then serve as cold-traps that provide sources of meltwater that begin at the crest of the slope face (B, D, F). (A) Zuni crater rim; HiRISE orbit PSP_002397_1880 (7.7°N, 166.1°E). (B) HiRISE orbit PSP_005985_1455 (34.1°S, 134.5°E). (C) Valley wall near Aram Chaos; HiRISE orbit PSP_003340_1830 (2.9°N, 341.8°E). (D) HiRISE orbit PSP_005586_1425 (37.4°S, 228.9°E). (E) HiRISE orbit PSP_006774_2020 (21.6°N, 184.3°E). (F) HiRISE orbit PSP_005706_1425 (37.1°S, 192.0°E).]
obliquity is decreased to values observed today (Head et al., 2003; Levrard et al., 2004). Prior to these analyses, interpretation of Viking-era images led to the conclusion that observed flow-like features (e.g., lobate debris aprons) were formed by vapor diffusion of water into pore spaces in debris aprons, initiating ice-assisted creep and flow of debris (e.g., Squyres, 1979). Recent work with high-resolution image and topographic data, however, has provided evidence for large-scale, integrated networks of episodic glacial flow (Head et al., 2006a,b; Levy et al., 2007; Dickson et al., 2008), with some regions exhibiting past ice thickness of nearly a kilometer (Dickson et al., 2008, 2009). Recent data from the Mars Reconnaissance Orbiter (MRO) Shallow Radar (SHARAD) has shown that some of these units have dielectric properties consistent with large amounts of ice at present, supporting a debris-covered glacial origin for these features (Holt et al., 2008; Plaut et al., 2009). The climate of Late Amazonian Mars has been, at times, considerably different than the Mars of present day, even within the last 5 Myr (Mustard et al., 2001; Laskar et al., 2002, 2004; Head et al., 2003), including episodes of seasonal snowfall in the mid-latitudes (Mischna et al., 2003). A Mars undergoing cyclical deposition and removal of ice provides the spatial and temporal context within which gullies have formed and evolved in the Late Amazonian.

The direct association between gullies and Late Amazonian glacial activity on Mars has been observed at the global scale (Milliken et al., 2003) and documented in detail at the local level (e.g., Head et al., 2008). In this contribution, we unite these detailed local investigations and the global three-dimensional distribution of gullies. This then provides the foundation for the incorporation of new observations obtained by the MRO. When observed in concert, these findings allow us to test the contrasting models of groundwater sources and surface/near-surface melting.

2. Global distribution of gullies

Based on initial observations using MOC images, Malin and Edgett (2000) defined gullies based strictly on their morphology, consisting of three components (Fig. 1): (1) a head alcove at the top of a slope, (2) main and secondary channels emanating from the head alcove and trending downslope, and (3) depositional aprons at channel termini that are sometimes incised by subsidiary channels. While variation in gully morphology does exist, this definition of gullies on Mars has proven to be robust and has provided the basis for the mapping of these features across the planet using several different optical data sets (Milliken et al., 2003; Heldmann and Mellon, 2004; Berman et al., 2005; Balme et al., 2006; Bridges and Lackner, 2006; Dickson et al., 2007a; Kneissl et al., 2009).

These various surveys offer several independent measurements that clarify the physical parameters of the martian surface that govern the formation and evolution of gullies. As we discuss below, gully occurrence and formation is highly correlated with four properties: latitude, elevation, orientation, and local slope (Figs. 3 and 4).

2.1. Latitude

Gullies occur exclusively poleward of 27° in each hemisphere (Figs. 3 and 4) (Malin and Edgett, 2000) and are more common in the southern hemisphere than in the north (Fig. 3), yielding more robust statistical data for the gullies in the southern highlands. Gullies are most common between 30° and 42° in each hemisphere (Milliken et al., 2003; Heldmann and Mellon, 2004; Balme et al., 2006; Heldmann et al., 2007). Polar-pit gullies slightly increase the frequency in the southern hemisphere between 69°S and 72°S (Figs. 3 and 4a).
Despite a smaller statistical sample set, northern hemisphere gullies mirror the latitudinal trend exhibited by gullies in the southern hemisphere (Fig. 4a). Each hemisphere is normalized separately to highlight the symmetry in distribution across the equator. The spike in gully occurrence at ~70°S is due to polar pit gullies. We interpret these findings to mean...
that, with regard to latitude, gully formation is symmetric between hemispheres on Mars, consistent with surveys conducted before dedicated MOC targeting of gullies (Milliken et al., 2003) (Fig. 4a).

2.2. Elevation

The 30°S–42°S latitude region, where the highest concentration of gullies occurs (Milliken et al., 2003) (Figs. 3 and 4a), is characterized by a substantial range in elevation from the summit of Thaumasia (~9.0 km above the datum) to the floor of Hellas (~8.2 km below the datum), the lowest topographic point on Mars. Gullies generally conform to the global distribution of topography (Heldmann and Mellon, 2004; Dickson et al., 2007a; Heldmann et al., 2007), with the majority of gullies occurring within southern highland terrain. However, gullies have upper and lower elevations beyond which they do not occur (Fig. 4c). Heldmann and Mellon (2004) used early MOC data to determine a range of elevations for gully formation of ~5000 m to ~2000 m. Using data acquired when MOC was specifically targeting gullies in 2000 and 2001 (Edgett et al., 2003; Dickson et al., 2007a) refined this window to ~5200 m to 3100 m (Fig. 4c). While gullies are common within southern highlands terrain, they are absent from the uplands of Thaumasia and the floor of the Hellas impact basin.

Heldmann et al. (2007) performed a similar elevation analysis for gullies in the northern hemisphere and observed a broadly similar trend to that observed in the southern hemisphere (Heldmann and Mellon, 2004; Dickson et al., 2007a). They calculated an elevation window of ~800 m to ~5400 m, with 95% of gullies forming below the datum. There is no preferential clustering of gully alcoves at one particular elevation, and the distribution of gullies matches well with the overall distribution of topography in the northern hemisphere (Heldmann et al., 2007).

2.3. Orientation

Several studies have documented the orientation of martian gullies in each hemisphere. Upon their discovery, Malin and Edgett (2000) observed that the majority of gullies in both hemispheres appear to have a poleward orientation. Further targeting of MOC showed that orientation preferences are ambiguous when gullies are binned by hemisphere (Edgett et al., 2003). When mapped as a function of latitude, however, gullies appear to show a latitude-dependence with regard to orientation.

Between 30°S and ~42°S, nearly all gullies are poleward facing (Figs. 1a and 4b) (Heldmann and Mellon, 2004; Balme et al., 2006; Dickson et al., 2007a). In a small sample of gullies using MOC data in the southern hemisphere, Costard et al. (2002) observed that poleward of ~40°S, gullies are not as strongly oriented towards the pole as gullies equatorward of ~40°S. Full surveys of the southern hemisphere (Heldmann and Mellon, 2004; Balme et al., 2006) show that between 44°S and 58°S, gullies preferentially face the equator. Poleward of 58°S (58°S–72°S), where most gullies are concentrated in polar pits between 69°S and 72°S, gullies return to poleward facing (Heldmann and Mellon, 2004). Later studies have mitigated the impact of possible MOC targeting bias by only mapping gullies in craters with both north-facing and south-facing slopes imaged (Berman et al., 2005) and utilizing lower-resolution but higher-spatial coverage data sets like the High Resolution Stereo Camera (HRSC) (Balme et al., 2006). Each of these studies does show a latitude-dependence for gully orientation between regionally (Berman et al., 2005) and over the entire southern hemisphere (Balme et al., 2006). These later studies show a slightly lower equatorward preference for gullies between 44°S and 58°S than described by Heldmann and Mellon (2004). All studies show that where gullies are most frequently observed (between 30°S and 42°S), they are almost exclusively poleward facing (e.g. Figs. 1a and 4a and b).

The northern hemisphere exhibits fewer gullies (Milliken et al., 2003; Heldmann and Mellon, 2004; Heldmann et al., 2007), yielding more diffuse and less reliable statistical trends with regard to orientation (Fig. 4b). Multiple surveys (Bridges and Lackner, 2006; Heldmann et al., 2007; Kneissl et al., 2009) show conflicting results with regard to orientation as a function of latitude. Bridges and Lackner (2006) observed that where gullies are most common (35°N–40°N), they are evenly distributed between pole- and equator-facing slopes, consistent with the 30°N–44°N latitude band as a whole, as calculated by Heldmann et al. (2007). Poleward of 44°N, very few gullies are found (Bridges and Lackner (2006) found 82 gullies total), but those that do exist preferentially face the equator (Fig. 4b), which corresponds to the orientations in the same latitude band in the southern hemisphere (Fig. 4a and b) (Heldmann and Mellon, 2004; Balme et al., 2006). A more recent survey of both MOC and HRSC data (Kneissl et al., 2009) shows orientation patterns in the northern hemisphere that are identical to those observed in the southern hemisphere, where gullies equatorward of 40° are mostly pole-facing (Heldmann and Mellon, 2004; Berman et al., 2005; Balme et al., 2006). This survey incorporates a considerably higher number of MOC images (n = 311) and uses 1° latitude bins instead of 14° (as used in Heldmann et al., 2007). Orientation measurements made with HRSC data agree with those made with MOC at this latitude, suggesting that targeting bias is not a strong factor. Further analyses will be necessary to reconcile these various surveys.

2.4. Slope

The small size of gullies relative to currently available regional topographic data density (MOLA global data set) makes the documentation of local topographic information difficult. Gully channels are generally less than 1000 m long (Heldmann and Mellon, 2004), so the MOLA global gridded data set (463 m/px) is generally of insufficient resolution to accurately measure local slopes. Further, the gridded data set is comprised of interpolated elevation values where no track data were acquired, and this introduces significant errors at the scale of martian gullies (Dickson et al., 2007a). When original track data alone are used (300 m shot spacing), well-defined trends are observed at both the global and local scales. Here, we assess slope as it pertains to gully distribution from two vantage points: the detailed measurements of slopes that host gullies, and the relationship of gullies to the global roughness of Mars.

2.4.1. Local slope

Multiple workers have attempted to measure the slopes of gullied surfaces using MOLA data (Heldmann and Mellon, 2004; Dickson et al., 2007a), and both studies have shown that gullies form only on steep slopes. Precise measurements of slope are critical for evaluating gully formation and fate, as steeper slopes will require less water input into the system to trigger and sustain flow.

For their survey of the entire southern hemisphere, Heldmann and Mellon (2004) collected all MOLA tracks around a given gully and used these data to generate localized elevation maps from which they calculated alcove slopes. In contrast, Dickson et al. (2007a) sought to eliminate any possible error introduced by interpolating between MOLA tracks by calculating slopes directly from the original track data for gullies between 30°S and 45°S. Since Mars Global Surveyor (MGS) collected data in a polar orbit, along-track slope measurements were only available for gullies that were N–S trending, so any gullies that were not within 30° of due-north or due-south were omitted. Both studies sought to
obtain the slope of the gully at its alcove, the source region for the channel-carving fluid.

Using locally gridded data, Heldmann and Mellon (2004) found that gullies occur on a wide range of slopes, from 5° to ~40° over all latitudes (their Fig. 16). The mean slope of gully alcoves was measured to be 21°, with most gullies falling short of the presumed angle of repose (>26°). Using only track data, Dickson et al. (2007a) observed that gullies form on considerably steeper slopes, distributed around the mean value of 26.5° (median = 26.8°). Further, they observed that 87% of gullies form on slopes steeper than 21°, evidence that gullies almost always require steep slopes to form. This is consistent with slope measurements of gullies within Hale Crater made with HRSC stereo topography (Reiss et al., 2009). Preliminary parallax measurements of high-resolution HiRISE stereo pairs in both hemispheres suggests that gully alcove slopes are likely to be even higher than those measured by Dickson et al. (2007a), suggesting that flow within gully systems is likely to be sediment-rich (Parsons et al., 2008).

Further supporting the supposition that gully channels may be carved by sediment-rich flows is that gullies rarely reach the base of their host slope before transitioning from erosional to depositional regimes. Heldmann et al. (2005a) reexamined the southern hemisphere survey of Heldmann and Mellon (2004) and observed that 80% of gullies terminate before reaching the base of the slope. This is supported by initial HiRISE stereo pair measurements, which show that for 9 stereo pairs of gullies, the mean slope of fan material is 17° (Fig. 5) (Parsons et al., 2008).

2.4.2. Global roughness

The distribution of gullies on Mars correlates with the global distribution of steep topography. Based upon Mariner 9 imagery, Soderblom et al. (1973) documented a “blanketing” of the surface poleward of 30° in each hemisphere, which they attributed to redistribution of eolian debris derived from the polar layered deposits. Once global mapping from the Viking orbiters was achieved, Squyres and Carr (1986) further documented the distribution of this terrain, and proposed that creep of ground ice in the near-surface resulted in the present subdued morphology. Kreslavsky and Head (2000) quantitatively verified these observations by using MOLA track data to calculate the differential slope of the martian surface at three different baselines (0.6 km, 2.4 km, and 19.2 km) and found, particularly at the 0.6 km baseline, that Mars is indeed smoother towards the poles than towards the equator in each hemisphere (Fig. 3).

Using the roughness of Mars derived from the 0.6 km baseline, Kreslavsky and Head (2000; their Fig. 12) mapped a latitudinal “diffuse boundary” between the steeper preserved topography towards the equator and the relaxed terrain towards the poles (yellow dashes in Figs. 3 and 4). In the southern hemisphere, this boundary varies from 30°S to 50°S, but primarily cuts across the majority of the southern highlands between 42°S and 47°S. Local variation does exist, most noticeably in the floor of Hellas basin, which is smoother at all baselines than typical southern highlands terrain. In the northern hemisphere, this boundary is less pronounced but is observed across homogeneous terrains such as Chryse Planitia and Utopia Planitia, where the boundary occurs at ~47°N (Fig. 3) (Kreslavsky and Head, 2000).

In each hemisphere, the boundary between smoothed and preserved topography corresponds with the transition in gully frequency as a function of latitude (Figs. 3 and 4). Given the higher density of gullies in the southern hemisphere and the resulting reliable statistics, combined with the more distinct roughness boundaries calculated in the southern hemisphere by Kreslavsky and Head (2000), the global-scale relationship between roughness and gully frequency is more illustrative in the southern hemisphere. Several studies (Milliken et al., 2003; Heldmann and Mellon, 2004; Balme et al., 2006; Dickson et al., 2007a) independently found that in both MOC and HRSC data, gully frequency is highest between 30°S and 42°S, south of which gullies become significantly less common (Fig. 3 and 4a). This downturn in gully frequency directly correlates with the threshold for softening of terrain as observed by Squyres and Carr (1986) and calculated by Kreslavsky and Head (2000) (Figs. 3 and 4). This dependence on slope for gullies is further exemplified by the lack of gullies on the floor of Hellas basin (Dickson et al., 2007a), which is smoother at the 0.6 km baseline than other terrains within its latitude bin (Kreslavsky and Head, 2000), and the general paucity of gullies in the northern plains, which exhibit comparably fewer steep slopes at the 0.6 km baseline (Fig. 3). The global change in roughness that occurs at ~42° in each hemisphere (Kreslavsky and Head, 2000) places the majority of gullies in the areas of steeper slopes equatorward of this transition (Milliken et al., 2003; Heldmann and Mellon, 2004; Balme et al., 2006; Dickson et al., 2007a).

3. The geology of gullies and their environment

The global trends for gully distribution, the similarity in gully scale and morphology across the surface, and the uniform youth of gully systems suggest that formation of most gullies is governed by broadly similar processes. This highlights the importance of detailed examinations of representative gullies and assessment of their immediate geologic context. The groundwater and surface-melting models can both be tested using detailed geologic analyses by asking the following questions: (1) Do gullies occur on the slopes of landforms that are conducive to groundwater reservoirs? (2) Do gully systems form in one distinct event or are they episodic? (3) Do gullies emerge from consistent elevations across slopes? (4) Are gullies associated locally or globally with any other geomorphic features? And (5) How old are gullies?

3.1. Local geologic context

Upon their discovery, Malin and Edgett (2000) observed that gullies form on a variety of landforms, including impact crater walls, valley network and outflow channel walls, and polar pits. They also observed gullies on central peaks, and since then many workers have documented other examples of gullies forming on the slopes of isolated peaks that are unlikely or unable to host

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Fig. 5. Perspective view of gullies and their slopes in the Centauri Montes region of Mars (38.3°S, 96.8°E). HiRISE image PSP_001714_1415 draped over HiRISE stereo digital elevation model (DEM) produced from PSP_001714_1415 and PSP_001846_1415. Slopes were calculated from DEM. “Alcove Slope” represents slope of the surface within the alcove itself. DEM produced and provided by the United States Geological Survey.
Gullies on isolated peaks follow the same latitudinal distribution of gullies on crater walls (Figs. 3 and 4a), as they are most common between 30°S and 40°S and become less common further south (Balme et al., 2006). Like crater/valley-wall gullies, gullies on isolated peaks only form within a distinct elevation window (Fig. 4c) (Dickson et al., 2007a), a window that is slightly smaller than that of all gullies, due to the small amount of terrain at relatively high and low altitudes between 30°S and 45°S. These gullies follow the same orientation patterns as crater or valley wall gullies, predominantly facing the pole between 30°S and 40°S, with less of an orientation preference further south (Fig. 4b) (Balme et al., 2006; Dickson et al., 2007a). Since all gullies that were not within 30° of due-north or due-south were omitted from the slope analysis of Dickson et al. (2007a), this left too few gullies on isolated peaks to provide significant statistical information with regard to local slope. The only other survey to measure slopes of gullies across the southern hemisphere did not include gullies on topographically isolated peaks (Heldmann and Mellon, 2004).

Gullies that form on isolated peaks share the morphologic properties of crater or valley wall gullies (Fig. 6), with the exception of gullies observed on dunes, which lack broad fans and exhibit prominent levees along channel margins. Alcove widths for gullies on isolated peaks are within the same range as crater/valley-wall gullies (Dickson et al., 2007a), and channel lengths for gullies on isolated peaks are generally consistent with crater/valley-wall gullies (Balme et al., 2006).

The similarities with regard to gully distribution (latitude, elevation, and orientation [Fig. 4a–c]) and morphology between gullies on isolated peaks and crater/valley-wall gullies argues that they form via the same process. Variability with regard to gully morphology appears to be a function of the nature of the material being eroded: gully channels found on dune facies are eroding into the dune itself, whereas gully channels on all other slopes erode into Late Amazonian mantling units. The process that carves gullies on isolated peaks appears to be the same process that forms gullies on crater and valley walls, and any model for the formation and evolution of gullies must account for the local geologic context of all gullies to explain how these features are formed.

3.2. Episodic formation of gullies

It has been known since gullies were discovered that depositional fans are often incised by secondary channels (Fig. 7) (Malin and Edgett, 2000). It is unclear, however, if these secondary channels represent a subsequent, repeat flow down the main gully channel or simply the waning stages of one major event, such as explosive release of a confined aquifer (Mellon and Phillips, 2001). Additionally, it can often be difficult to determine if the stratigraphically older fan was in fact deposited through fluvial activity or is, alternatively, an initial talus pile generated from mass wasting on ultra-steep slopes, subsequently eroded by gully channels (Fig. 2).

Acquisition of HiRISE data has allowed for the detailed analysis of stratigraphic relationships within gully fan systems. Schon et al. (2009) examined a typical southern highlands gully site and found several generations of channel incision and fan emplacement within one gully fan system. They interpreted secondary craters emplaced upon the lowest stratigraphic unit to be evidence for significant temporal expanses between episodes of gully fan
emplacement, which they argued could represent multiple high-obliquity excursions within the last ~1.25 Myr.

Here, we report similar stratigraphic relationships elsewhere in the southern highlands. Fig. 8 shows two examples (Fig. 8a and c) where stratigraphically older fan material is fractured downslope, while fresh fan material is draped over the fractures and the fans, similar to stratigraphic relationships mapped by Head et al. (2008) along the eastern rim of Newton Crater. Fig. 8c reveals two types of fractures within the older fan material: (1) parallel linear faults with steep scarps facing the crater wall, and (2) linear pit chains that trend parallel to the linear faults and are observed to coalesce in places. We interpret the linear faults to form from the coalescence of pits, indicating that geologically significant periods of time are necessary for the faults to fully form. We hypothesize that the linear pits may form through differential sublimation of ice within the surface mantle unit, as mantle material is exposed to more sunlight at the base of the crater wall. Gully fans were emplaced before and after the linear faults (Fig. 8) and these events must have been separated by significant periods of time and were not formed by one gully carving event. Older fan material that is faulted by the

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**Fig. 7.** Channels incising and cross-cutting gully fans, suggesting that gully channels have been active at multiple times. (A) HiRISE orbit PSP_001691_1320 (47.5°S, 4.4°E). (B) HiRISE orbit PSP_007855_1370 (42.9°S, 196.2°E). (C) HiRISE orbit PSP_003675_1375 (42.3°S, 201.8°E). (D) HiRISE orbit PSP_006853_1395 (40.3°S, 196.8°E). (E) HiRISE orbit PSP_002291_1335 (46.2°S, 184.5°E). (F) HiRISE orbit PSP_007498_1415 (38.4°S, 224.1°E).
linear fractures retains incised channels (Fig. 8c and d), showing that the older fans were not deposited by dry mass movements. Interior channels within the broader gully valleys are also observed (Fig. 8c and d), suggestive of multiple distinct gully events.

Episodic activity within gullies demands that any model for gully formation include a mechanism for multiple generations of channel-carving activity. In addition to describing how a gully formed, theories of origin must also explain the evolution of the entire gully system over time.

3.3. Association between gullies and bedrock layering

In their detailed explanation of the groundwater model for gully formation, Mellon and Phillips (2001) devised a conceptual framework for the trapping, freezing and release of a confined liquid aquifer at depth (their Fig. 11). Among the constraints that this places on the confined groundwater model are: (1) liquid water-rich soil must be trapped on all sides except the slope face by impermeable rock layers, which serve as aquicludes so that water can only escape laterally; and (2) the aquifer must exist at some depth beneath the surface under a blanket of unconsolidated regolith (they estimate ~100 m) to be sustained in the liquid state by geothermal heating. Mellon and Phillips (2001) argued that these constraints are in strong agreement with MOC observations, consistent with the initial observation of Malin and Edgett (2000) of an association between gully source regions and bedrock layering. Upon their discovery, however, several gullies exhibited limited or no association with subsurface layering (Malin and Edgett, 2000; their Figs. 3a, d, f, 4, and 5a), suggesting a more complicated relationship.

None of the global, hemispheric, or regional surveys of martian gullies (Heldmann and Mellon, 2004; Berman et al., 2005; Bridges and Lackner, 2006; Balme et al., 2006; Dickson et al., 2007a) has documented a widespread association between bedrock layering and gully formation, as was reported upon their discovery (Malin and Edgett, 2000). Gilmore and Phillips (2002) used 76 MOC images acquired from three southern hemisphere regions to show gully channels that appear to emanate from bedrock layers. Broader surveys of gullies have not quantitatively reported on this relationship (Milliken et al., 2003; Heldmann and Mellon, 2004; Balme et al., 2006; Bridges and Lackner, 2006; Dickson et al., 2007a; Heldmann et al., 2007; Kneissl et al., 2009). Given the relatively small spatial footprint of MOC data, these relationships are often difficult to assess, but recently obtained Context Camera (CTX) and HiRISE data from MRO provide the opportunity to analyze these relationships in detail. In our survey of HiRISE data containing gullies, we found that 26% of gullies emanate at bedrock layers, and only 11% show suites of gullies that all emanate from one consistent bedrock layer. Even in examples of MOC data in which gullies appear to emanate from beneath a layer of bedrock, HiRISE data show channels contributing to the gully system from above the outcrops (e.g. Fig. 9f).

HiRISE data provide the resolution necessary for the analysis of the detailed morphology of head alcove regions. We investigated alcoves to determine whether channelization commences at the head of the alcove, at the base, or in the middle of the alcove itself.
From our initial survey of 124 HiRISE images, many alcoves exhibit fluvial morphology, but some do not (Fig. 9). Channels frequently emanate from the head of the alcove and merge with other channels from the sidewall escarpments (Fig. 9b and e–f), eventually forming a primary channel downslope. Alcoves formed as a product of mass wasting are frequently observed on steep slopes in equatorial regions and do not have associated gullies (Fig. 2a, c, and e; see equator-facing slopes in Figs. 10a and 11a). Therefore, alcoves can form in dry mass-wasting environments, and may not be directly associated with the gully-forming process. Alcoves may certainly be widened and further eroded as the entire gully system evolves (Levy et al., 2009a), including localized headward erosion of unconsolidated material.

Heldmann and Mellon (2004) calculated the depth of gully alcoves in relation to the host ridge, and they observed a wide range, both to the head of the gully alcove (Heldmann and Mellon, 2004; their Fig. 6) and to the base of the alcove (Heldmann and Mellon, 2004; their Fig. 7). While some gullies form at depth, many form within 50 m of the top of the slope, which would not provide enough of a blanket to raise the melting isotherm for a subsurface

Fig. 9. Fluvial channels beginning at the crest of head alcoves instead of the base. (A) HiRISE orbit PSP_001528_2210 (40.6°N, 120.1°E). (B) HiRISE orbit PSP_003464_1380 (41.5°S, 202.1°E). (C) HiRISE orbit PSP_003583_1425 (37.1°S, 191.9°E). (D) HiRISE orbit PSP_003810_1222 (57.7°S, 118.3°E). (E) HiRISE orbit PSP_004044_1165 (63.4°S, 212.0°E). (F) HiRISE orbit PSP_005943_1380 (41.6°S, 202.3°E).
aquifer (Mellon and Phillips, 2001). Gully alcoves show no evidence for clustering at a similar elevation beneath the crest of the overlying ridge (Heldmann and Mellon, 2004; their Figs. 6 and 7). Most gullies form on fresh craters with raised rims (e.g., Fig. 10), with channels commencing at elevations above the surrounding plains (Fig. 10c).

3.4. Relationship to other young features on Mars

Using initial data returned from MOC and MOLA, Kreslavsky and Head (2000), Mustard et al. (2001), Milliken et al. (2003), and Head et al. (2003) documented a latitude-dependent mantling unit that was dissected at lower latitudes; they interpreted the mantles to be a layer of atmospherically-deposited dusty ice, emplaced recently and currently undergoing desiccation at lower latitudes. Milliken et al. (2003) mapped the global distribution of gullies in relation to both this dissected mantle and “viscous flow features” (VFF) (Hartmann et al., 2003), downslope-trending lobate landforms that they interpreted to be evidence of near-surface ice-assisted creep of debris, analogous to larger ice-related features on Mars, such as lineated valley fill (LVF) and lobate debris aprons (LDA) (Squyres, 1979) (Fig. 6). They observed a consistency between the distribution as a function of latitude among gullies, dissected mantle, and VFF, all occurring most commonly between 35°S and 40°S (Fig. 3).

Characterizing the role of water–ice on the surface of Mars in the Late Amazonian has been a frequent goal of recent studies, using new high-resolution image, altimetry and radar data. Based upon Viking data, Squyres (1979) interpreted lobate debris aprons...

Fig. 10. An unnamed gullied crater on the eastern margin of Newton Crater (40.1°S, 204.7°E), showing evidence for extensive glaciation and subsequent gully activity, all emanating from pole-facing slopes, as reported by Head et al. (2008). (A) CTX orbit P02-1842-1397. Notice how small alcoves are formed on the equator-facing slopes where no gully channels or fans are observed. These alcoves are presumed to form through mass wasting of material. (B) Nested HiRISE false-color image PSP_001842_1395 (Red: 900 nm; Green: 700 nm; Blue: 500 nm) showing seasonal frost deposits in southern hemisphere winter (Ls = 152.1°). Frost is preserved only on the pole-facing slopes, and is concentrated within the gully alcove, with a gully channel emanating from this sheltered region near the crest of the crater rim. (C) Local context for (B) with HiRISE false-color image PSP_001842_1395 superposed over HiRISE RED channel PSP_001842_1395. MOLA tracks were extracted from orbits 17,764, 18,449, 17,940, 19,404, and 17,852 (from west to east). The head of the channel observed in (B) is ~160 m above the surrounding plains. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)
(LDA) and lineated valley fill (LVF) to represent Late Amazonian transport of debris downslope, facilitated by ice in pore space that would initiate viscous creep of material (see also Lucchitta, 1984). With new data, it has been shown that these landforms frequently coalesce into integrated networks (Head et al., 2006a,b) and constrict between topographic obstacles (Head et al., 2005), arguing for flow driven by a significant component of ice, and a debris-covered glacial origin for the deposits (Head et al., 2006a,b), analogous to cold-based glacial flow within the Antarctic Dry Valleys (see Marchant and Head, 2007 and references therein). Data from the CTX camera on MRO, in conjunction with MOLA topography, show relict glacial features that presently grade upslope, implying a past thickness of ice of at least ~1 km at some locations (Dickson et al., 2008, 2009). Glaciation is also likely to have been episodic (Head et al., 2005; Levy et al., 2007; Dickson et al., 2008), arguing that activity in these systems was largely controlled by fluctuations in spin-axis/orbital parameters for Mars in the Late Amazonian. Mapping of the flux of small impacts that have occurred on Mars over the last decade (Malin et al., 2006) has shown that crater densities can be reliable indicators of recent surface ages on Mars (Hartmann et al., 2008). Hartmann (2007a) performed crater counts to calculate the age of several VFF in the terrain to the east of Hellas. Regardless of the isochron system or production model used, these features are on the order of 1–10 myr, temporally consistent with the generally accepted upper boundary for gully formation on Mars (Malin and Edgett, 2000; Reiss et al., 2004; Schon et al., 2009).

Milliken et al. (2003) also observed relationships between gullies and VFF at the local level that suggest an evolutionary association between VFF and gullies. Data acquired since then have shown these relationships to be common (Arfstrom and Hartmann, 2005; Berman et al., 2005). Head et al. (2008) analyzed in detail a young ~10 km diameter crater on the eastern margins of Newton crater (Fig. 10) and documented stratigraphic relationships that they interpreted to represent multiple episodes of glacial advance.
and retreat, with gullies forming from surface melting of snow/ice following the final stage of glacial recession. Lobate material has resurfaced the floor of this crater, emanating from the northern rim (poleward facing), and this material is in turn modified on its northern boundary by a suite of arcuate ridges that encompass flow to their north. Head et al. (2008) interpreted the arcuate ridges to be deposits from former glacial lobes, and the hollows to represent the former sites of glacial ice that formed from atmospherically-derived ice that collected along the northern rim, and that subsequently sublimated. These hollows are now superposed by gully fans, suggesting that gully formation was the latest stage of activity in this system. Berman et al. (2005) mapped similar relationships between gullies and arcuate ridges in the vicinity of Newton and found 104 craters that exhibit these relationships, the majority exhibiting a poleward orientation.

The acquisition of CTX data motivated us to conduct a survey for features that could represent this transition from ice-dominated flow to recession and localized melting. At 41°S, 156°E, we observe a suite of gullies with fans that superpose hollows bounded by arcuate ridges identical to those observed by previous workers (Milliken et al., 2003; Arfstrom and Hartmann, 2005; Berman et al., 2005; Head et al., 2008) (Fig. 11). One alcove, however, appears to still host what we interpret to be evidence for viscous flow of ice-rich material. As observed in Fig. 11, an extended alcove hosts material that is lineated downslope, similar to tributary systems observed elsewhere on Mars (Dickson et al., 2008) and analogous to alpine-glacial systems on Earth. Once the lineated material encounters the crater floor, it is distributed laterally as well as towards the center of the crater, resulting in arcuate fractures that are concentric to the main trunk of lineated material (Fig. 11b and d). Further downslope are sinuous arcuate ridges identical to those observed by other workers (Milliken et al., 2003; Arfstrom and Hartmann, 2005; Berman et al., 2005; Head et al., 2008). We consider this to be evidence that the material that flowed from the alcove is responsible for the formation of the sinuous arcuate ridge further downslope before subsequently recession, consistent with the interpretations of previous workers (Milliken et al., 2003; Berman et al., 2005; Head et al., 2008).

In addition to viscous flow and glacial-like features, it has been proposed that the latitude-dependent mantling material itself could serve as a volcanic-source for melting and carving gully channels (Christensen, 2003). Observational evidence from THEMIS VIS data show gullies emerging from beneath what is interpreted to be a water-rich dusty mantling unit, suggesting that gullies have formed at these locations as a product of melting of the mantling unit at high obliquity in the last 10,000–100,000 years (Christensen, 2003). Recent modeling efforts of a particular gully system observed by Christensen (2003) have shown that small amounts of melting can be achieved at this location under present-day conditions, though it is unlikely that snow deposited during the latest high-obliquity regime would persist unprotected by a dust lag until today (Williams et al., 2008). When applied to the rest of Mars at higher obliquity (35° and 45°), this model predicts melting of surface snowpacks at the locations where gullies are observed in each hemisphere (Williams et al., 2009), consistent with previous calculations performed by Costard et al. (2002).

Finally, high-latitude gullies are frequently observed among and superposing polygonally-patterned ground (Malin and Edgett, 2000). Polygonally-patterned ground blankets the majority of Mars at high-latitudes (Mangold, 2005; Levy et al., 2009b), so no genetic inferences should be made simply by their proximity to each other. Frequently, however, the mantling unit that gully channels typically incise is characterized by polygonally-patterned ground, and HiRISE data have allowed for detailed analysis of how polygons affect gully morphology (Levy et al., 2009a). Using the south fork of Upper Wright Valley in the Antarctic Dry Valleys (ADV) as an analog (Marchant and Head, 2007) (Fig. 12), Levy et al. (2009a) found evidence for polygon troughs serving as cold-traps for wind-blown snow on Mars and conduits for flow upon melting. While following the distribution properties for gullies as a whole (Levy et al., 2009b), gullies that form in regions of polygonally-patterned ground frequently exhibit a unique morphology, with alcove lengths frequently six times as long as their width (Levy et al., 2009a). This prompted Levy et al. (2009a) to propose a model for gully evolution and alcove expansion in terrains with polygonally-patterned ground. In their model, successive phases of accumulation and melting of wind-blown snow erodes channels over time on sheltered slopes. Upslope, these channels continue to erode until an alcove is formed, with multiple channels merging downslope. This alcove then can serve as another sheltered trap for wind-blown snow, leading to an increased volume of channel-carving material. While flowing downslope, water infiltrates the unconsolidated surface material and when water supply on the surface can no longer support flow, fans are deposited over polygonally-patterned ground. HiRISE data show that gully fans both drape over polygonal fractures and are fractured themselves, suggesting that gully formation/deposition occurs contemporaneously with polygon formation at high-latitudes on Mars (Levy et al., 2009a).

The latitude-dependence and symmetry about the equatorial region for all of these features (Figs. 3 and 4a) (Milliken et al., 2003) suggests that volatile-content was atmospherically-derived (Head et al., 2003), arguing that the material that carved the gullies in each hemisphere was atmospherically-derived as well. Periods of high obliquity (>35°) have occurred in the last 5 Myr (Laskar et al., 2002, 2004), providing increased insolation at the poles, leading to transport of volatiles to the mid-latitudes (Head et al., 2003). Upon the return to lower obliquity conditions like that observed today, water is once again transported and redeposited at higher-latitudes (Levrad et al., 2004), where high concentrations of near-surface water ice are detected (Boynton et al., 2002; Feldman et al., 2002). Measurements by SHARAD (Holt et al., 2008; Plaut et al., 2009) show that earlier in the history of Mars, considerable amounts of ice were trapped at mid-latitudes when this cycle occurs; this demonstrates that ice can persist under a debris layer for millions of years at these locations even under low-obliquity conditions such as those observed today (Head and Marchant, 2008). This global transport of water provides a source for gully-carving material, and additionally provides a recharge mechanism, as Mars has undergone many excursions with regard to its obliquity and eccentricity over the last 20 Myr, driving the cyclic transport of water from high-latitudes to low-latitudes (Head et al., 2003; Laskar et al., 2004).

3.5. Age of gullies

Gullies are unequivocally young in comparison to other fluvial landform on Mars (Malin and Edgett, 2000). They superpose and cross-cut other young features such as dunes (e.g., Reiss et al., 2004) and polygonally-patterned ground (e.g., Levy et al., 2009a), form within young Amazonian impact craters (Schon et al., 2009), exhibit fresh morphologies, and are rarely superposed by impact craters. Malin and Edgett (2000) used the deformation rates of dunes and polygons to suggest that gullies may be younger than a million years old, but the lack of superposed impact craters makes absolute measurements of crater-size frequency distribution difficult, particularly given the small spatial area and steep slopes that gullies occupy. This has made calculating the absolute age of gully systems on Mars difficult, but multiple workers (Reiss et al., 2004; Schon et al., 2009) have attempted to use stratigraphic relationships in conjunction with crater-size frequency distributions to calculate upper bounds (oldest possible ages) for young
gullies on Mars. These studies provide valuable temporal constraints that also serve as context for evaluating the environmental conditions under which gullies form on Mars.

The clearest example of gully fans superposing eolian dunes is found along the walls of Nirgal Vallis (Malin and Edgett, 2000; their Fig. 9a). The floor of Nirgal Vallis is mostly covered by dunes, and wherever the two landforms intersect, gullies superpose the dunes (Reiss et al., 2004). The dunes do preserve small craters, which prompted Reiss et al. (2004) to perform crater counts on the dunes themselves using MOC data to provide an upper age limit for gully formation within Nirgal. This necessitated the use of very small craters (<100 m diameter), which has been a controversial practice given the contributions to the populations made from secondary craters (McEwen et al., 2005; McEwen and Bierhaus, 2006). The discovery of primary impact craters that formed on Mars during the lifetime of Mars Global Surveyor (MGS) (Malin et al., 2006) do provide good fits to pre-existing production functions (Malin et al., 2006; Hartmann, 2007b), however, and these production functions have been used on test areas with craters with diameters of ~11 m (Hartmann et al., 2008). This provides credence to the counts performed by Reiss et al. (2004), who found that the dunes of Nirgal have a best-fit absolute model age range from 140,000 to 380,000 years, with an upper bound of 1.4 Myr. Given the uncertainty involved in counts of this nature, they concluded that dune activity on the floor of Nirgal Vallis ceased no later than 3 Myr ago, and was likely to have been more recent, possibly younger than 300,000 years (Reiss et al., 2004). Since gully fans superpose the dunes of Nirgal Vallis, this provides a conservative upper bound of 3 Myr for gully formation in this region.

The other attempt to provide absolute age constraints to gully formation was made by Schon et al. (2009), who used the same gully system that provided evidence for episodic activity (see Section 3.2) to calculate an upper bound for the most recent episodes of gully activity. Schon et al. (2009) performed a regional search for the primary impact crater that produced the secondary cluster of craters that superposes the stratigraphically older material within the gully system. This material is superposed by younger gully fans, so an absolute age for the source crater of the secondaries could provide an upper bound for the most recent episodes of gully activity and fan emplacement at this location. This search revealed a ~7 km diameter rayed crater within ~100 km of the gully site that was interpreted to be the source of the secondary craters within the gully system. Crater counts of multiple units of smooth rim material using HiRISE data yielded consistent fits to a crater retention age of ~1.25 Myr (Schon et al., 2009).

These studies show that gullies on Mars are no older than several million years, but do not constrain how recently they have been active. Repeat targeting of gully systems with MOC revealed two small channels that have been active in some manner over the last decade (Malin et al., 2006). Data acquired late in the MGS mission revealed relatively bright units at the base of two small channels incised into crater walls. The bright units, one of which is in Terra Sirenum and the other in Centauri Montes east of the Hellas impact basin, were absent in early MOC images but have persisted into the Primary Science Phase of MRO. The persistence of these bright units over several martian seasons rules out surface ice deposits for the origin of the brightness, and CRISM has not detected any mineralogic signature of salt deposits or hydrated minerals (Murchie, 2007). As dust on Mars is almost always brighter than the units that it superposes, Malin et al. (2006) concluded that these units are not simply the removal of dust that reveals a brighter substrate, and that the digitate termini of the units are indicative of fluvial transport and deposition of bright material originating upslope. HiRISE observations have shown that features indicative of both fluvial and dry transport are observed in the Centauri Montes features, and that their origin cannot be presently determined (McEwen et al., 2007). The channels in question are smaller and less sinuous than typical gully channels, and also do not show diagnostic fluvial bedforms: these unusual characteristics compared to typical gullies makes it difficult to place them in the spectrum of martian gully morphology. Each example fits broadly into the global distribution of gullies in the southern hemicircle.
sphere (Fig. 4), with some notable exceptions. The Centauri Montes example is equator-facing, which is extremely rare for gullies at that latitude (38°S) (Fig. 4b) (Heldmann and Mellon, 2004; Berman et al., 2005; Balme et al., 2006; Dickson et al., 2007a), and traditional alcove-channel-fan gullies are observed on the pole-facing wall of the host crater. The Terra Sirenum bright deposits occur at a very high elevation (~3000 m above MOLA datum), which is at the extreme upper limit for gullies in the southern hemisphere (Fig. 4c) (Dickson et al., 2007a).

Modeling that incorporates 1 m spatial resolution topographic models from HiRISE stereo has shown that the observed features in Centauri Montes can be accounted for by dry granular flow more readily than by fluvial activity (Pelletier et al., 2008). While this does not rule out fluvial activity at these sites during the MGS mission, further observational evidence must be acquired before it is definitively shown that fluvial activity within gully systems is occurring on contemporary Mars, particularly since these examples are not typical of the majority of gullies (Fig. 4).

The debate regarding the role of water in the recently-formed bright deposits does not modify the evidence described above for the more general role of liquid water in the formation and evolution of gully systems on Mars. Multiple studies have used stratigraphic and crater size-frequency data to show that well-developed gully systems with fluvial morphologies have been active within the last several million years (Malin and Edgett, 2000; Reiss et al., 2004; Schon et al., 2009).

4. Terrestrial analogs

4.1. Gullies in terrestrial polar environments

Mars-like gullies form in both Arctic and Antarctic regions on Earth, and multiple workers have attempted to extract information from these features as a proxy for understanding the formation and evolution of gullies on Mars. Most fieldwork has been conducted in the Arctic (Devon Island, Canada: Lee et al., 2001; Jameson Land, East Greenland: Costard et al., 2002; around the Esja plateaus, Iceland: Hartmann et al., 2003; Axel Heiberg Island, Canada: Andersen et al., 2002 and Heldmann et al., 2005a) providing a range of terrains and environmental conditions to evaluate gully formation and evolution. It should be noted that the study of Axel Heiberg Island, Canada, as an analog for martian gullies (Heldmann et al., 2005a) was explicitly devoted to documenting flow properties within the channel system, as the channels of interest exhibit flow of brines (>10% salt content (Andersen et al., 2002)) throughout the entire year (Heldmann et al., 2005b). Sources of water for the Axel Heiberg seeps are thought to be from subglacial meltwater or from higher-elevation surface lakes (Andersen et al., 2002).

Investigations that focused on the formation and evolution of gully systems all observed processes that involve atmospheric deposition of snow that undergoes melting to carve channels. Lee et al. (2001) observed that in Devon Island, Canada, seasonal snow deposits accumulate in gully alcove regions and within the gully channel itself, providing the source of meltwater in gully channels. It was also observed that layered bedrock outcrops provide excellent shelters for surface snow deposits, which gives the appearance that gullies emerge from beneath those layers, though no evidence for groundwater seepage was observed (Lee et al., 2001; their Fig. 3). Costard et al. (2002) reported observations of steep-sloped gullies in Greenland and concluded that the thermal wave provided by solar heating penetrated to deposits of ground ice in the active layer (the uppermost non-frozen layer of soil), inducing water flow down steep slopes and carving landforms similar to those on Mars. Hartmann et al. (2003) studied similar landforms in Iceland and observed a similar formation mechanism to that discussed by Costard et al. (2002), with snow and ground ice in the active layer melting and carving gullies downslope.

Gullies are also observed in the Antarctic Dry Valleys (ADV) (Marchant and Head, 2007; Head et al., 2007; Dickson et al., 2007a; Levy et al., 2009a; Morgan et al., 2007, 2008) (Figs. 12 and 13), a hyperarid polar desert that represents the largest ice-free exposure of the Antarctic continent. While no terrestrial analogs have the exact same environmental conditions as Mars (see Marchant and Head, 2007) the setting of the ADV as an analog for Mars and martian gullies is particularly useful as: (1) it is an extremely cold, hyperarid polar desert, (2) it is not subject to rainfall that could enhance erosion within gully systems (as is the case in arctic environments), and (3) it exhibits a suite of landforms that strongly resemble glacial/periglacial features on Mars (Head and Marchant, 2003; Shean et al., 2007; Marchant and Head, 2007; Levy et al., 2009a,b). It has been argued that slight variations in climatic properties within the ADV result in significant changes in surface erosion and resultant landforms (Marchant and Denton, 1996; Marchant and Head, 2007). Marchant and Denton (1996) observed trends with regard to precipitation, wind direction, relative...
humidity, temperature, and soil-moisture content that lead them to partition the ADV into three separate zones, Zones 1–3, which are now referred to as the Coastal Thaw Zone (Zone 1), the Inland Mixed Zone (Zone 2), and the Stable Upland Zone (Zone 3) (Marchant and Head, 2007) (Fig. 12). Of these three zones, the Coastal Thaw Zone (CTZ) is least like Late Amazonian Mars, as the climate and summer winds off of the Ross Sea increase the relative humidity (Marchant and Denton, 1996), generating a suite of landforms not observed on modern Mars (Marchant and Head, 2007). The Stable Upland Zone (SUZ) and Inland Mixed Zone (IMZ), however, display landforms that suggest that similar climate-dependent processes observed in the ADV may have occurred on Mars in the Late Amazonian, with the SUZ approximating average conditions on Mars and the IMZ representing optimal conditions for accumulation and melting on Mars.

Marchant and Head (2007) observed that, among other factors, landform evolution in all microenvironments is strongly affected by elevation, orientation, and local slope. This is particularly apparent with regard to gullies in the ADV, which share the general morphologic components of gullies on Mars (alcove, channel, fan) (Fig. 13). Gullies are absent from the SUZ and the minimal surface melting observed is restricted to near low-albedo surface rocks (Marchant and Head, 2007). Gullies do occur within the IMZ, particularly along the steep walls of the South Fork of upper Wright Valley, which separates the Asgard and Olympus ranges (Fig. 12). Gullies occur preferentially on the warmer north-facing (equator-facing) slopes of upper Wright Valley, emanating from broad alcoves cut into dolerite outcrops that are in excess of 30° in slope (Morgan et al., 2007, 2008). Channels that are incised into the alcoves trend downslope for lengths of generally 1–2 km, depositing multiple generations of alluvial fans on the floor of the valley. During the austral summer of 2006–2007, these channels were active, caused by melting of surface snowpacks in both alcoves and the channels themselves (Morgan et al., 2007, 2008). Observations made during the 2008–2009 field season showed considerably less activity, due to abnormally low winter precipitation, showing that winter snowfall is the dominant contributor to summer surface flow (Morgan et al., 2009).

Flow within gully systems in the IMZ at present would not be predicted under regionally-averaged conditions. Mean annual precipitation is on the scale of centimeters (Marchant and Head, 2007) and mean atmospheric temperature is −7 °C (LTER), such that the small amount of deposited snow would sublimate instead of melt. So what explains the occurrence of gullies that are observed to form from erosion of melted surface snowpacks (Morgan et al., 2007, 2008; Dickson et al., 2007b)? As on Mars, optimal conditions in specific microenvironments instead of average conditions govern the deposition, accumulation, and melting of atmospherically-derived snow (Head et al., 2007).

Snow that is deposited in Wright Valley, particularly during austral winter, is transported down-valley by the strong katabatic winds that emanate from the East Antarctic Ice Sheet, and up-valley by winds from the coastal regions (Fig. 12). This snow collects and accumulates within and around topographic obstacles, such as massive boulders, alcoves and channels and is preserved there well into the austral summer as these traps serve as shelters for snow against insolation and sublimation (Marchant and Head, 2007). This process produces expansive perennial meters-thick snowpacks in gully alcoves (Morgan et al., 2007, 2008) and seasonal 1–2 meter thick snowpacks in gully channels that extend for hundreds of meters in places (Dickson et al., 2007b) (Fig. 13). It was observed during the 2006–2007 austral summer that the local climate of gully alcoves is more conducive to the deposition of snow from regional storms than lower elevations, as lower-altitude clouds hug the alcoves and preferentially deposit snow, increasing the amount of snow available to the upper reaches of the gully system (Fig. 14).

The temperature range during austral summer in the IMZ straddles the melting point on cloud-free days (Morgan et al., 2007, 2008). This controls the melting and drainage of gully systems, as snow melts near peak insolation during the day and re-freezes into a thin layer of ice when the Sun is behind the Asgard range to the south (Fig. 12). This cycle operated to remove all channel-trapped snow by mid-December of 2006, while perennial snowbanks in alcoves continued to melt around their margins (Morgan et al., 2007, 2008). No evidence for subsurface aquifers or seeps
from beneath the permafrost layer was observed (Marchant and Head, 2007; Morgan et al., 2007, 2008, 2009).

All terrestrial analogs need to be considered cautiously due to the differences between the atmospheric properties of Earth and Mars. Nonetheless, the evolution of gullies in the ADV provides valuable insight into some of the conditions that might lead to the evolution of gullies on Mars. Gullies in the ADV are not features formed in average conditions on the surface; they occur at specific elevations, on specific slopes, and under peak seasonal illumination conditions based on their orientation (Marchant and Head, 2007). On Earth these are properties that are intimately tied to climate. This leads to significant cold-trapping of wind-blown snow in winter, allowing for accumulation of meters-thick snow deposits in an environment classified as a hyperarid polar desert (Marchant and Head, 2007). On Mars, we observe similar patterns with regard to elevation (gullies do not typically form at high elevations with low-pressure), slopes (gullies only form on very steep slopes) and orientation (gullies generally form where ice can be stable and insolation is low), which points to the likelihood of a similar conclusion: when only annually averaged conditions are considered, gullies on Mars do not appear likely to have formed by liquid water-related processes; however, when microenvironments and peak local conditions are considered, their formation by liquid water seems much more likely (Fig. 13).

4.2. Applications to Mars

While snow is unlikely to accumulate at gully locations in the current climate regime on Mars, we can learn about the preservation of snow/water–ice by investigating the composition and fate of seasonal frost in the martian mid-latitudes. Schorghofer and Edgett (2006) documented seasonal frost at latitudes as low as 80°S, and performed a one-dimensional thermal model that predicted that most of the seasonal frost is CO2, covering a small amount of H2O frost. This led them to predict a limited window during autumn in the southern hemisphere when H2O frost would be detectable from orbit on cold pole-facing slopes: $L_S$ between 59° and 74°, which corresponded to late May to early July in 2006 (Schorghofer and Edgett, 2006).

MRO entered its Primary Science Phase (PSP) in early November of 2006 ($L_S = 140.6°$), well into winter in the southern hemisphere. Early targeting of frost in the southern hemisphere by the CRISM spectrometer revealed that even in the coldest portion of winter in the southern hemisphere, frost on cold pole-facing slopes in the southern mid-latitudes is dominated by H2O (Murchie et al., 2007). A CRISM target of gullies in Terra Sirenum acquired on November 25, 2006 ($L_S = 140.6°$) revealed a laterally-expansive deposit of water frost along the cold pole-facing crater wall, with CO2 frost only occupying the coldest sheltered portions of the slope (Murchie et al., 2007) (Fig. 15a and b), visible in a nested HiRISE image (Fig. 15c). Once frost deposition has begun, the thermal properties of the surface change (albedo), producing a feedback effect that facilitates the accumulation of further frost. While further hyper-spectral data and dedicated monitoring are required, this concentration of H2O frost on the pole-facing slope of a mid-latitude crater at its coldest season implies that temperatures may not be cold enough in this microenvironment to permit significant deposition of CO2 frost, relegating it only to terrains that receive the smallest amounts of insolation, where it blankets deposits of H2O frost.

While the HiRISE camera cannot identify the composition of frost on the surface, it is capable of resolving frost at significantly higher spatial resolution than CRISM (25 cm/px) (Fig. 15c), particularly with its two 500 nm (Blue–Green) CCDs. This makes HiRISE color data an ideal product for evaluating the fate of seasonal frost deposits. As the PSP for MRO continued through the end of 2006 and beginning of 2007, HiRISE was able to image the recession of frost in the southern hemisphere. This prompted us to utilize HiRISE color data in conjunction with higher-spatial coverage HiRISE monochrome data from the 10 red CCDs to evaluate geometric relationships between seasonal frost accumulation and gully landforms. In the crater reported on by Head et al. (2008) along the eastern margin of Newton crater in the southern hemisphere, a HiRISE image was acquired on December 17, 2006 ($L_S = 152.1°$ [winter in the southern hemisphere]) of the eastern wall, which

![Fig. 15. The contemporary preservation of seasonal H2O and CO2 frost on pole-facing slopes during winter in the southern mid-latitudes of Mars (from Murchie et al., 2007). All data were acquired on November 25, 2006, corresponding to winter in the southern hemisphere ($L_S = 140.6°$). (A) CRISM false-color targeted observation (FRT000003266) of the pole-facing wall of a ~20 impact crater in the Terra Sirenum region of the southern mid-latitudes (38.9°S, 195.9°E) (Red: 2.53 μm, Green: 1.51 μm, Blue: 1.08 μm). Box represents context for nested HiRISE image observed in (C) (B) Identical CRISM target but with CO2 and H2O frost mapped as green and blue, respectively. CO2 frost is relegated only to the coldest sheltered locations within gully alcoves, where it drapes a layer of H2O frost (Red: 1.33 μm brightness; Green: 1.45 μm absorption; Blue: 1.50 μm absorption). (C) Nested HiRISE image PSP_001552_1410 of gully alcoves exhibiting a blanket of primarily H2O frost. CO2 frost drapes over H2O frost in the most sheltered (coldest) regions of the alcoves. Context provided in (A). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this paper.)](image-url)
exhibits both gullies and what have interpreted to be relic glacial landforms (Head et al., 2008). Frost is observed along the pole-facing slope, and a CTX image obtained at the same time shows no frost accumulation on the equator-facing crater wall (Fig. 10a). The crater wall oriented due-south exhibits a blanket of frost over its entire slope, but the slope imaged by HiRISE is oriented towards the southwest and shows patches of frost, largely focused in gullies alcoves (Fig. 10b). Frost is concentrated in the pole-facing regions of gully alcoves, providing more localized microclimates that are capable of sheltering surface frost for longer periods of time through the martian winter. One patch of frost is observed at the head of a gully channel that emanates nearly from the crest of the crater rim (Fig. 10b and c). Regardless of the composition of the frost (CO$_2$ or H$_2$O), this high-resolution data underlines the importance of local geometry with regard to accumulation of condensed volatiles on the surface of Mars.

We have also observed and investigated a gully system that exhibits preferential accumulation of frost within the gully channels themselves (Fig. 16). A ~55 km crater centered at 54.7°S, 301.2°E (southwest of Argyre) exhibits gullies on its pole-facing slopes. Given its high-latitude and cold temperatures, frost is stable in sheltered locations along the crater wall and floor even in southern summer, as seen in CTX orbit P06_003223_1206 (Fig. 16a). One of these sheltered locations is in the channels of gullies. Nearby HiRISE data acquired along the same pole-facing wall reveals the relationship between frost and gully channels in detail. HiRISE orbit PSP_007126_1210 was acquired on February 2, 2008, corresponding to early autumn in the southern hemisphere ($L_s = 26.4^\circ$). This orbit (Fig. 16b) shows a broad gully alcove that tapers in width downslope, where it is incised by a network of five channels that merge downslope into one primary gully channel. The channel floors show fluvial bedforms and the terrain surrounding the channels is characterized by polygonally-patterned ground. Channel floors are blanketed by a layer of frost, only detectable with the 500 nm (Blue–Green) CCDs on the HiRISE camera. The frost covers the lowest portions of the channel floor, but is not detected on any of the streamlined islands, suggesting that the slopes of these islands receive too much insolation to preserve frost. Multiple observations at this site are not available so it is unclear if this frost deposit represents the first deposit of the new autumn season in the southern hemisphere, or residual frost that persists throughout the year at higher-latitudes. Regardless, we consider this evidence for gully channels, like gully alcoves, serving as even smaller microclimates that facilitate the accumulation of frost/snow, and under favorable orbital conditions can contribute to meltwater that further carves gully channels (Hecht, 2002), as is observed in the ADV (Marchant and Head, 2007).

5. Synthesis

Late Amazonian gullies on Mars have attracted an immense amount of attention since their discovery due to their enigmatic formation in an epoch not conducive to the flow of liquid water across the surface. These various studies have served to both clarify and complicate the debate with regard to the derivation of the liquid water that is presumed to have carved the gully channels (Malin and Edgett, 2000). In this section we utilize the results from these various studies and new observations from MRO data to define a list of observations that any model for gully formation and evolution must explain.

5.1. Observations that must be addressed by gully formation/evolution models

5.1.1. Global three-dimensional distribution

The global distribution of gullies is well-established by independent analyses using several data sets and provides boundaries with regard to (1) latitude, (2) elevation, (3) orientation, and (4) global roughness (Figs. 3 and 4). These observations are robust and have been tested for instrument targeting bias (Berman et al., 2005; Balme et al., 2006). Gullies are dependent upon all of these parameters and show latitude-dependence for orientation, most well-displayed in the southern hemisphere (Heldmann and Mellon, 2004; Berman et al., 2005; Balme et al., 2006). Gullies only form on steep slopes at mid- to high-latitudes at elevations and orientations conducive to the deposition, accumulation and melting of water snow/ground ice (Fig. 4).
5.1.3. Age and evolution of gully systems

Gullies form most often on the interior of crater walls (Malin and Edgett, 2000), as these are the most abundant source for steep slopes on Mars. Gullies have been observed, however, on the flanks of a variety of other landforms, such as dunes, central peaks, mesas, buttes, massifs, knobs, and the exterior of raised crater rims (Balme et al., 2006; Dickson et al., 2007a) that these gullies are similar to crater/valley-wall gullies with regard to morphology, orientation, elevation, and latitude-distribution. Gullies on isolated peaks appear as fresh as crater/valley-wall gullies (Fig. 6b) (Balme et al., 2006), broadly suggesting that they formed in the same era of gully formation on Mars. Models for gully formation on Mars must account for the presence of these types of gullies.

Locally, gullies form at a wide variety of elevations along the same slope face (Fig. 9) (Gilmore and Phillips, 2002; Dickson et al., 2007a). HiRISE has revealed that main gully channels are frequently fed by smaller channels that incise the alcove itself (Figs. 5 and 9), as opposed to abruptly emanating from the base of outcrops in an alcove, as would be expected from undermining of unconsolidated material upon the release of an aquifer. Gullies are also regularly found in conjunction with features interpreted to be ice-related in origin (Figs. 10 and 11) (Milkken et al., 2003; Arfstrom and Hartmann, 2005; Berman et al., 2005; Head et al., 2008), suggesting that gullies are not anomalous features in these locations, but late-stage products of the evolution of a local glacial system.

5.1.3. Age and evolution of gully systems

The major implications of the analysis of Schon et al. (2009) are twofold: (1) gullies have been active within the last ~1.3 Myr, and (2) gullies are episodically active systems and are not formed simply in one catastrophic event (e.g., Figs. 7 and 8). The first implication is a quantitative confirmation of the qualitative analysis of Malin and Edgett (2000), that gullies are extremely young in relation to other fluvial landforms on Mars. The second implication requires models of gully formation to account for multiple stages in a gully system as it evolves over time.

5.2. An assessment of theories for formation and evolution of gullies on Mars

5.2.1. Groundwater expulsion from a confined aquifer

Using these constraints, we were unable to devise an end-to-end scenario in which subsurface aquifers can account for the majority of observed gullies on Mars. Mellon and Phillips (2001) argued that a groundwater reservoir must be confined between two aquicludes to prevent vertical transport of water, and by another barrier behind the aquifer, forcing release under pressure along the slope face. This mandates an association between gully source regions and impermeable rock layers, which has not been documented in any of the many surveys of martian gullies, and it is inconsistent with more detailed observations made from HiRISE data (Figs. 9 and 10). Even in regions that do show gullies that may be associated with layers, this association is more reasonably explained by outcrops serving as cold-traps for wind-blown snow, as observed in northern Canada (Lee et al., 2001) and the Antarctic Dry Valleys (Marchant and Head, 2007), or melting of ground ice that percolates through permeable regolith until it encounters an aquiclude (Gilmore and Phillips, 2002). These latter types of models do not require liquid water (groundwater) to be stable beneath the surface at variable shallow depths, conditions difficult to achieve on Late Amazonian Mars (Mellon and Phillips, 2001).

Gullies on topographically isolated peaks have been known for many years (e.g. Baker, 2001), but no literature has addressed how a groundwater model can explain this sub-class of gullies (Fig. 6). Gullies on central peaks could be explained by upwelling of water and thermal anomalies from the crater-forming event, but temporal relationships make this unlikely, such as young gullies on the central peak of the ~150 km diameter Lohse Crater, east of Argyre (43.3°S, 343.3°E). It is possible that gullies on isolated peaks are geomorphically distinct from classic gullies found along crater rims (Heldmann et al., 2008). However, this has yet to be demonstrated, as independent analyses report no significant morphological trends that distinguish gullies on the flanks of isolated peaks from gullies found along crater/valley walls (Balme et al., 2006; Dickson et al., 2007a) (Fig. 6b).

While lithology can influence the final morphology of gullies (e.g. gullies on dunes), gullies on isolated peaks follow the same trends with regard to latitude, elevation, and orientation that are shown by crater/valley-wall gullies (Balme et al., 2006; Dickson et al., 2007a). These similarities are unlikely to be coincidental and the frequent occurrence of gullies on isolated peaks is difficult to explain by a subsurface aquifer model.

The absence of gullies within the Hellas basin is difficult to reconcile with the groundwater model. A condition of the groundwater model is a layer of ground ice between the aquifer and the atmosphere on the slope face (Malin and Edgett, 2000; Mellon and Phillips, 2001). As the aquifer undergoes freezing cycles and expansions as a function of perturbations in spin-axis/orbital dynamics, the ground ice layer would fracture, followed by the expulsion of the aquifer through its only permeable boundary (Mellon and Phillips, 2001). Hellas provides a very likely location for this process to occur, as the low elevation would (1) serve as a sink for regional groundwater flow and (2) would elevate atmospheric pressure and humidity, providing a more stable environment for ground ice (Mellon, 2003). Yet multiple surveys of the southern hemisphere have failed to observe gullies on the floor of Hellas (Fig. 3) (Heldmann and Mellon, 2004; Dickson et al., 2007a). We consider the lack of steep slopes on the floor of Hellas to be the most likely reason for the lack of gullies (Dickson et al., 2007a), which would imply that ground ice alone is unlikely to account for gully formation and evolution.

5.2.2. Accumulation and melting of surface ice and the regeneration of gullies

The wealth of data acquired since the discovery of gullies points toward an origin of gullies that has little dependence upon subsurface stratigraphy and groundwater aquifers at depth. We find instead that the vast majority of gully systems that we have observed can be explained by the accumulation of frost, snow and ice that collects in optimal locations in the mid-latitudes of Mars, and subsequently melts, leading to gully formation. Here we outline the model in more detail and link it to the observations and constraints discussed above.

Gully activity on Mars is initiated in the alcove. With MOC data it was hypothesized that alcoves may represent the product of undermining and collapse above a seepage point subsequent to the release of an aquifer at depth (Malin and Edgett, 2000; Heldmann et al., 2008), but HiRISE data have revealed alcoves that are channelized nearly to the crest of the overlying ridge (Figs. 5, 9 and 10). Numerous studies have shown that gullies initiate at a wide range of depths in relation to their host overlying ridge (Gilmore and Phillips, 2002; Heldmann and Mellon, 2004), even along the same slope face (Gilmore and Phillips, 2002; Dickson et al., 2007a). This argues against structural control by subsurface strata and implicates the geometry of the local alcove environment itself as the key driver for accumulation of volatiles that subsequently melt to create gullies (Fig. 10): If this variability in alcove elevation is a result of groundwater release, then groundwater could be responding to fractures beneath the surface that dictate where
water outcrops. But this eliminates the freeze–thaw explosive pressure release mechanism of Mellon and Phillips (2001), which requires aquicludes that confine the aquifer on all sides except the slope face. We then lack (1) a way to preserve water beneath the surface in the liquid state and (2) a mechanism to force the water to the surface. We are unable to devise a groundwater model that would behave in this manner.

Alcoves at the crests of steep slopes form at all latitudes and elevations on Mars and are not exclusive to gully systems (Fig. 2; see equator-facing slopes in Figs. 10a and 11a). Young craters in equatorial regions of Mars and globally on the Moon show alcoves that form not by undermining from a released aquifer, but by mass wasting of dry material as the steep crater wall environment erodes to an equilibrium state. This creates a small region of highly irregular topography at the crest of an extremely steep slope that, at higher-latitudes on Mars where gullies are observed, can serve as (1) a catchment for wind-blown snow and (2) a sheltered region protected from maximum insolation that would induce sublimation (Figs. 13 and 14). The importance of alcoves in providing sheltered locales for volatiles is seen in the present climate during monitoring of the temporal distribution and evolution of seasonal frost (Figs. 10, 15 and 16). Alcoves can be generated and modified by activity within the gully, such as polygonal troughs serving as cold-traps and conduits for flow, successively eroding and, on steep slopes, coalescing to form elongated alcoves that further accumulate volatiles and contribute to the evolution of the entire gully system (Levy et al., 2008a).

The process of cold-trapping is most effective on cold pole-facing slopes in the mid-latitudes (Hecht, 2002) (Fig. 15), and gullies are observed oriented towards the poles between 30° and 45° in each hemisphere. Impact craters are ideal locations for cold-trapping, as ice that is sublimated from the equator-facing wall can be immediately re-deposited on the opposite pole-facing wall (Forget et al., 2008). At latitudes poleward of ~42°, temperatures are low enough to allow for ice stability on more equator-facing slopes (e.g. Costard et al., 2002). This orientation preference as a function of latitude is observed strongly in the southern hemisphere (Heldmann and Mellon, 2004; Berman et al., 2005; Balme et al., 2006; Dickson et al., 2007a) and recent analysis of the entire MOC database, in addition to HRSC data (Kneissl et al., 2009), appears to show a similar dependence in the northern hemisphere, though other surveys show a less distinct pattern (Bridges and Lackner, 2006; Heldmann et al., 2007). The lower elevations and higher pressure of the northern hemisphere may yield more optimal accumulation conditions and more melting stability regimes on all surfaces, such that gully formation is governed more by steep slope availability and less by orientation and insolation conditions.

Steep slopes are necessary for gully formation as they provide (1) initial mass wasting that leads to alcove generation (Fig. 2; equator-facing slopes in Figs. 10a and 11a), (2) highly sheltered environments conducive to the accumulation of snow and ground ice (Fig. 13), and (3) slope faces conducive to gravity-driven flow and erosion with small amounts of input of volatiles into the gully carving system (Dickson et al., 2007a). This dependence of gully formation on the presence of steep slopes (~21°) is observed at the local level (Dickson et al., 2007a) and at the global level, as gully frequency dramatically declines poleward at the boundary between rough preserved topography and softened topography, as calculated for the 600 m baseline (Figs. 3 and 4) (Kreslavsky and Head, 2000; Milliken et al., 2003; Head et al., 2003). The dependence on steep topography also accounts for the lack of gullies on the floor of Hellas basin.

Gullies transition from poleward facing between 30° and 44°S to a mix of poleward- and equator-facing gullies between 45° and 60°S (Fig. 4b) (Heldmann and Mellon, 2004; Balme et al., 2006). The lack of steep slopes south of 45°S and hence the lack of gullies adds uncertainty to the orientation distribution, but a greater number of equator-facing gullies at higher-latitudes is to be expected as snow/ground ice will be more stable and more likely to accumulate on all slopes provided lower temperatures. Pole-facing slopes at higher-latitudes also receive less direct sunlight than lower-latitudes, such that accumulated snow/ground ice in these environments is less likely to achieve melting conditions. The increase in gully frequency in polar pits (Figs. 3 and 4a) (Milliken et al., 2003; Heldmann and Mellon, 2004; Balme et al., 2006) and their poleward-facing preference (Fig. 4b) (Heldmann and Mellon, 2004; Balme et al., 2006) may be due to increased insolation over the pole at high obliquity on poleward-facing slopes (Costard et al., 2002; Kreslavsky et al., 2008, their Fig. 6). Melting of surface snow and ground ice can be achieved to depths of ~10–50 cm at obliquities as low as 33° (Costard et al., 2002), conditions that have been achieved on Mars during the most recent era of gully activity (Head et al., 2003; Laskar et al., 2004; Schon et al., 2009).

Melting of accumulated snow/ground ice changes the local topography of the gully system by (1) further eroding and broadening the alcove environment (note tributary alcoves/channels in Fig. 9), and (2) creating channels that in turn act as cold-traps for the catchment of snow, similar to what has been observed in the Canadian arctic (Lee et al., 2001) and the ADV (Marchant and Head, 2007; Morgan et al., 2007, 2008) (Fig. 13). Gully channels on Mars are observed to preferentially shelter frost deposits in the present climate (Fig. 16). This feedback effect provides a model for how a gully system evolves over time: during repeat obliquity excursions in the Late Amazonian, water deposited at the poles during low-obliquity conditions is transported to the mid-latitudes as obliquity increases (Head et al., 2003). This water can be deposited as snow and ice across the entire mid-latitudes, but it is likely to accumulate in local cold-traps such as poleward facing alcoves and channels that provide ideal microenvironments. In some regions there is enough accumulation to initiate glacial-like flow that ends with a phase of surface melting (Milliken et al., 2003; Head et al., 2008), and in some regions there is not enough accumulation for glacial-like flow but enough for repeat melting within gully systems, deposition of new gully fans over old gully fans (Schon et al., 2009) and incision of new channels into older gully fans (Fig. 7).

Because CO\textsubscript{2} condenses at a lower temperature than H\textsubscript{2}O, the coldest portions of alcoves are likely to exhibit H\textsubscript{2}O frost or snow that is blanketed by a layer of CO\textsubscript{2} frost (Fig. 15). At high obliquity, these deposits will be exposed to direct sunlight near the summer solstice, quickly removing the CO\textsubscript{2} layer and rapidly warming the underlying H\textsubscript{2}O deposit (Costard et al., 2002; Forget et al., 2008). Gully channels are short (generally <1 km (Heldmann and Mellon, 2004)) and terminate on steep slopes (Fig. 5) (Heldmann et al., 2005a; Parsons et al., 2008), suggesting that water may only need to be present for a matter of hours to flow down steep slopes and erode channels (Hecht, 2002). Laboratory experiments (Hecht, 2002) and modeling (Williams et al., 2008) of mantling material hypothesized to be a remnant snowpack on the walls of Dao Vallis (Christensen, 2003) both have shown that conditions for small amounts of melting can be achieved in the present martian environment. Increasing salinity in the gully system and changes in the orbital parameters (Costard et al., 2002; Williams et al., 2009) of Mars will increase the capacity for surface melting at gully sites.

The short length of gullies (Heldmann and Mellon, 2004) and the fact that they deposit fans on slopes >15° (Heldmann et al., 2005a; Parsons et al., 2008) suggests that small amounts of water are involved in the formation of gullies. This has prompted workers to consider flows analogous to terrestrial debris flows, where water serves as a lubricating agent for large-clast comprised debris flows (Costard et al., 2002; Mangold et al., 2008). On Earth, debris flows...
generally deposit pronounced levees along channel margins as flow velocities diminish along the banks of the channel. Gully channels with leveed margins have been observed on Mars, particularly for gullies carved into dune facies (Mangold et al., 2003; Reiss and Jaumann, 2003; Miyamoto et al., 2004; Védie et al., 2008). But levees are not observed on gullies that do not form on dunes and gully fans show no evidence for a preponderance of boulders at HiRISE scale; thus, this is generally inconsistent with transport of large-particle material. Recently, leveed channels with lobate snouts at their termini have been documented in the northern lowlands in association with gullies (Levy et al., 2009c), analogous to debris flow termini on Earth, and in sharp contrast to traditional gully fan material. Combined with the fine-scale fluvial bedforms within gully channels revealed by HiRISE (McEwen et al., 2007), these observations suggest that flow within gullies may be sediment-rich but not necessarily related to the process of large-particle debris flows. There is likely to be a wide array of sediment-concentration for flow within martian gullies, and we consider debris flows like those observed on dunes and by Levy et al. (2009c) in the northern lowlands to be an end-member on that spectrum.

What form would the source water take on the surface/near-surface? Seasonal frost accumulation (Hecht, 2002), snow-rich mantling deposits (Christensen, 2003), snowpacks trapped in local catchments (Head et al., 2008), and very shallow ground-ice reservoirs (distinct from groundwater reservoirs at greater depth) (Cordard et al., 2002; Gilmore and Phillips, 2002) are all plausible and certainly could exist in association and contemporaneously. Costard et al. (2002) showed that at high obliquity, ice in the top ~50 cm of the soil is susceptible to melting and could produce gullies similar to water-assisted debris flows in Greenland. Given the abundance of ice observed in the near-surface soil at high-latitudes today (Boynton et al., 2002; Feldman et al., 2002), shallow ground ice is likely to have been common at middle- and high-latitudes within the last ~1.3 Myr. The fate of melted ground ice has been debated: Costard et al. (2002) argued that melted ground ice would flow within the top layer and carve debris-flow-like channels, while Gilmore and Phillips (2002) argued that melted ground ice would percolate through a permeable soil layer and encounter an aquiclude and outcrop along the slope face. We prefer the Costard et al. (2002) model of flow within the active layer as the majority of gullies are found on crater rims, where most impermeable layers along the upper portions of a crater rim would be uplifted from the impact event and dip away from the crater floor (Melosh, 1989). The ground ice layer is also likely to be impermeable itself at depths below the melting isotherm, such that flow of meltwater would be controlled by the topography of the ice-ce ment table, not subsurface bedrock layers, before outcropping at the surface.

Observed today are seasonal frost accumulations formed by volatiles condensing out of the atmosphere and being preserved in sheltered locations (Figs. 10, 15 and 16). These deposits have been shown to be a plausible source of melting under current martian conditions when H2O is suddenly exposed to insolation from beneath a CO2 blanket (Hecht, 2002) (Fig. 15). This could readily explain short gullies (several hundreds of meters), though many gullies extend for distances of over a kilometer and would require a greater input of volatiles. This is, though, a likely source for modification of gully channels over time.

Vast mantling deposits (e.g. Head et al., 2003) appear to have sourced gullies in certain locations (Christensen, 2003), preferentially at low elevations along the walls of Dao Vallis. Localized cold-trapping of wind-blown snow within gully alcoves and channels (Head et al., 2008) is consistent with most observations of gully distribution and morphology and may be the most common reservoir for water in gully systems across Mars. Gullies are commonly observed in terrains that contain units interpreted to be glacial in origin (Figs. 10 and 11) (Milliken et al., 2003; Berman et al., 2005; Head et al., 2008), suggesting that in these locations significant volumes of water have been deposited and accumulated (Figs. 10 and 11). All observations of gullies, from global distributions (Fig. 4) (orientation, latitude, elevation, slope) to local analyses (Head et al., 2008) argue that top-down melting of cold-trapped water snow and ice is the most likely source of volatiles for gully formation and evolution on Mars.

Important remaining questions include: (1) understanding the physical nature and proportions of gully source material (frost, snow, snowpacks, ice-rich mantles, ground ice), (2) documenting the temporal evolution of gully systems in addition to their formation mechanism, (3) assessing the plausible conditions permitting melting and flow of water ice on the surface of Mars today, and (4) assessing the biologic implications of intermittent liquid water flow in these microenvironments.

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