Icarus 251 (2015) 244–263

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Long-term monitoring of martian gully formation and evolution with MRO/HiRISE

Colin M. Dundas [a,*], Serina Diniega [b], Alfred S. McEwen [c]

[a] Astrogeology Science Center, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, USA
[b] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[c] Lunar and Planetary Laboratory, The University of Arizona, Tucson, AZ 85721, USA

ARTICLE INFO

Article history:
Received 20 December 2013
Revised 15 April 2014
Accepted 10 May 2014
Available online 21 May 2014

Keywords:
Mars, surface
Mars, climate
Geological processes
Ices

ABSTRACT

Gully landforms are commonly taken as evidence for surface liquid water in the recent geological history of Mars. Repeat observations with the High Resolution Imaging Science Experiment (HiRISE) instrument on the Mars Reconnaissance Orbiter demonstrate widespread activity in gullies in the southern hemisphere, particularly in those with the freshest morphologies. This activity includes substantial channel incision and large-scale mass movements, and constitutes ongoing gully formation rather than degradation of older landforms. New apron deposits that are bright, dark and neutrally toned have all been observed. The timing of gully activity is seasonally controlled and occurs during the period when seasonal frost is present and defrosting. These observations support a model in which currently active gully formation is driven mainly by seasonal CO_2 frost. Gullies in the northern hemisphere are far less active than those in the south. This may be due to the current timing of perihelion near the northern winter solstice. Integrated over time, activity like that observed within the past few years appears capable of forming all of the martian gully landforms on timescales of millions of years. Additionally, the current style and rate of activity is able to erase meter- to decameter-scale surface features that might have been uniquely produced by other processes during the last obliquity high ~0.4 Ma. Although it is impossible to rule out a past role for water in the formation of martian gullies, a model in which gullies form only through currently active processes with little or no liquid water is consistent with our observations.

Published by Elsevier Inc.

1. Introduction

1.1. Background

Martian gully landforms were first reported by Malin and Edgett (2000). These kilometer-scale landforms consist of an alcove feeding into a channel and depositional apron (Fig. 1), and strongly resemble terrestrial fluvial or debris-flow features. They are among the youngest and best-preserved landforms on the martian surface. They were initially regarded as evidence for liquid water in the present day and/or the recent past (Malin and Edgett, 2000), and most subsequent workers have followed this interpretation.

A substantial body of work documents the basic properties and distribution of gully landforms. Classic martian gullies are concentrated in the mid-latitudes, mainly between 30° and 50° north and south, and are particularly abundant in the southern hemisphere (e.g., Malin and Edgett, 2000; Heldmann and Mellon, 2004; Balme et al., 2006; Bridges and Lackner, 2006; Dickson et al., 2007; Heldmann et al., 2007; Kneissl et al., 2010). The orientation distribution is complex. In the southern hemisphere, gullies equatorward of c. 45°S have a strong tendency to face the pole (e.g., Heldmann and Mellon, 2004; Balme et al., 2006; Dickson et al., 2007). At higher latitudes Heldmann and Mellon (2004) report a transition to equator-facing and then back to pole-facing, while Balme et al. (2006) found little preference. In the northern hemisphere, Bridges and Lackner (2006) reported an overall tendency to face the equator. Heldmann et al. (2007) found little orientation preference between 30 and 44°N, transitioning to equator-facing from 44 to 58°N and then back to a distribution with little preference at high latitude. Kneissl et al. (2010) observed a transition from pole-facing to equator-facing above 40°N. In the northern hemisphere, Heldmann et al. (2007) found that gullies tend to appear more degraded than those in the south, and Bridges and Lackner (2006) noted that near-polar gullies were less developed but better preserved than those at lower northern latitudes. Harrison et al. (2014) provide a global map of pole-facing and non-pole-facing mid- to high-latitude gullies from Mars

* Corresponding author.
E-mail address: cdundas@usgs.gov (C.M. Dundas).

http://dx.doi.org/10.1016/j.icarus.2014.05.013
0019-1035/Published by Elsevier Inc.

Reconnaissance Orbiter (MRO) Context Camera (CTX) images, with better areal coverage and fewer biases than previous studies. In the southern hemisphere, they found a transition from pole-facing gullies below 45°S to equator-facing at higher latitude. In the northern hemisphere, Harrison et al. (2014) report a transition from pole-facing to equator-facing at 40°N, with some longitudinal variations, and no preference poleward of 50°N. They also found that pole-facing gullies in both hemispheres were better-developed, and that northern gullies were less developed and more degraded than those in the south. Auld and Dixon (2014) mapped gullies seen in High Resolution Imaging Science Experiment (HiRISE) images, including some in equatorial latitudes omitted by many previous studies other than Treiman (2003). The differences between the studies are attributable to different latitudinal binning and data sets: various studies use different latitude divisions when aggregating orientation data, and incorporate different subsets of data from the Mars Orbiter Camera (MOC), the High Resolution Stereo Camera (HRSC) and CTX. Additionally, Auld and Dixon (2014) included some features without channels in their survey of "gullies".

Gullies on sand dunes with a channel-dominated morphology were described by Mangold et al. (2003) and Reiss and Jaumann (2003). This morphology is sometimes described as "linear" (Vedie et al., 2008). These dune gullies have often been regarded as a separate category and left out of surveys of gully properties, due to the unusual substrate and the non-standard morphology (e.g., Heldmann and Mellon, 2004; Balme et al., 2006; Heldmann et al., 2007). However, they are also generally regarded as evidence for recent water-rich debris flows (e.g., Mangold and Costrad, 2003; Reiss and Jaumann, 2003; Vedie et al., 2008). Gullies with a "classic" alcove–channel–apron morphology are also seen on dunes (Reiss et al., 2007; Diniega et al., 2010; Dundas et al., 2012).

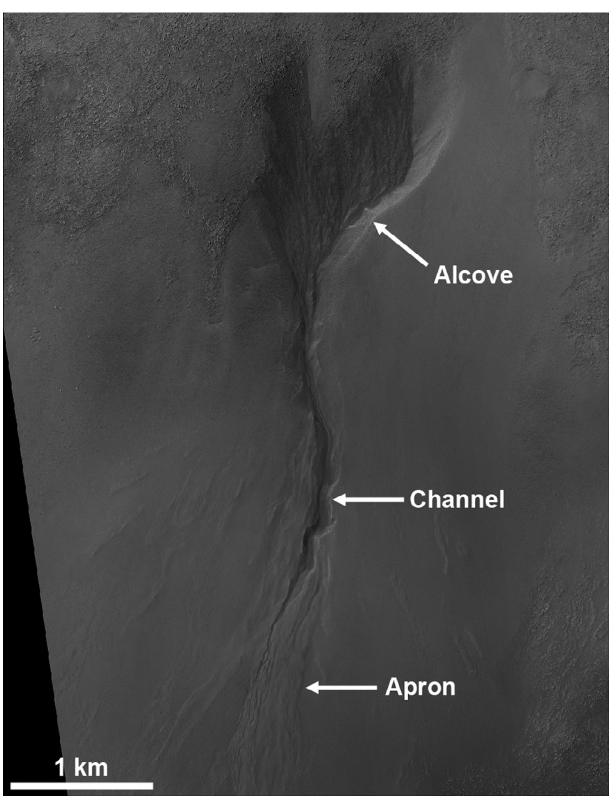

Fig. 1. Example of a classic martian gully (Malin and Edgett, 2000) with alcove, channel and apron. The alcove is largely cut into mantling material, revealing rocky ground below. (HiRISE image ESP_014312_1320, located at 47.4°S, 305.3°E. Illumination from the upper left. For all HiRISE images in this paper, north is up. Images in all figures have been stretched to best show detail; in some cases where features of interest are in shadow, sunlit areas appear saturated. Original images are available from www.hirise.lpl.arizona.edu or via the Planetary Data System.)

Although gully formation was immediately attributed to liquid water, the source of the liquid has been much debated. Initial explanations focused on groundwater (Malin and Edgett, 2000; Mellon and Phillips, 2001; Gaidos, 2001; Hartmann, 2001). However, observations of gullies on isolated hills and sand dunes posed challenges for these models. Alternatives emerged favoring melting atmospherically sourced ice, including vapor-deposited ground ice (Costard et al., 2002), cold-trapped surface frost (Hecht, 2002), or snow (Christensen, 2003). Proposed water-free formation processes include dry mass wasting (Treiman, 2003; Shinbrot et al., 2004), liquid CO_2 aquifers (Musselwhite et al., 2001), and avalanching or sublimation of seasonal CO_2 frost (Hoffman, 2002; Ishii and Sasaki, 2004; Balme et al., 2006; Cedillo-Flores et al., 2011).

Some models for gully formation appeal to different climate conditions in the past, particularly at high obliquity (~35° compared with the present 25°), producing conditions for melting and runoff (e.g., Costard et al., 2002). Consequently, it was of great interest when Malin et al. (2006) reported observations of two light-toned mass movements in present-day gullies, although spots and streaks due to seasonal defrosting had previously been noted (Bridges et al., 2001; Hoffman, 2002; see also Mangold et al., 2008). Malin et al. (2006) argued that the deposits indicated present-day groundwater release, and Heldmann et al. (2010) suggested that they could be mudflows. Other workers suggested that the observed flows could be dry mass movements (Pelletier et al., 2008; see also Kolb et al., 2010a) or that they are abetted by non-melting frost (i.e., frosted granular flow; Hugenholtz, 2008). Persistence over time demonstrated that frost or ice was not the cause of deposit brightness (Williams et al., 2007), and spectral data showed no evidence for evaporites or hydrated minerals in the new deposits (McEwen et al., 2007b). As a result, it was suggested that major gully-forming processes on Mars are currently inactive and that observed changes indicate dry degradation of older water-formed gullies (e.g., Kolb et al., 2010b; Schon and Head, 2011).

Continued monitoring provided additional examples of activity in gullies and suggested seasonal control (Harrison et al., 2009; Dundas et al., 2010). Gullies on sand dunes were also seen to be active (Reiss et al., 2010; Diniega et al., 2010; see also NASA Planetary Photojournal image PIA04290 from 2005). Dundas et al. (2012) confirmed that activity in both dune and non-dune gullies had a strong seasonal association with the occurrence and defrosting of seasonal CO_2 frost. Dundas et al. (2012) also observed small-scale channel incision in non-dune gullies as well as formation of complete alcove–channel–apron systems and large channels in dune gullies. These observations suggested that CO_2-driven processes could be responsible for gully formation with no involvement of liquid water. This is consistent with the composition of these features: Nunez et al. (2013) examined high-resolution CRISM spectral data and found that gully apron materials show no evidence for rock–water interaction (unless present in the source area) but do show seasonal accumulation of CO_2 ice. A detailed study of a polar pit gully location by Raack et al. (2015) favored CO_2-supported dry activity at that location.

Since publication of Dundas et al. (2012), continued and more systematic observation of the martian surface has revealed new details about current activity and its implications for gully formation. This paper reports on observations of changes using images from HiRISE (McEwen et al., 2007a). Section 2 describes the data and methods used to search for gully activity. Section 3 summarizes our observations of changes and the properties of active gullies, and Section 4 discusses their implications for gully formation.

2. Gully monitoring with HiRISE

2.1. Terminology

Under terrestrial definitions, gullies are small channels in unconsolidated material, usually produced by running water (Neuendorf et al., 2005). The alcove–channel–apron landforms referred to as gullies in the Mars literature by many authors (including our previous work) are typically kilometer-scale, and in some cases have alcoves cut into bedrock. As such, they should more properly be considered ravines, but we will refer to them as gullies or gully landforms in this paper for consistency with other Mars work. The channel components of the alcove–channel–apron features more closely resemble gullies under the terrestrial definition, as do some isolated fine channels or troughs.

Martian seasons are denoted by L_S, the areocentric longitude of the Sun. Northern spring begins at $L_S = 0°$, northern summer at $L_S = 90°$, etc. Perihelion occurs at $L_S = 251°$. We use the Mars calendar of Clancy et al. (2000), in which Mars Year 1 (MY1) began at $L_S = 0°$ on April 11, 1955. The MRO spacecraft (Zurek and Smrekar, 2007) began science operations in mid-MY28, and this paper uses observations through early MY32.

2.2. Data

HiRISE images are high-resolution targeted observations of Mars, with a pixel scale as small as 0.25 m, and have a high signal-to-noise ratio (SNR) except under poor illumination or poor weather conditions (e.g., haze). Some images are binned to improve SNR or reduce data volume, at the cost of reduced image resolution. Images taken in the red channel are typically 5–6 km wide and 10–20 km long, and a central color swath (1–1.2 km wide) is also acquired through blue–green (BG) and near-infrared (IR) filters to produce enhanced-color images. Precise commanding of spacecraft rolls permits repeat imaging centered within a few hundred meters of the specified target. The RED9 CCD (westernmost in the image swath) stopped responding to commands in August 2011, so subsequent images have been 10% narrower, occasionally truncating features of interest from earlier images. We focus on HiRISE images because before-and-after high-resolution images of changes are essential to characterizing the detailed morphology of new deposits, including topographic changes. Surveys of images using MOC (Malin et al., 1992), CTX (Malin et al., 2007) and the Mars Express HRSC (Neukum et al., 2004) imagery have the potential to detect changes in more gullies, but with lower resolution and less sensitivity to low-contrast changes.

We focus on looking for activity in sites that have been imaged by HiRISE over a long time baseline. Before-and-after HiRISE image coverage is required in order to detect all but the largest topographic changes. As in Dundas et al. (2012), we examined sites where the minimum time separation between the first and last HiRISE images was 4000 MRO orbits (about half of a Mars year). Most HiRISE long-baseline monitoring targets span at least a Mars year. Our southern-hemisphere monitoring extends the work of Dundas et al. (2012) with an additional Mars year of data covering many additional sites. We also add a northern-hemisphere survey. Initial studies (Dundas et al., 2010) found few fresh-appearing deposits (with distinct albedo and little sign of modification by other processes) and detected no activity associated with gullies in the northern hemisphere, but since that time, many more monitoring images have been acquired. We use HiRISE data acquired through MRO orbit 35599 (March 1, 2014; $L_S = 96°$, MY32). In both hemispheres we restrict our data set to latitudes 25–75°, which encompasses the vast majority of "classic" gullies. This does exclude the latitude of activity seen on sand dunes in the north polar erg that produces gully-like alcove–apron landforms lacking clear channels (Hansen et al., 2011, 2013). Monitoring of equatorial gully sites with RSL activity began in MY31.

The HiRISE data used in this paper covers 98 sites in the northern hemisphere and 258 in the south (Fig. 2). An initial list of overlap sites was constructed by searching for locations where the midpoint of one image falls within the extremes of another, so some minor overlaps are excluded. A "site" is defined as a location with gullies covered by at least two HiRISE images with an adequate time separation. In a few cases, sites are adjacent to one another (e.g., east and west halves of a crater that is too large to fit within a single HiRISE footprint). These are treated as separate locations for statistical purposes, although there may be some overlap between images assigned to adjacent sites. When appropriate, those images are used to check features in both sites. The quality and characteristics of the data used for comparison (e.g., lighting similarity, atmospheric clarity, image binning, and time interval between first and last image) varies substantially between sites. Possible surface changes that could not be confidently distinguished from lighting effects are excluded. MRO is in a sun-synchronous orbit with local mean solar time near 3 PM, but lighting nevertheless varies with the seasons.

We distinguish between non-dune and dune sites. Although the gully morphologies are often similar (except when dune gullies

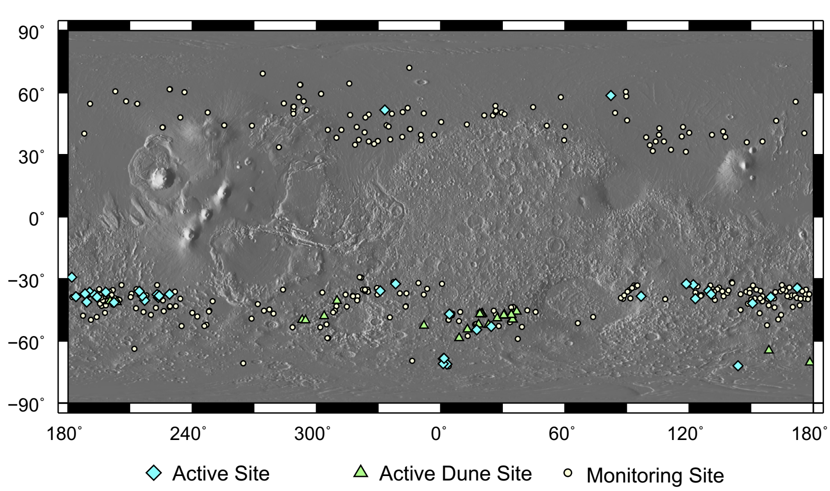

Fig. 2. Map of monitoring sites and active locations for non-dune gullies. Locations of active dune/sandy-slope gullies are also shown for reference, but not analyzed in detail here.

have "linear" morphology) and the driving processes appear to be the same, gullies on sand surfaces appear to be far more active, probably because of the unconsolidated substrate (Dundas et al., 2012). We include obvious sand-covered slopes with dune gullies, but mixed or unclear examples are included with non-dune gullies. Fig. 2 shows known active dune and sandy-slope gullies for reference, but they are not further analyzed here. Details of activity at several sandy gully sites were given by Diniega et al. (2010) and Dundas et al. (2012), but the high level of activity makes it difficult to catalogue all changes across a large number of sites.

2.3. Methods

In order to characterize our study sites, we binned gully orientation into eight sectors and noted the orientation of gullied and non-gullied slopes within our monitoring sites. For each sector at each site, we also noted whether gully channels/aprons appeared fresh, intermediate or degraded, and whether the alcove was poorly, moderately or well-developed. Poorly developed alcoves are shallow and/or are only slightly wider than the channel, while well-developed alcoves are wide and deep, and dominate the local slope. Degraded gullies have muted appearance, significant modification (e.g., thermal contraction cracks on the apron) or are not distinct from surrounding material, while fresh gullies are those with sharply defined channels, particularly distinct aprons and/or distinct color or tone. These designations are qualitative judgments, but those judgments permit an initial characterization of their relationship to gully activity. The freshest gully on a given slope segment was used to classify the state of the segment, and sites were classified based on the freshest and best-developed gullies on any slope segment. Due to the number and complexity of individual gullies, we record the state of gullies on a slope segment of given orientation rather than documenting each individual gully. Note that although Kolb et al. (2010b) used a similar classification scheme for freshness, the gullies in our study encompass a much larger range of preservation states and even the most degraded gullies considered by Kolb et al. (2010b) would not be considered degraded here, since their aprons are distinct and channels generally sharp.

We used reduced-resolution (1 m/pix) HiRISE images of aprons to search for fresh deposits that are relatively bright, dark, or distinct in color. "Fresh" deposits are those that show no sign of modification. They usually have sharp edges and lack eolian ripples or periglacial polygons. This approach likely misses some small, subtle changes, which are also difficult to distinguish from illumination effects or eolian changes. We also directly compared channels and aprons in older and newer images to look for changes by blink-comparison of non-orthorectified images at reduced resolution. These comparisons uncovered a few neutral-toned changes not found by Dundas et al. (2012). Additionally, some candidates for activity have been found by the CTX team and suggested to the HiRISE team for follow-up imaging, or discovered in the course of other work. These additional detections are included in our data set, as are some other events that we have been able to confirm using non-HiRISE data based on initial indications from HiRISE. For this paper, we focus on changes indicating mass movements along channels and onto aprons, which are true gully-forming events. Ambiguous candidate flows (lacking topographic changes and with poorly defined albedo effects, or diffuse/widespread differences likely due to eolian processes or lighting effects) were not included.

When changes are observed, we record details of the new deposit. Specifically, we note the gully orientation and whether resolvable topographic changes occurred, and constrain the timing of the event with available imagery. In some cases, some available images were not used as time constraints because it was doubtful that the new deposit would have been observable in that image, due to data quality or other issues. However, images with quality issues were used as constraints if the new deposit was positively identifiable in them.

As in Dundas et al. (2012), we do not treat Recurring Slope Lineae (RSL) as a form of gully activity. RSL (McEwen et al., 2011, 2014; Ojha et al., 2014) are fine dark flows that incrementally grow downslope, commonly following small channels ("gullies" by the terrestrial definition), and recur at similar locations from year to year. Unlike the observed gully activity, RSL in the southern mid-latitudes occur mainly on equator-facing slopes in southern summer (McEwen et al., 2011). RSL in equatorial regions have more ambiguous seasonality but also favor warm slopes (McEwen et al., 2014). To date, no topographic changes directly associated with RSL have been observed. RSL occasionally occur within gully alcoves, but are more often found within fine channels (smaller than the "classic" alcove–channel–apron gully landforms) or on apparently un-gullied slopes. By contrast, the gully activity studied here mostly consists of one-off events producing deposits on gully aprons, and preferentially occurs in winter or spring in association with seasonal frost. The two forms of activity are distinct and likely reflect different processes.

We also exclude detailed descriptions of defrosting activity in this paper. Seasonal defrosting spots and flows can transport material in gullies (Gardin et al., 2010; Dundas et al., 2012), but in the present work we focus on the major flows through channels and onto aprons. Cases with large mass movements seen over frost are included here as any flow superposing frost can be inferred to be new even without a previous image. Small, incrementally growing defrosting features are not included with the activity considered here, although small annual changes may make a substantial contribution to the evolution of gully morphology over time.

2.4. Potential biases

The portion of Mars that HiRISE can image is very limited, so only a small number of sites can be frequently monitored. Locations known to be active were most intensely monitored, but sites without known activity were chosen for occasional repeat observations, especially if they contained morphologically fresh gullies. Thus, our data set may preferentially include the youngest and/or most active gullies on Mars, if freshness correlates with activity. This is an unavoidable result of the targeted HiRISE data set.

An additional influence is that MRO data-relay procedures for the Mars Science Laboratory (MSL) *Curiosity* rover in Gale crater (5.3°S, 137.7°E) have restricted HiRISE observations of a broad swath of the southern mid-latitudes at longitudes near those of the landing site. Consequently, repeat observations of gullies in this zone have been rare since MSL landed on August 5, 2012 ($L_S = 150°$, MY31). Because HiRISE observations cannot be scheduled close together in time, a similar but weaker effect occurs at longitudes where orbits cross high-priority targets like Valles Marineris or candidate landing sites. However, since there is currently no evidence for longitudinal variations in activity this effect may not bias the results.

A final effect on the data that should be noted is that repeat imaging of gullies in the southern hemisphere competes with monitoring of RSL found in the same latitude band (primarily from $L_S = 240°$ to $340°$), another high priority objective for HiRISE. Gullies in the same images as RSL sites may be very well-covered, but this monitoring reduces repeat observations of nearby locations outside a typical image footprint. It is possible that the conditions supporting RSL growth correlate (positively or negatively) with those favoring gully activity. However, those conditions are not well-known and this hypothesis is untested. A number of

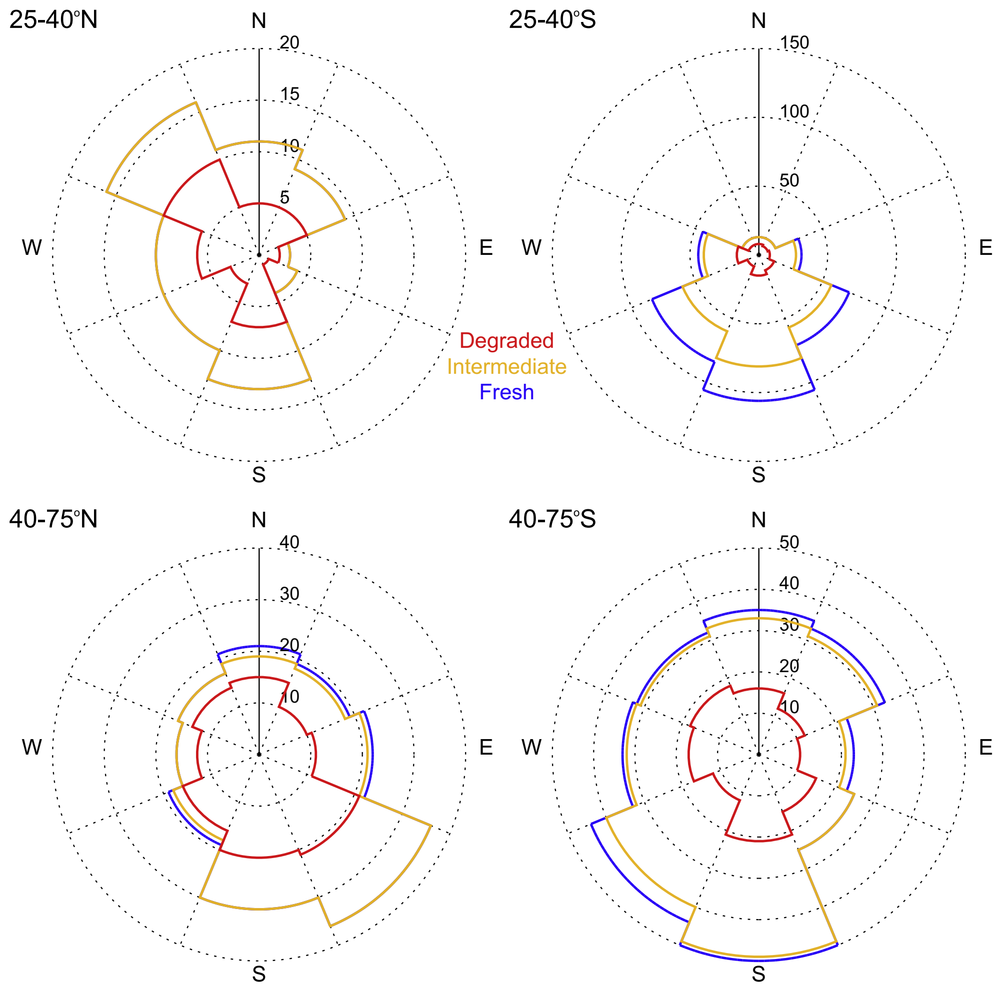

Fig. 3. Orientation of gullied slope segments examined in this study. The freshness of gullies on slope segments is also shown.

locations do exhibit both RSL and gully activity, although usually on different parts of the slope and always in different seasons.

3. Observations

3.1. Population characteristics of monitoring sites

The geographic distribution of gully sites in our study (Fig. 2) resembles the results of surveys of gullies in MOC, CTX and HRSC images with broader coverage (Balme et al., 2006; Malin et al., 2010; Kneissl et al., 2010; Harrison et al., 2014). The orientation distribution (Fig. 3) is also similar. The gullied slopes in our data set have a pole-facing preference at lower southern latitudes (25–40°S), and a weak poleward preference at lower northern latitudes. At higher latitudes (40–75°) in both hemispheres, there is a modest south-facing tendency. This latter tendency (suggesting that the hemispheres are not simply mirror images) is observed in broader surveys (Balme et al., 2006; Kneissl et al., 2010). The weak pole-facing tendency in our higher-latitude southern gullies does not match the observations of Harrison et al. (2014), but while they report a transition to equator-facing at 45°S they also show that gullies at the highest southern latitudes often face the pole or have no preference. Our data may reflect this latter effect.

The gullies in our northern-hemisphere data set are less pristine in appearance than those in the south. In the southern-hemisphere sites, 25% of sites were classified as fresh (based on the state of the freshest gully), while 17% were degraded. In the northern hemisphere the corresponding figures are 4% and 47%.

Hence, our monitoring sites are a reasonable match to the geographic and orientation patterns of survey studies, and match the observation of Heldmann et al. (2007) and Harrison et al. (2014) that northern-hemisphere gullies appear more degraded than those in the south. At a local scale there may be a tendency to favor reimaging the freshest-appearing gullies, which is difficult to quantify. However, our monitoring sites do include a substantial sample of degraded and poorly developed landforms. While the biases noted above are real effects, they do not appear to seriously distort our results.

3.2. Southern hemisphere

Since publication of Dundas et al. (2012), a number of additional active sites have been found in the southern hemisphere. Table 1 summarizes the known active, non-dune gully sites and Fig. 2 shows their geographic distribution. 14% of all southern-hemisphere monitoring sites have shown activity in at least one gully; several have been active in multiple years or had multiple flows within a single year. Fig. 4 shows the rate of activity as a function of latitude, which appears enhanced in the highest-latitude bin. We looked for any statistically significant effect from latitude using the Mann–Whitney test, a nonparametric test that evaluates the likelihood that the distribution function of some continuous variable is the same for two populations, the active and

Table 1
Active non-dune gully sites.[a]

Lat.[b]	Lon.[b]	Orientation	Multiple flows?[c]	Multiple years?[c]	Thick flow?[d]	Channel incision?[d]	Comment
−29.1	181.8	S	Y	Y			
−32.4	118.6	S					
−32.4	338.2	S, SW	Y	Y			Most distinct in color
−32.7	122.1	SE	Y				
−34.3	172.3	S	Y	Y			Shadow-only flows; Dundas et al. (2012), Fig. 13
−35.7	129.4	SE, S, SW	Y	Y	Y	Y	Fig. 8; Dundas et al. (2010, 2012)
−35.8	330.8	E					
−36.0	214.3	S	Y				
−36.3	198.3	SE					Malin et al. (2006)
−36.4	190.4	SE					
−37.2	188.3	E, SE	Y	Y			Shadow-only flows
−37.4	130.7	NE					
−37.4	229.0	S, SW	Y		Y		Fig. 9
−37.5	223.0	S			Y	Y	Fig. 6, Supplementary Animation 1
−37.7	192.9	S			Y	Y	Fig. 7, Supplementary Animation 2
−38.1	224.1	SW			Y		
−38.1	224.0	SE			Y	Y	
−38.1	215.9	SW				Y	
−38.4	96.8	NW					Malin et al. (2006)
−38.6	183.8	SE	Y				
−38.7	194.0	SE					
−38.8	159.5	S, SW	Y	Y		Y	Dundas et al. (2010), Fig. 1
−38.9	223.7	SW				Y	Dundas et al. (2012), Fig. 9
−39.6	123.1	SW					
−40.3	217.1	SW					Topo change in channel
−41.1	189.0	SW				Y	
−41.5	202.3	SW				Y	Dundas et al. (2012), Fig. 12
−41.7	150.6	E					
−46.9	4.3	NW	Y				Fig. 14
−52.9	24.4	SW	Y				Dark halos around channels
−54.6	17.5	S					
−68.4	1.7	NW					
−68.5	1.3	E, N	Y	Y	Y		Dundas et al. (2012), Fig. 11
−71.0	1.3	S					
−71.2	3.1	NW					
−71.9	143.7	NE	Y				Polar layered deposits
51.7	333.0	S, SW	Y		Y		Supplementary Animation 3
58.7	82.3	E					Fig. 12

[a] Locations of possible activity which are considered unconfirmed are not included. Some active sites where multiple events are not indicated have additional ambiguous changes.
[b] Planetocentric latitude, east longitude.
[c] Multiple flows implies that multiple flow events have occurred at a site. Multiple years means that the site (not necessarily an individual gully) has been active in more than one Mars year.
[d] Thick deposit indicates that some part of the deposit has resolvably changed the topography at HiRISE scale. Channel incision implies that a new channel segment formed, or more commonly, that some erosion or removal of material occurred within a channel. In some cases no test is possible because there is no HiRISE image that predates the flow.

inactive gullies (Ross, 2000). The test determines the probability (p-value) that the distribution functions are the same (the null hypothesis). A p-value <0.05 is formally considered statistically significant, subject to one significant caveat. This and subsequent statistical tests implicitly assume that at each site the observing time interval, number and properties of gullies, and image quality is the same, such that they are equivalent trials. Although the variations may average out, this is not true in detail so the real statistical significance of such comparisons is not as strong as the p-values given. Although activity in the highest-latitude bin seems enhanced, there is no statistically significant dependence on latitude ($p = 0.29$). No major regional variations are apparent. The new deposits have a strong tendency to face the pole (Fig. 5), matching the general orientation of gullies at the lower southern latitudes where most of the activity has been observed. The greater number of southwest-facing versus southeast-facing flows may reflect the midafternoon orbit of MRO, which makes it easier to detect flows on the better-lit surfaces and might also lead to preferential imaging of those slopes. (A similar discrepancy is seen in Fig. 3, although weaker.)

Gully freshness appears to have a correlation with activity levels. We compared activity between subsets of gullies using the Fisher–Irwin test. This test evaluates the probability, p, that the true success rates in two binomial distributions are the same (Ross, 2000). Here we treat the detection of activity as "success" and use this test to evaluate whether various non-continuous factors affect the true success rate of subsets of sites. The freshness of sites was tabulated based on the state of the sharpest gullies at the site, not necessarily the active gully. On this basis, 17 out of 65 fresh sites in the southern hemisphere (26%) were active, compared with 1 out of 44 degraded sites. This difference is statistically significant (Fisher–Irwin test, $p = 0.001$). Even the classification of the lone active degraded site (38.1°S, 215.9°E) is somewhat ambiguous, since the channels are far from pristine in appearance, yet have some distinctive colors more commonly associated with a classification of fresh. There is also a statistically significant difference in activity levels between gullies classified as fresh and intermediate (18/149 intermediate sites were active; $p = 0.021$), although the caveat above may affect results that are only moderately significant. There was not a statistically significant difference between intermediate and degraded sites ($p = 0.082$). The level of gully development had no detectable effect on the likelihood of activity. 17/125 (14%) of well-developed sites were active, compared with 14/94 (15%) of moderately developed and 5/39 (13%) poorly developed sites.

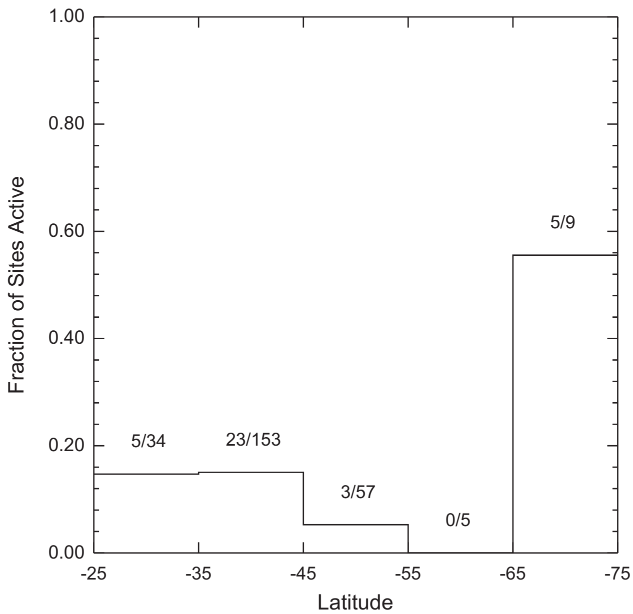

Fig. 4. Fraction of southern-hemisphere monitoring sites with known activity as a function of latitude.

Table 2
Active southern-hemisphere dune and sandy-slope gully locations.

Lat.[a]	Lon.[a]	Comment
−40.5	309.9	
−40.8	200.3	Sandy slope
−41.1	203.5	Sandy slope
−45.8	36.7	
−47.0	20	Kaiser crater dunes (multiple sites)
−47.0	18.8	Sandy slope
−47.2	34	Multiple sites
−47.5	30.4	Proctor crater dunes (multiple sites)
−48.0	303.7	
−49.0	27.2	
−49.5	34.7	Matara crater dunes (multiple sites)
−49.8	293.1	
−50.0	294.6	Sandy slope
−51.9	18.2	
−52.2	23	
−52.5	351.8	
−54.3	12.9	Russell crater dunes
−58.6	8.8	
−64.5	158.4	
−70.4	178.2	

[a] Planetocentric latitude, east longitude.

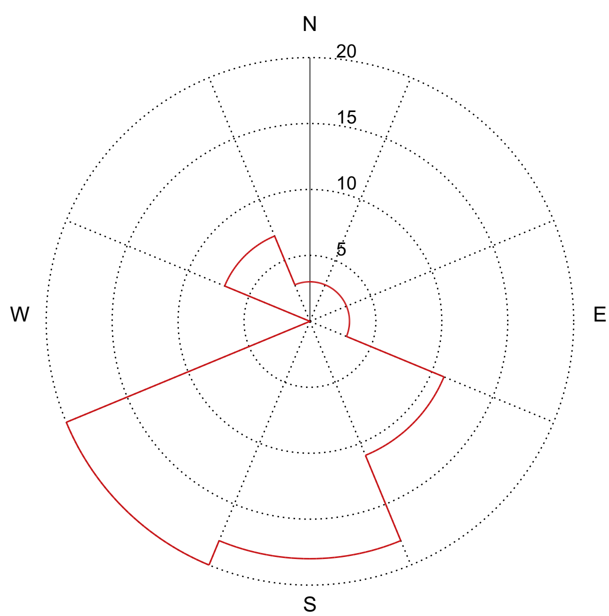

Fig. 5. Orientation of new deposits in the southern hemisphere. The strong south-facing tendency is similar to the orientation of gullies as a whole at lower southern latitudes where most changes have been observed. The two sites with many shadow-only changes (Dundas et al., 2012) are excluded from this plot since those apparent changes are numerous and it is difficult to be confident of all observations under the inherently poor lighting conditions, but they also tend to face the pole.

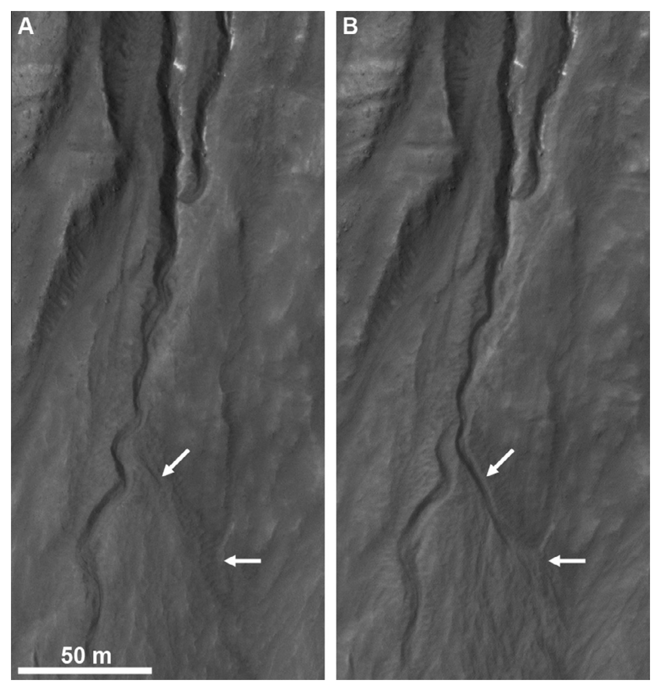

Fig. 6. Avulsion and major channel incision (upper arrow) and new lobate deposit (lower arrow). The active flow broke out of the previous channel and cut a new one, possibly directed long the track of a shallow or infilled older channel. (A: HiRISE image ESP_013115_1420, located at 37.5°S, 222.9°E, acquired at $L_S = 266°$, MY29; B: HiRISE image ESP_032011_1425, acquired at $L_S = 325°$, MY31. See also Supplementary Animation 1. For all figures, comparisons to show changes generally use images selected for similar lighting or viewing geometry and do not necessarily use the images that give the tightest constraints on the timing of activity.)

In addition to improving the sample of active events, the new observations have revealed some important details. Fig. 6 shows the most extensive channel incision yet observed, on a much larger scale than reported in Dundas et al. (2010, 2012). In this case a flow has broken out of a pre-existing channel and incised a new trough, likely directed by the presence of a previous shallow channel. This observation demonstrates formation of new channels morphologically identical to the older channels at the same site, and shows how channel abandonment (and formation of multiple generations of channel) can occur through currently active processes. Supplementary Animation 1 shows that this flow resulted in erosion of the outer parts of curves, a process that could gradually form sinuous channels.

Multiple examples of substantial mass movements with resolvable thickness are now known (e.g., Figs. 6 and 7, Supplementary Animations 1 and 2). These morphologically resemble features previously described as debris flows. Typically, there is little topographic difference at the source region but progressively more change downslope to the flow terminus. The intermediate reaches

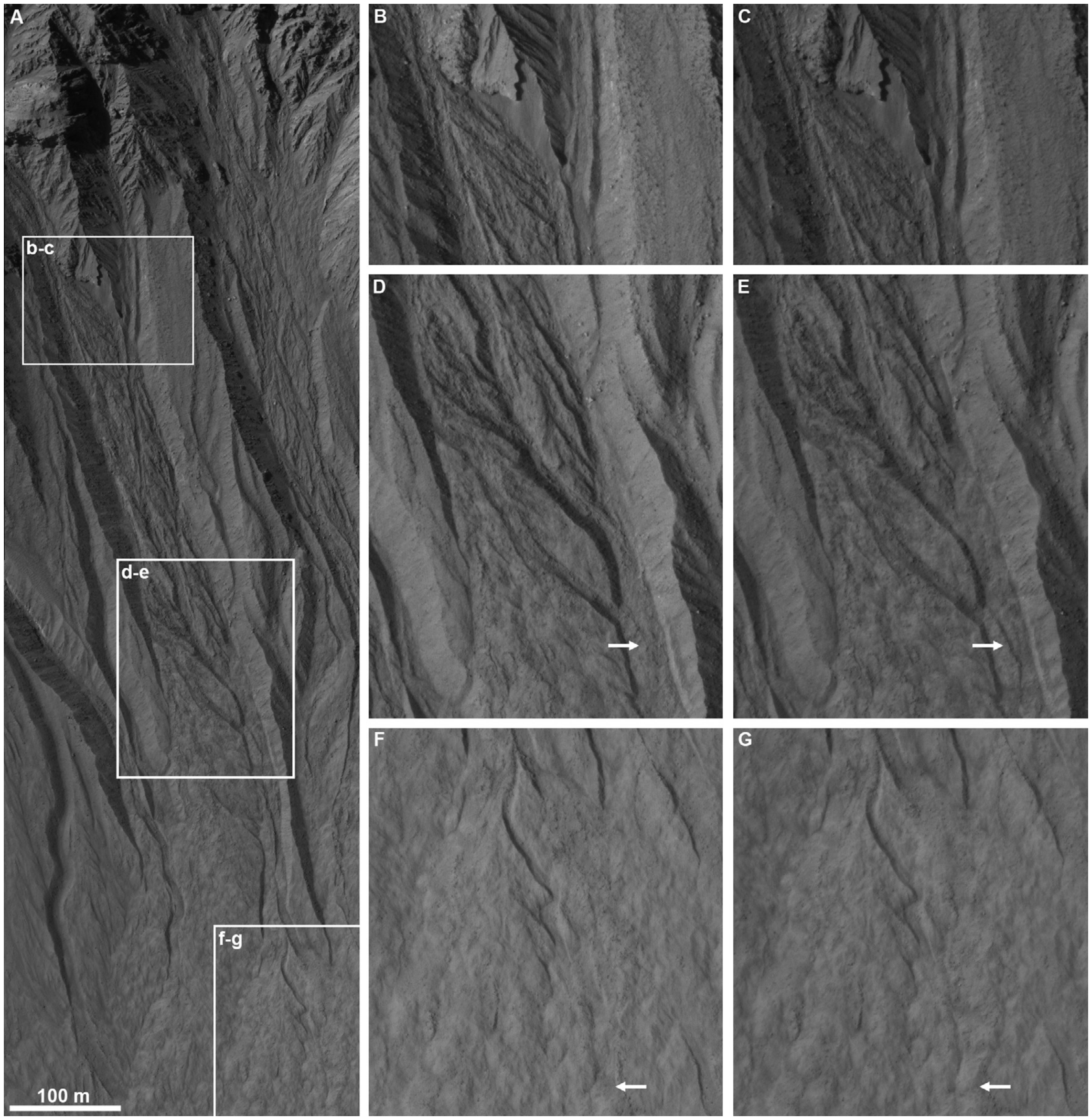

Fig. 7. Large-scale change in a gully. (A) Overview. (B and C) Only minor changes occur upslope near the origin of activity, diminishing to nothing upslope. (D and E) Incision and deposition both occur in the mid-slope region. Arrow indicates formation of an apparent terrace by incision within the older channel. (F and G) Formation of a lobate snout at the terminus. Arrows indicates the deposit toe. (ACEG: HiRISE image ESP_032078_1420, located at 37.7°S, 192.9°E, acquired at $L_S = 328°$, MY31. BDF: HiRISE image PSP_003939_1420, acquired at $L_S = 248°$, MY28. Light is from upper left in both images. See also Supplementary Animation 2.)

often have mixtures of erosion and deposition. Boulder movement along channels is common as well. However, the majority of flow deposits are not resolvably thick at HiRISE resolution and have no detectable topographic effects.

Several of these mass movements are neutral-toned in the HiRISE RED channel (although sometimes distinct in color) and would be difficult to detect in any data set other than HiRISE-to-HiRISE comparisons (Fig. 8), despite sometimes having important morphologic effects. Since light, dark and neutral examples are observed, deposit tone probably reflects only material lithology and grain size and carries no information about process (cf. Heldmann et al., 2010). Bright and dark deposits are sometimes observed in close proximity. The best example of this is in Gasa crater, where light deposits tend to face E–SE and neutral to slightly dark flows are oriented S–SW. A photometric explanation for this variation can be ruled out since similar tones are observed at different orientations at other sites.

Dundas et al. (2012) reported two sites with multiple examples of relatively dark flows that were visible in shadow but could not be distinguished once illuminated. Observations over another Mars winter demonstrate different patterns of flows at these sites, so these are true indications of activity and not previous flows highlighted by differential frost coverage. The most likely explanation is that these are neutral-toned thin flows made visible by contrast with a trace coating of frost on the gully aprons. The large number of such flows observed at single sites is notable. A more definitive example of the effect of frost contrast is shown in Fig. 9, where there were also barely resolved topographic changes.

We used a list of candidate, likely, and confirmed southern-hemisphere RSL locations from Ojha et al. (2014) to compare gully activity rates at sites with and without RSL. At sites with RSL (not necessarily within the gullies, but found in the same image series), 12 out of 49 locations (24%) were active, compared with 24 out of 209 (11%) with no detected RSL. At face value, this comparison is

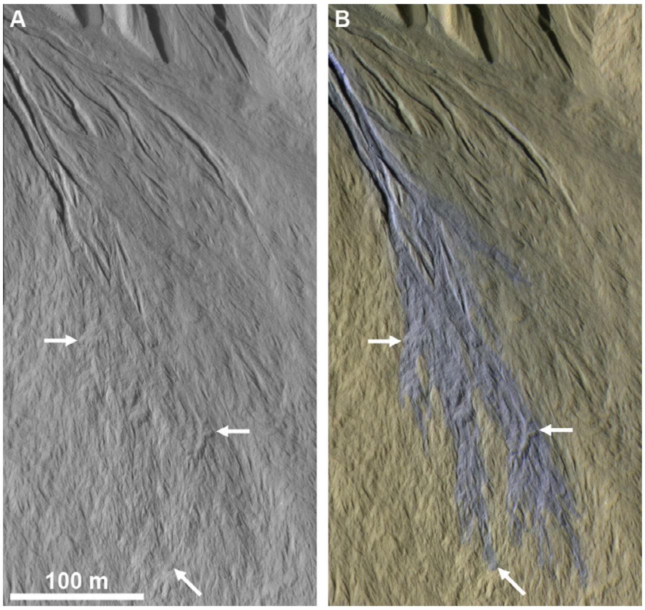

Fig. 8. Neutral-toned new flow in Gasa crater, which is distinct in color. (A) HiRISE red filter image. The outline of the new deposit is indistinct. (B) Color composite using HiRISE IR, red and BG filter images. The new flow (Dundas et al., 2012) appears blue in this enhanced-color composite. Arrows indicate some boundaries of the flow for comparison between panels. Both panels are HiRISE observation ESP_020661_1440 (35.7°S, 129.4°E), with illumination from the left.

statistically significant at the 5% level (Fisher–Irwin test, $p = 0.041$). However, this comparison is compromised by the fact that RSL sites are more heavily monitored on average: the mean number of winter solstices spanned by observations at RSL sites (a proxy for the number of active seasons observed) is 2.18, compared with 1.98 at all southern-hemisphere sites. Additionally, since mid-latitude RSL are visible primarily in southern summer (McEwen et al., 2011), any site with RSL candidates must have been imaged at least once under good lighting conditions. The other issues with the statistical test noted above also apply here. Since the nominal statistical significance ($p = 0.041$) is marginal we consider it possible, but unproven, that locations favoring gully activity also favor RSL activity. At the scale of individual landforms, RSL and gully mass movements are generally uncorrelated, so if this correlation is real it might simply reflect longer or steeper slopes rather than any special environmental conditions. Indeed, many of these sites correspond to well-preserved impact craters.

Several physical factors were assessed as possible influences on gully activity (Fig. 10). We examined Mars Orbiter Laser Altimeter (MOLA) topography (using the global Digital Elevation Model, providing information about the regional setting rather than a specific morphologic feature of the landforms), Thermal Emission Spectrometer (TES) albedo (Christensen et al., 2001), and TES-derived thermal inertia (Putzig and Mellon, 2007). We took a 5×5 pixel median of the thermal inertia data in order to avoid noisy pixels. Because of the near coincidence of perihelion with southern summer solstice, seasonal variations in temperature are much stronger in the south and seasonal frost abundances are greater, so we do not make comparisons across hemispheres. Formally, there is no difference between active and inactive sites in the distribution of either albedo (Mann–Whitney test, $p = 0.23$) or elevation ($p = 0.14$). Thermal inertia does show a statistically significant difference ($p = 0.028$). However, this is strongly skewed by the anomalously low-thermal inertia polar pit gullies, which are particularly active. If the test is applied to sites between 25 and 60°S (which excludes only ten locations), thermal inertia of active and inactive sites does not differ significantly ($p = 0.18$). Although latitude had no statistically significant effect on activity (see above), the lack of any detectable effect equatorward of 60°S leaves us uncertain as to whether the controlling variable is thermal inertia, a subtle latitudinal effect (perhaps threshold-driven rather than continuous) or some other unique property of the polar pit gullies. If the highest-latitude sites are excluded, there is no convincing evidence that active gully locations are in any way distinctive in multi-km-scale albedo, elevation or thermal inertia.

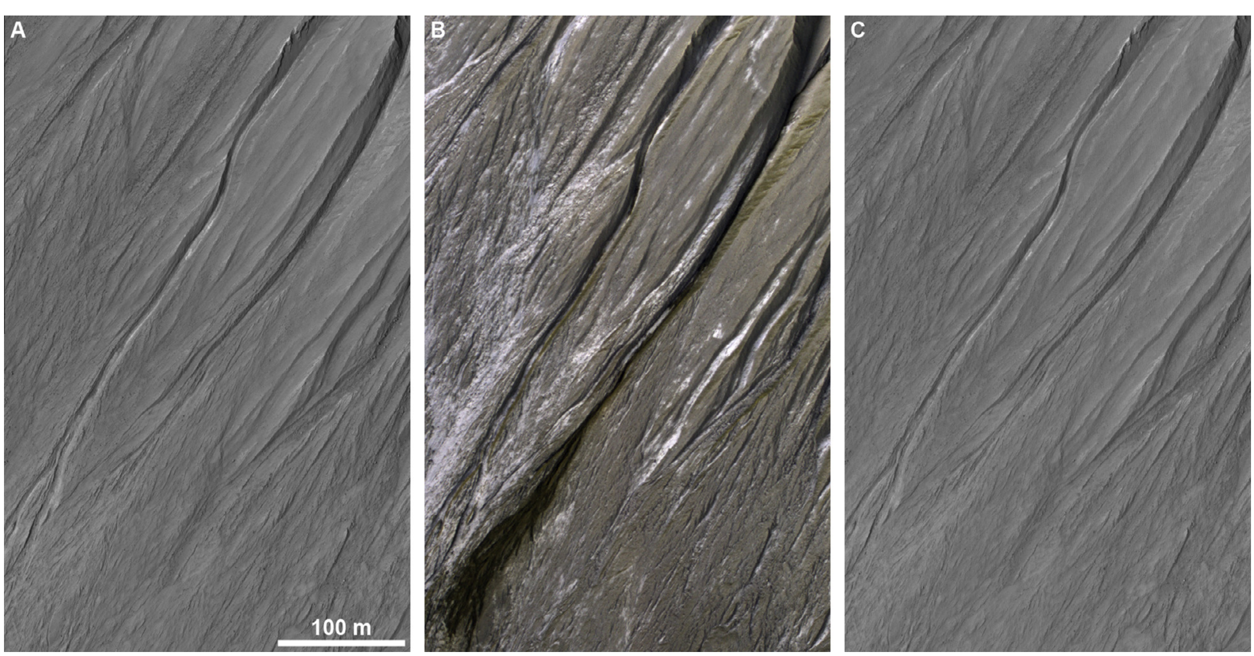

Fig. 9. Neutral-toned flow (in visible filters) seen over frost (37.4°S, 229°E). (B) Shows a dark flow over a frosted surface. (A and C) Show the surface before and after; only small topographic changes are visible. A second flow in this crater produced more substantial topographic changes. (A: HiRISE image PSP_003674_1425, acquired at $L_S = 235°$, MY28; B: ESP_027567_1425, acquired at $L_S = 124°$, MY31; C: ESP_030323_1425, acquired at $L_S = 245°$, MY31. Illumination from upper left in (A and C). (B) is in shadow.)

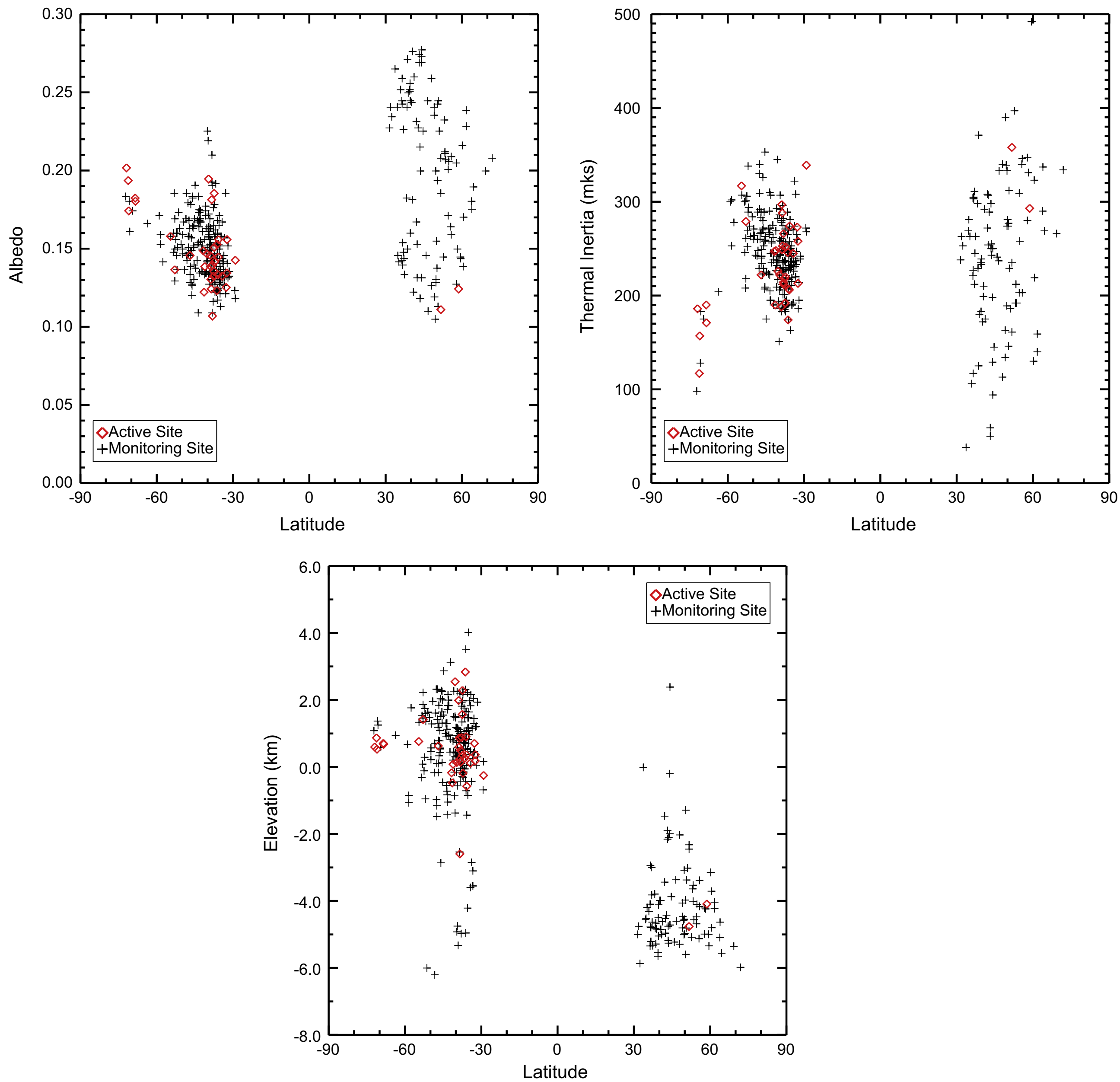

Fig. 10. Properties of monitoring sites, including active sites. In the southern hemisphere the mean albedo for active sites is 0.15, matching the mean for all sites; the means for thermal inertia are 241 and 229 (mks units), and for elevation they are 0.5 and 0.6 km. In the north, the means are 0.19, 246 and −4.1 km.

Dundas et al. (2012) showed a strong association between gully activity and seasonal frost or the defrosting period. The added data in this paper include few well-constrained events, but remains consistent with this observation. Fig. 11 summarizes the event timing for all activity.

3.3. Northern hemisphere

Changes have been discovered at two gully locations in the northern hemisphere, albeit at a very modest scale. At one location (Fig. 12), a thin dark flow with appeared at the mouth of a gully channel, with discontinuous albedo changes in the channel upslope. At the other, small topographic changes occurred in minor channels within a fresh crater (Supplementary Animation 3). At the latter site the landforms are so poorly developed that their relation to alcove–channel–apron gullies is unclear. Other ambiguous candidates have not been included. An example of a defrosting flow has also been observed in the north (Fig. 13), but it was confined to an upper alcove and so did not meet the definition above. This rate of activity is unambiguously lower than that in the southern hemisphere (Fisher–Irwin test, $p = 0.00066$).

With only two known active sites, meaningful statistical comparisons of active and inactive northern-hemisphere sites are not possible. Northern gullies as a whole have average thermal inertia values similar to those in the south, although with greater scatter. The fact that the north includes more low-thermal inertia locations than the south, yet less activity, makes the relevance of thermal inertia (discussed above) uncertain. The albedo and elevation are systematically different, reflecting regional variations between the hemispheres: northern-hemisphere gully sites have a higher average albedo and lower elevation. However, those parameters had no definitive effect on activity in the south.

One side effect of the bias towards imaging fresh and active sites is that northern-hemisphere gullies tend to be imaged less often

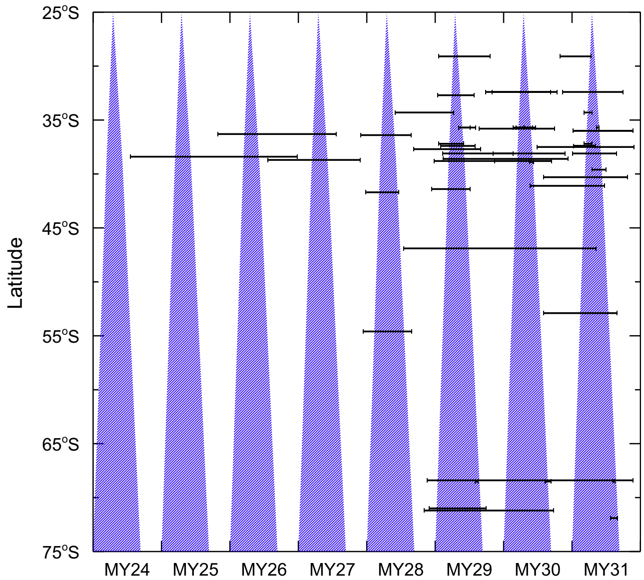

Fig. 11. Timing of known gully activity in the southern hemisphere. Black bars indicate the time intervals in which known gully changes could have occurred. The blue region shows an approximation of the occurrence of pole-facing seasonal frost in gullies seen in HiRISE images. This generalized outline is based on (1) traces of seasonal frost at the active site at 29.1°S at L_S = 100–112°, (2) seasonal frost in the active site at 38.9°S from L_S = 74–158°, and (3) seasonal frost remaining near gullies at 68.5°S at L_S = 247°; this envelope is conservative, as recent images have shown somewhat later frost at the lower latitudes. The real distribution of frost depends on slope, orientation, thermophysical properties and shadowing in addition to latitude. Note that HiRISE cannot distinguish between H_2O and CO_2 frost and only observes in midafternoon. CO_2 frost has not been confirmed below ~34°S (Vincendon et al., 2010b); see text for further discussion. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

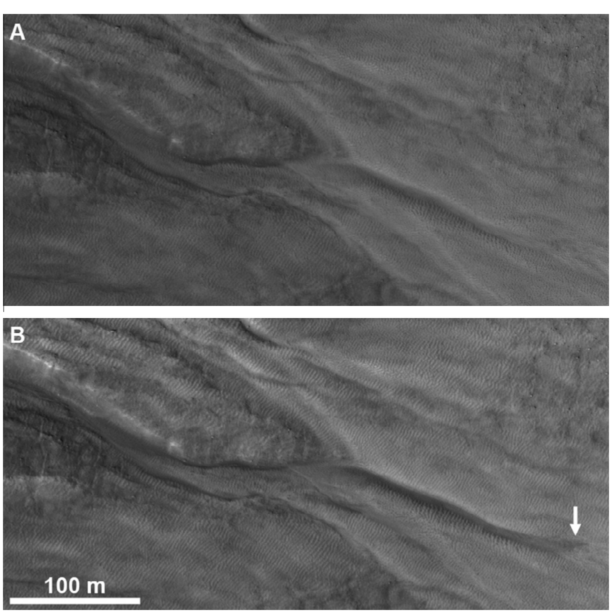

Fig. 12. (A and B) Before-and-after images of activity in a northern hemisphere gully. Arrow in (B) indicates the toe of the flow. No topographic effect was observable and some parts of the channel show no dark deposit, suggesting a thin and easily modified flow. (A: HiRISE image ESP_017102_2390, located at 58.7°N, 82.3°E, acquired at L_S = 67°, MY30; B: ESP_034811_2390, acquired at L_S = 69°, MY32. Illumination from lower left.)

than those in the south, due to more degraded appearance and a lack of activity known prior to 2014. The seasonal clouds of the polar hood also complicate northern winter observations. However, northern-hemisphere monitoring spans an average of 2.16 winter solstices between the first and most recent HiRISE image, compared with 1.98 in the south (although note that several southern-hemisphere changes predate the first HiRISE image of a location, most notably those from Malin et al. (2006), making this an imperfect proxy for monitoring duration). The number of monitoring sites in the northern hemisphere is much less than in the south because gullies (of any preservation state) are less common in the north.

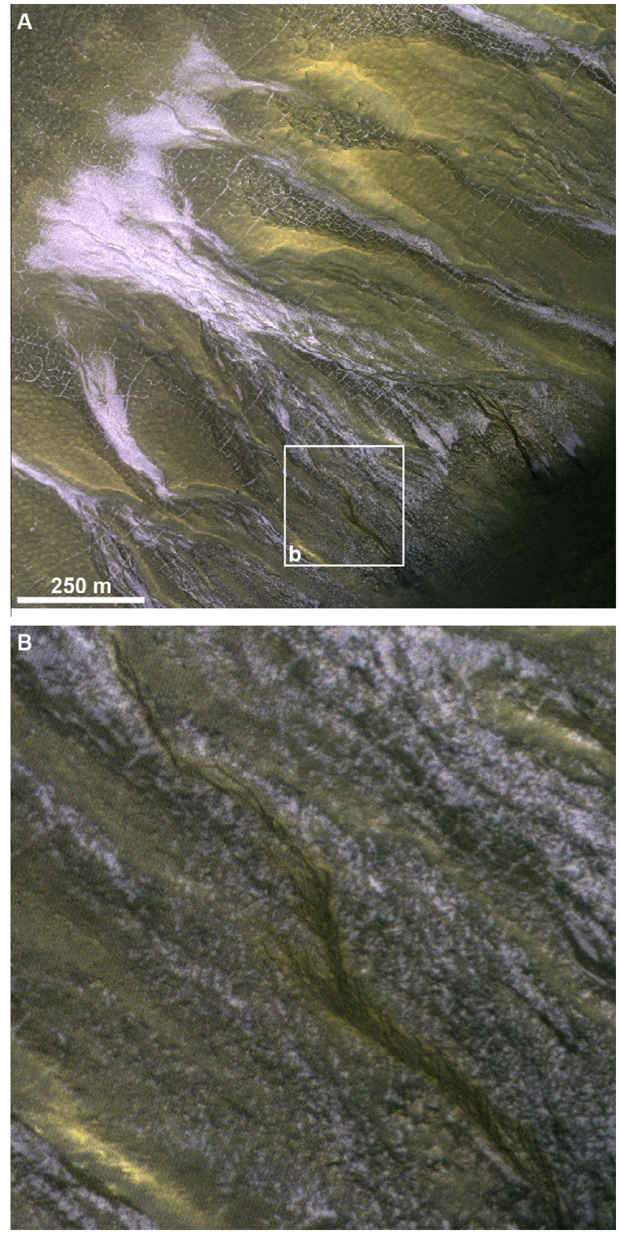

Fig. 13. Defrosting in a northern-hemisphere gully. (A) Gives an overview of the frosted gullies. (B) A flow appears in an upper alcove, but did not reach the channel or apron and so is not considered an active-gully flow by the definition used here. However, defrosting flows are common in many southern-hemisphere gullies and may transport material. (A and B: HiRISE image ESP_032912_2385, located at 58.2°N, 89.7°E. Illumination from lower left.)

4. Discussion

4.1. Present activity and gully formation

The observation of current activity leads us to consider two connected hypotheses. The first is that mass movements like those observed could be responsible for the formation of gullies, without involvement of other processes that could only have been active in the past. The second is that current activity is driven by frost, primarily CO_2, in the absence of liquid water.

The first hypothesis is directly supported by observations. Current activity is creating substantial new features within existing gullies, and is not merely a form of degradation of older landforms. Large-scale incision of new segments of typical channels, generally regarded as the distinguishing feature of gully landforms, has now been observed in non-dune gullies (Figs. 6 and 7). The new incision in Fig. 6 appears to follow the track of a shallow or infilled older channel. This is likely typical of many gully channels, which are often incised into aprons built up by previous events. The widespread occurrence of isolated channel segments suggests that abandonment and infill are common processes, and incompletely buried channels are likely to capture new flows as the surface evolves. Additionally, the morphologies of thus-far inactive alcoves and aprons appear similar to the results of present-day mass movements. Bolstering this conclusion, there is a positive correlation between site freshness and activity—landforms that look sharpest are the most likely to be active. This strongly suggests that the fresh appearance of gullies is generally a consequence of current activity. If the events that we see today were instead degrading older landforms, we would expect the opposite correlation. Activity is observed at many southern-hemisphere sites, and these gullies are not differentiated from those at other sites in any way except by a preference for sharper morphologies (other than the polar pits). This is consistent with the hypothesis that similar activity would occur in most or all moderately fresh southern-hemisphere gullies, given a sufficient period of observation.

Although we did not conduct a detailed analysis of dune-gully activity in this paper, the observed level of activity in gullies on sand surfaces (Table 2) supports the idea that they are forming today. Some dune gullies have linear morphology and might be the product of sliding blocks of ice (Diniega et al., 2013), rolling or creeping frost (Di Achille et al., 2008), and/or jetting sublimation (Hansen et al., 2007). However, others have classic alcove–channel–apron morphology, and formation of a complete alcove–channel–apron system has been observed (Diniega et al., 2010; Dundas et al., 2012). Over half of our long-baseline dune gully or sandy-slope monitoring sites have shown activity, many of them repeatedly. Many of the sites with no observed changes have only been covered by a small number of images, not necessarily well-suited for comparisons. Given this level of activity and the widespread sand motion on Mars (Bridges et al., 2012) that would likely degrade and erase gullies, it seems likely that most or all fresh-appearing dune gullies are active on timescales of years to decades. The massive alcove–channel–apron dune gully in Matara crater described by Diniega et al. (2010) and Dundas et al. (2012) has undergone significant morphologic changes annually and could plausibly have formed on a timescale of decades to centuries.

Dundas et al. (2012) extensively discussed arguments that current activity is driven by CO_2 frost, which we briefly recap here. Volatile-free mass wasting is consistent with the morphology of some recent deposits (Pelletier et al., 2008; Kolb et al., 2010a) and is likely to occur in steep alcoves, but it cannot account for the strong seasonality observed in present-day activity, closely correlated with seasonal frost. Groundwater release can be seasonally modulated (Goldspiel and Squyres, 2011), but is particularly unlikely near the crest of active dunes or from slopes covered with CO_2 frost at temperatures below 150 K. Furthermore, the largest observed flows typically have minor morphological effects in the upslope area, while a groundwater breakout would likely have a detectable effect on the source area. Sudden heating of seasonal water frost upon removal of CO_2 frost is the most likely way to generate liquid at the appropriate time of year (Hecht, 2002; Kossacki and Markiewicz, 2004). However, at best, only trace amounts of meltwater are expected under current conditions, and dampening soil increases cohesion. Instead, the most likely driver of activity is frost. The seasonality of activity is highly correlated with the presence of frost, and CO_2 frost could cause activity through avalanching, sublimation, or simply loading loose surface material on steep slopes (Hoffman, 2002; Ishii and Sasaki, 2004; Cedillo-Flores et al., 2011; Ito et al., 2013).

Two additional lines of evidence favor seasonal frost as the driver of activity. Seasonal CO_2 frost is more abundant near the pole and on low-thermal inertia surfaces, and the high-latitude, low-thermal inertia polar pit gullies appear to be more active than average. Observations of multiple similar flows occurring at a single site within a given timeframe (Fig. 14) also support a volatile trigger. It is unlikely that several adjacent volatile-free flows would occur in this manner, but explicable if they are triggered by similar frost conditions.

Schorghofer and Edgett (2006) observed seasonal frost at latitudes as low as 24°S. They proposed that this frost was CO_2 rather than H_2O, but the MOC images used as their primary data set cannot definitively distinguish the two, leaving open the possibility that the lowest-latitude frost was water ice. HiRISE has observed frost at active gully sites at 29°S (Dundas et al., 2012), but cannot determine the composition. Seasonal CO_2 frost has been observed on pole-facing slopes in spectral data by Vincendon et al. (2010b) down to ~34°S latitude. Some gullies (including active sites) are found equatorward of Vincendon et al.'s frost detections (Fig. 14), generally by no more than 5–10°. CO_2 frost could occur somewhat closer to the equator than currently known, for several reasons: small frost patches may be unresolved or difficult to detect, especially if patchy or in shadow (as in steep gully alcoves), and transient frost could occur at night. We should expect that the shortest-lived frost patches are under-sampled, especially since they will occur only when the lighting is worst for imaging. Alternatively, the small amounts of H_2O frost that occur nearer the equator in the present climate could drive activity via frosted

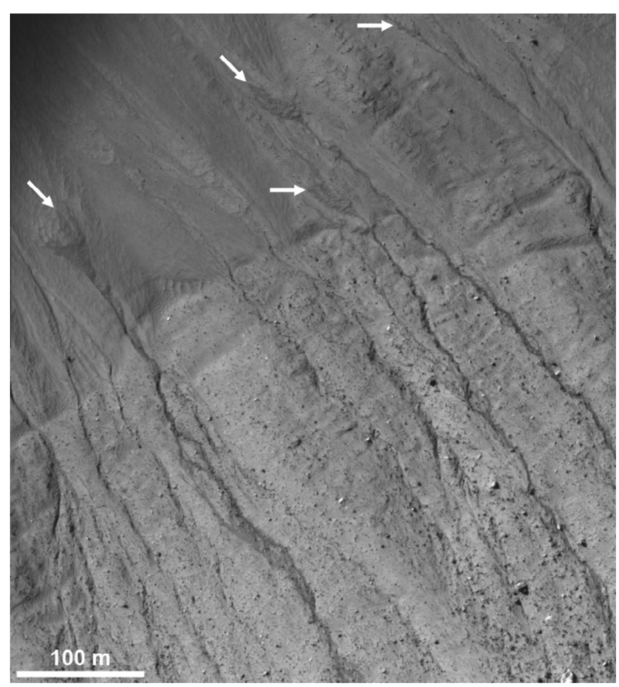

Fig. 14. Multiple dark flows in separate gullies in Asimov crater. (HiRISE image ESP_027628_1330, located at 46.9°S, 4.3°E. Illumination from upper left and downhill direction is to the upper left.)

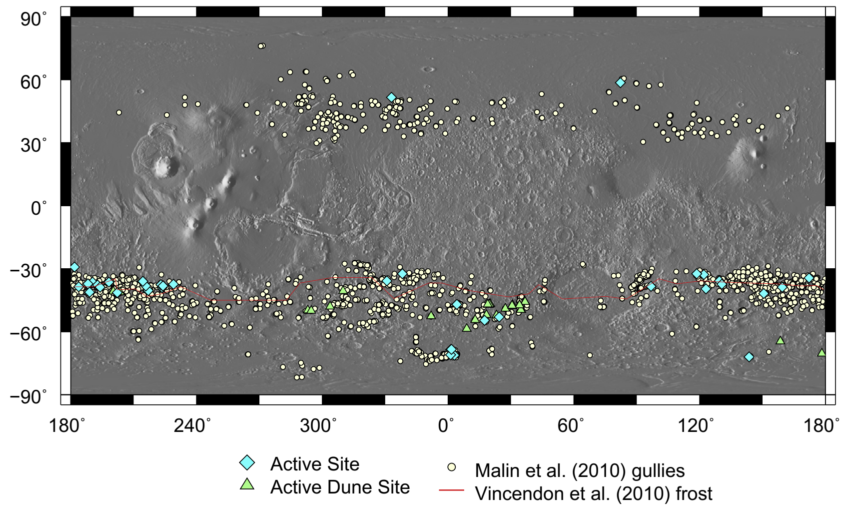

Fig. 15. Distribution of mid- to high-latitude gullies and southern-hemisphere seasonal CO_2 frost detections. The gully locations are from a global survey by Malin et al. (2010). The frost line represents a generalized form of the observations of Vincendon et al. (2010b), indicating the northernmost CO_2 frost detected in the southern hemisphere. See Section 4.1 for discussion of the offset between gullies and frost detections.

granular flow (cf. Hugenholtz, 2008). Vincendon et al. (2010a) reported daytime water frost down to 13°S, and Landis et al. (2007) documented early-morning water frost at the Opportunity landing site at 2°S. If seasonal CO_2 extends marginally closer to the equator than the Vincendon et al. (2010b) detections, there are some intriguing correlations between the spatial distribution of gullies and the shape of the CO_2 frost margin: gullies are rare in the high-elevation Thaumasia region (Fig. 15) where frost detections are lacking equatorward of 45°S, and a swath from approximately 0–50°E has both gullies and frost found somewhat poleward of the norm at other longitudes.

Thermophysical properties like thermal inertia and albedo should influence seasonal frost abundance. As noted above, albedo has no statistically significant effect on gully activity, and the apparent effect of thermal inertia could be due to some other property of the polar pit gullies since it had no detectable effect at lower latitudes. Several explanations exist for this lack of correlation. It is possible that small amounts of frost are sufficient to trigger some activity, such that the absolute abundance of frost is not a key control, although the high activity of the polar pit gullies is notable. Insolation (a function of latitude, orientation and slope) is the main control on frost abundance. Alternatively (or in addition), there could be differences in landform-scale thermophysical properties that are not observable in multi-km-scale data sets. Finally, it is also possible that correlations exist but are not strong enough to be detected in current data.

The recent discovery of RSL also casts gully formation processes in a new light. RSL are the best candidates for present-day flows of liquid water or brine, although the source is not known (McEwen et al., 2011, 2014). As noted above, sites where RSL occur may be more likely to have active gullies. However, at local scales, substantial alcove–channel–apron gully landforms are not typically correlated with RSL. For instance, at the Corozal crater monitoring site, medium-sized gullies (including active gullies) are found on slopes facing south and southwest while RSL mainly face west and northwest. RSL are often found in association with fine channels ("gullies" in the terrestrial sense; McEwen et al., 2011, 2014), many of which may have been unresolved in surveys of martian gullies using lower-resolution data. However, large alcove–channel–apron gully landforms show no general connection to these most likely examples of water flow on Mars, although RSL are sometimes seen on the equator-facing portions of large gully alcoves. One possible scenario is that RSL are responsible for formation of many fine channels, particularly facing the equator, and seasonal frost drives formation of the larger classic (Malin and Edgett, 2000) gully landforms, typically facing the pole. In this case it is possible that there are some landforms where both processes affect the geomorphology. However, no topographic changes due to RSL have yet been detected.

4.2. Gully formation rates

Dundas et al. (2012) made an order-of-magnitude examination of activity in Gasa crater and found that integrating present activity over time is consistent with forming large gullies within the age of the young crater. However, the gullies of Gasa crater are the most active non-dune gullies known on Mars. Here we consider the implications of observed activity for the full population of gullies in the southern hemisphere. Fourteen percent of our southern-hemisphere gully monitoring sites are known to be active, some of them repeatedly, with an average HiRISE monitoring interval of less than 4 years (although some of the activity does predate HiRISE coverage (Malin et al., 2006; Harrison et al., 2009; Dundas et al., 2010), 11% have been active with before-and-after HiRISE images). As noted above, it is likely that most or all moderately fresh gullies can currently be active. Since the number of gullies at an individual site is usually a few to a few tens, the recurrence interval for activity in an individual gully is on the order of centuries. This has two major implications. First, Mars' obliquity has been relatively stable near 25° since ~0.4 Ma (Laskar et al., 2004), and thus climate (and presumably the rate of gully activity) has probably been relatively stable over that interval. This means that any morphological features that might have been produced only when the obliquity was >30° have likely been reworked. Thus, the evidence of processes that were active in earlier climate regimes are likely to be obscured. Second, since a significant fraction of observed mass movements produce deposits with resolvable topographic changes over hundreds of m^2 (so volumes are likely tens to hundreds of m^3), the formation timescale of gully alcoves with volumes of 10^5–10^7 m^3 is on the order of several Myr at current rates. However, this estimate does not account for deposition (e.g., of atmospheric dust and ice; Dickson et al., 2013) at gully sites, partially burying gullies.

The climate of Mars undoubtedly does vary due to the changing obliquity and argument of perihelion, and this should have an effect on seasonal frost and the rates of current processes. In light of the hemispheric differences discussed below, it may be that the southern hemisphere is currently more active than the recent average. However, the greater intensity of the seasonal cycle at higher obliquity (Haberle et al., 2003) could enhance seasonal frost processes for intervals at times before a few hundred ka. The key point is that current processes can produce fresh-appearing gullies on geologically short timescales.

This raises another question: why has gully formation not had a larger geomorphic effect? Gasa crater is perhaps the youngest crater of its size in the southern mid-latitudes (formation date ~1 Ma; Schon et al., 2012), but paradoxically has some of the largest gullies. Many older craters have far less gully development. In the case of Gasa, this may be resolved if the crater formed by impact into debris-covered glacial materials. Schon and Head (2012) suggested that this event could form the gullies directly by melting the ice, but an alternative is that such an event led to the type of alcove collapse modeled by Okubo et al. (2011) and subsequent gully activity has occurred within those alcoves. This does not explain why the gullies in Gasa crater would also be the most active known (residual heat from the impact has long since faded). The most likely explanation is that young and steep slopes are exceptionally unstable.

Perhaps easier to understand is why older craters are not more extensively gullied. Many gullies are developed within the mid-latitude mantle (Fig. 1; Dickson et al., 2010; Schon and Head, 2011; Raack et al., 2012), which is thought to be dust and ice deposited at high obliquity (Mustard et al., 2001; Head et al., 2003). If many gullies develop primarily within an ephemeral unit that is repeatedly deposited and eroded, they might leave little geomorphic trace on the surface underlying this mantle (Dickson et al., 2010; Raack et al., 2012). Dickson et al. (2013) present evidence for interactions between gully activity and mantle deposition, supporting this hypothesis. However, large rocks are observed on and within the mantling deposit (McEwen et al., 2007b; Searls et al., 2008). Although a mix of fine-grained material and transported debris might occur on active slopes, the general problem of boulders within the proposed atmospheric deposit remains unresolved.

4.3. Hemispheric differences

Only two active locations have been observed in the northern hemisphere to date. Extensive activity is observed on sand dunes in the north polar erg, producing alcove–apron features that resemble small gullies, albeit without channels (Hansen et al., 2011, 2013). There are a few additional candidates for northern-hemisphere activity and rare examples of fresh, bright deposits associated with northern gullies (Fig. 16), but marginal candidates and non-new distinct deposits are found in the south as well. It is clear that there is a significant difference in the level of activity in each hemisphere (Fisher–Irwin test, $p = 0.00066$ that activity rates are the same). Gullies in the north are also much more likely to appear degraded, further supporting the idea that current activity causes landforms to appear fresh.

The explanation for the hemispheric difference in activity may be related to current hemispheric differences in seasonal frost abundance. Because aphelion occurs in late southern autumn, the southern highlands develop more frost than the north, reaching lower latitudes (e.g., Schorghofer and Edgett, 2006). This suggests that activity in the north might occur at higher latitudes than the south. The northern-hemisphere activity seen to date is above 50°N latitude, which is consistent with this hypothesis, but two examples are not enough for a meaningful test. It is interesting to note that there are some hemispheric differences in the defrosting of the seasonal cap as well: activity in the north is concentrated on dunes and does not form the eroded araneiform features ("spiders") seen at high southern latitudes (Hansen et al., 2013).

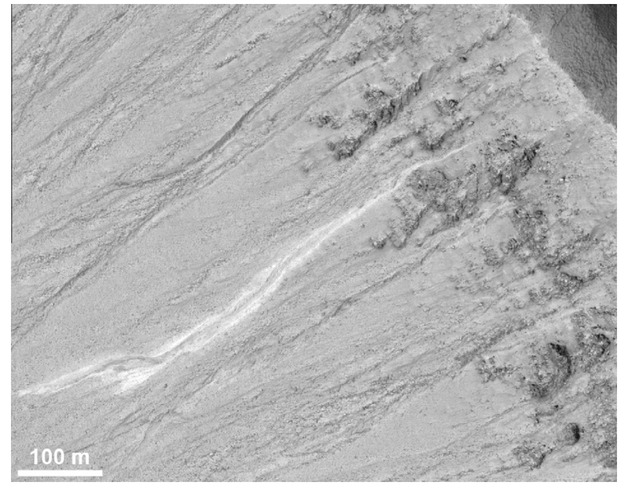

Fig. 16. Bright deposit associated with a poorly developed gully in the northern hemisphere. The relatively sharp outline and lack of ripples suggests that this mass movement is recent (HiRISE image ESP_026564_2405, located at 60.2°N, 236.3°E. Illumination from the left.)

The hemispheric asymmetry due to the longitude of perihelion should reverse every ~25 kyr. Is the current degraded appearance of northern gullies consistent with them having been more active within tens of kyr? Significant reworking of the surface is possible on relatively short timescales: some fresh gully deposits are known to lose all albedo contrast in a matter of years (Dundas et al., 2012), and eolian processes are active planet-wide (Bridges et al., 2012) and could cover aprons with ripples or remove fine-grained material. Where ground ice is present, mature networks of thermal contraction polygons can develop in 0.1–1 Myr (Mellon et al., 2009). The mid-latitude mantle in which many gullies form may degrade on the timescale of obliquity variations, at least at some locations (Mustard et al., 2001; Head et al., 2003). There is some evidence for rapid evolution of gully aprons: De Haas et al. (2013) suggested that gully aprons were quickly smoothed at one location. In fact, activity continuing up to the present calls their assumptions about ages into question and could allow more rapid smoothing. However, their estimate depends on the assumption that the surface relief of older flows is the same as the most recent event. (The assumption is partially based on the absence of boulders on the older mantle, but the abundant rocks on the pre-gully surface calls into question the hypothesized rapid rock breakdown rates.) Further investigation of the details of gully degradation is warranted, but it does not appear implausible for northern-hemisphere gullies to be visibly degraded (but not erased) on 10^4-year timescales. Alternatively, gully processes could be affected by the permanent (topographic and possibly substrate) differences between hemispheres.

4.4. Other observations

Many observations made by other workers have been given in support of various theories of gully formation. Here we consider how several of these relate to the hypotheses that gullies are formed by current processes and that they are driven mainly by CO_2 frost, versus prior hypotheses invoking fluvial processes.

4.4.1. Gully morphology

It has been argued that many morphological features of gullies are necessarily formed by fluvial processes. In particular, channels have been argued to be diagnostic of flowing water (e.g., Heldmann and Mellon, 2004). However, typical-appearing gully channels do

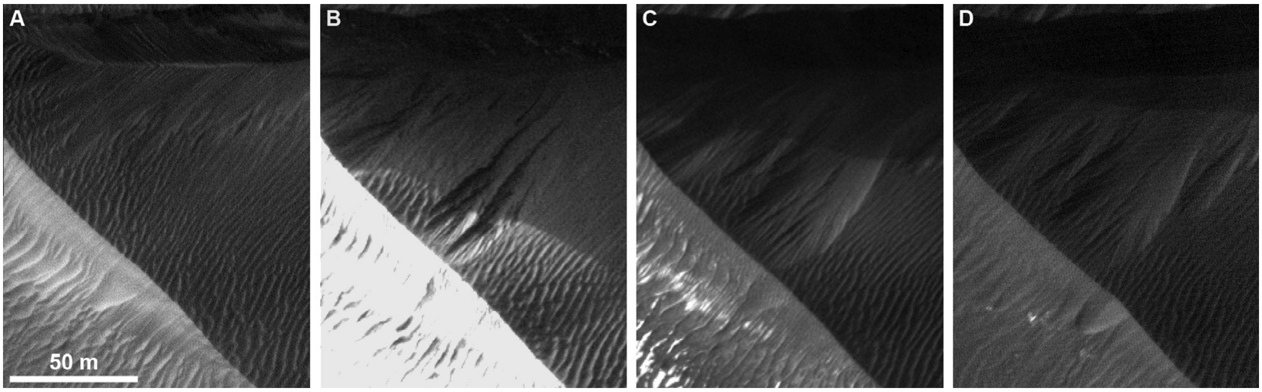

Fig. 17. Erosion of an equator-facing slope in the alcove of a large dune gully in Matara crater. Erosion proceeds by headward retreat after presumed undercutting. Such undercutting permits un-frosted walls to erode. (A: HiRISE image ESP_013478_1300, located at 49.5°S, 34.9°E, acquired at $L_S = 283°$, MY29; B: ESP_019003_1300, $L_S = 134°$, MY30; C: ESP_019781_1300, $L_S = 165°$, MY30; D: ESP_020203_1300, $L_S = 183°$, MY30.)

form or extend in the present climate (Fig. 6), when large volumes of liquid water are not present. McEwen et al. (2007b) suggested braided channels and terraces as diagnostic of running water. However, current activity is observed to form apparent terraces locally, by erosion within partially filled channels (Fig. 7e). Current mass movements readily divide and rejoin within branching channels (Fig. 8), so apparent braiding may readily be explained by a combination of channel avulsion (Fig. 6) and division of flows around pre-existing surface roughness. Note that braided channels in terrestrial streams form on much lower slopes. Likewise, debris flow-like snouts (Levy et al., 2010) are observed to form through present processes (Fig. 7). Dickson and Head (2009) noted channels in the upper reaches of gully alcoves, which is consistent with incision caused by frost on those slopes. Schon and Head (2012) observed that the pole-facing sides of alcoves in Gasa crater appear to have been more extensively eroded. This is reasonable in a frost-driven model where seasonal condensation is primarily on pole-facing slopes, and we observe similar deflection at some other sites. Non-deflected alcoves would suggest that erosion undercut the equator-facing slope, causing it to retreat as well. This process is observed to occur in the dune gully in Matara crater (Fig. 17).

Mangold et al. (2010) examined sinuous gully channels and found that their model for individual dry flows could not reproduce this sinuosity on the observed slopes. To date, no example of a highly sinuous new channel has been observed to form from scratch. However, if gullies form by many events, the observed channel breakout (Fig. 6) suggests an alternate explanation: repeated energetic flows may erode the outside of minor curves, leading to development of sinuosity. Evidence for this process is seen in Supplementary Animation 1. This is further supported by channel evolution seen in a dune-gully channel (Fig. 18). In the latter case the outer bank of a subtle bend was eroded, converting a gently curving channel into a sigmoid shape.

Some morphological constraints on gully formation over time have been suggested. Dickson and Head (2009) observed evidence for episodic or repetitive activity in gullies, such as multiple

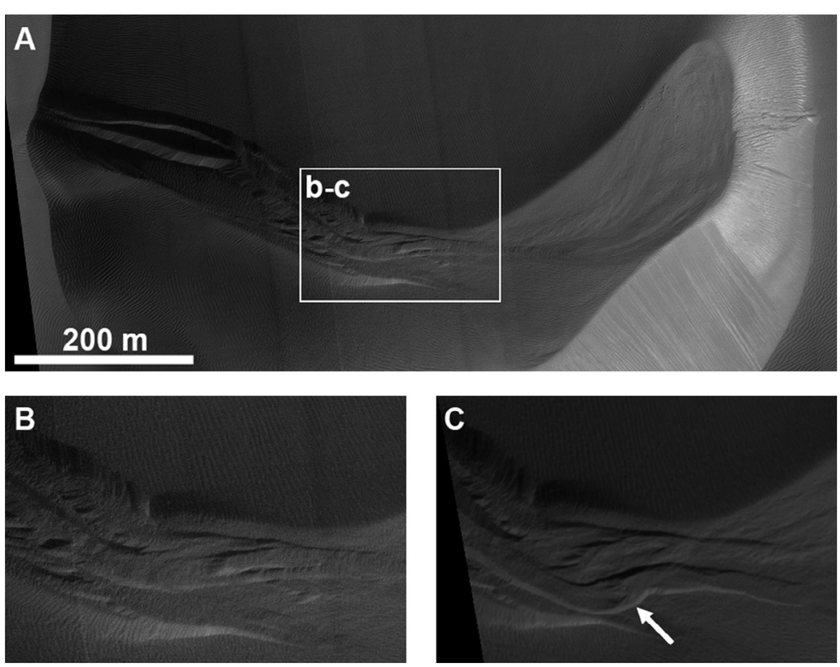

Fig. 18. Incision of a dune gully channel demonstrating development of sinuosity by erosion of the outer bank of a channel. (A) Overview of the gully. (B and C) Enlarged before and after images showing that the mildly curving channel has been partially incised and the curvature enhanced. (A and B: HiRISE image PSP_006780_1320, located at 47.6°S, 30.4°E, acquired at $L_S = 14°$, MY29; C: ESP_024291_1320, acquired at $L_S = 9°$, MY31.)

generations of channels and channels cut into depositional aprons. They commented that gully formation models must allow multiple channel-cutting events, which is directly observed to occur under present processes (Figs. 6 and 7). The integration of current activity over time would make most well-developed gullies a product of hundreds or thousands of events. Crater count-based age constraints requiring that gully formation has been active since ~1–3 Ma (Reiss et al., 2004; Schon et al., 2009; Raack et al., 2012) are easily met if formation is ongoing.

Kolb et al. (2010b) reported that the deposits of the freshest-appearing gullies in their study began on typically higher slopes than those in the more degraded gullies, suggesting that gully flows were more fluidized in the past. As noted above, we observed a preference for activity in the freshest gullies. Our qualitative classification scheme was different from that of Kolb et al. (2010b): we based our categorization of freshness on the morphology of the lower channel and apron. Kolb et al. (2010b) also looked at polygonal fractures and indications of mass wasting in the alcoves as signs of degradation. We note that signs of mass wasting might actually indicate very recent activity, and polygonal fractures are mainly seen in alcoves within the mid-latitude mantle (cf. Levy et al., 2009) and so may not be seen in all gullies of similar preservation. Because of this difference in classification methods, the relative order of age classification is not necessarily the same. In fact, in our independent examination we classified their intermediate type-example gully as fresh and both the fresh and degraded type examples as intermediate. We take this as a cautionary sign regarding the quantitative use of qualitative classification schemes. We examined a much broader range of gullies than Kolb et al. (2010b) and regard our most robust result to be the far higher level of activity in fresh gullies versus degraded gullies. Because degradation style and rate may be site-specific, we also re-examined their results on a site-by-site basis (Fig. 19). Examined in this fashion, and using their independent freshness classification, we found one site (their site C) where there is evidence that fresher gullies have less-fluidized deposits. This substantially reduces the argument for greater fluidization in past gully activity. Intriguingly, although four of Kolb et al.'s five sites were between 35.1 and 38.5°S, the one higher-latitude site (46.1°S) had the lowest depositional slopes. This suggests (but does not confirm) greater fluidization at high latitudes where more frost occurs.

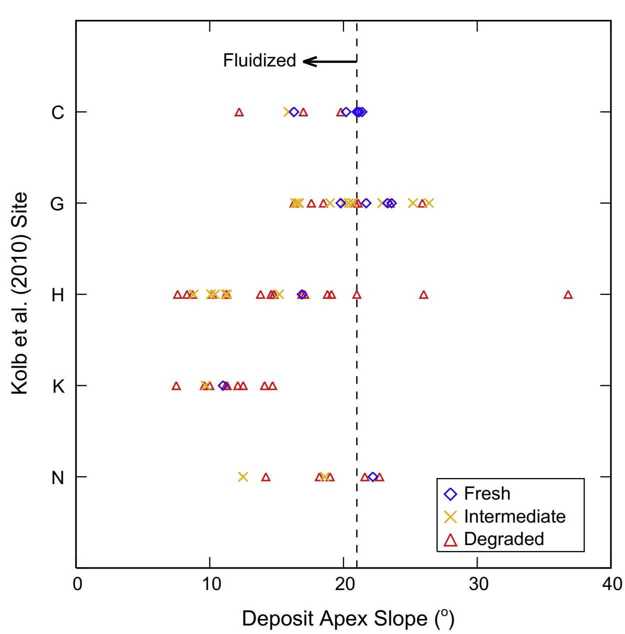

Fig. 19. Kolb et al. (2010b) data (their Table 3) on slope at the initiation of deposition for five gully sites, shown with their classification of freshness; see text for discussion. (Site C, 38.4°S, 96.8°E; site G, 35.7°S, 129.4°E; site H, 35.1°S, 324.7°E; site K, 46.1°S, 18.8°E; site N, 38.5°S, 202.9°E.)

Lanza et al. (2010) reported that there is an inverse relationship between slope angle and upslope contributing area in a sample of gullies from three locations. This relation is similar to that observed for terrestrial debris flows, and Lanza et al. suggested that this indicated broadly distributed, shallow fluid in the source area. The expected relation for CO_2-triggered flows is unknown, and further complicated by the likelihood that martian alcoves are the product of many events, but seasonal frost is also broadly distributed in gully alcoves.

Okubo et al. (2011) reported that alcove failures and crown fractures in Gasa crater are best explained by various configurations of saturated ground or melting ice, or by dry failures under dynamic loading. The alcoves of Gasa crater are also anomalously large and might be related to unusual properties of the impact site (Schon and Head, 2012; see Section 4.2). These crown fractures represent failures leading to mass movements of much larger scale than those considered here, which so far are associated with movement of loose material in alcoves and channels. To date we have not observed any substantial failure of bedrock within an alcove. Although mass movements like those modeled by Okubo et al. (2011) may be important to alcove growth, an alternate hypothesis is that weathering (perhaps the extreme temperature change upon removal of CO_2 frost) breaks down alcove material into debris that can be transported by frost-driven superficial mass movements. Furthermore, the common development of alcoves within the mid-latitude mantle means that in those cases little erosion of bedrock is required.

4.4.2. Gully setting

Several constraints based on the setting and geographical distribution of gullies have been proposed. Heldmann et al. (2007) noted that gullies sometimes occur in places where nearby slopes (on which atmospheric volatile deposition is also expected) are un-gullied. Such cases could be due to local variations in thermophysical properties influencing the behavior of frost, or structural inhomogeneities creating weak sections on the slopes. Alternatively, feedback effects where the erosion of a gully alcove creates cold-trapping conditions might favor further incision in particular locations. If some gullies form primarily in mid-latitude mantle material (Schon and Head, 2011; Raack et al., 2012; Dickson et al., 2013), the distribution of that mantle also affects the location of gullies. Schon and Head (2011) and Raack et al. (2012) took the erosion of gullies into the mantle to indicate that they formed by melting of the mantle ice, but frost-driven erosion could operate quite effectively on such a substrate, since ice is expected to occur under a loose, desiccated sublimation lag. The occurrence of gullies on isolated prominences was taken by several workers as evidence for atmospheric water sources but is equally consistent with atmospherically deposited CO_2, as noted by Balme et al. (2006).

The orientation distribution of gullies has been studied by several workers (Heldmann and Mellon, 2004; Balme et al., 2006; Bridges and Lackner, 2006; Dickson et al., 2007; Kneissl et al., 2010; Harrison et al., 2014). Details of the results differ based on latitudinal binning and data sets. The most complete coverage is likely in those surveys that made use of HRSC (Balme et al., 2006; Kneissl et al., 2010) or CTX (Harrison et al., 2014) data. The results of those surveys indicate that gullies at low latitudes have a strong tendency to face the pole, transitioning to equator-facing or weak preferences at higher latitudes. This is broadly consistent with the distribution of seasonal frost, which is widespread at high latitudes but only occurs on pole-facing slopes or small shadowed locations in the lower mid-latitudes. Equator-facing gullies with

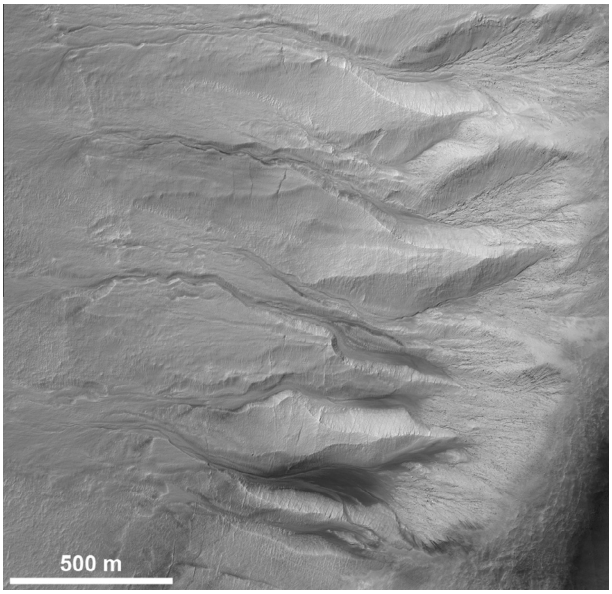

Fig. 20. Gully landforms within the Hellas basin at −6.8 km elevation. (HiRISE image ESP_033045_1345, located at 45.2°S, 73°E. Illumination from upper left.)

little seasonal frost could have minor deposits in local shadows, and/or might reflect different past frost conditions.

CO_2-driven processes might be expected to produce abundant high-latitude gullies, in contrast with the observed preference for the lower mid-latitudes. This is explained by the observation of Dickson and Head (2009) that gullies are predominantly found below a transitional latitude, above which steep slopes are rare (Kreslavsky and Head, 2000). Where high-latitude slopes are found, as in the polar pits, gully landforms are very common. Consequently, the latitudinal distribution of gullies may reflect the overlap between seasonal frost occurrence and available steep slopes.

Dickson et al. (2007) noted that between 30 and 45°S, gullies are found at most altitudes except below −5.5 km (the floor of Hellas) and above 3.1 km (the Thaumasia region near 270°E). The rarity of gullies on the floor of Hellas is explained by a lack of steep slopes, as well as poor image coverage since the typically high optical depth makes it more difficult to image than other mid-latitude targets. The CTX-based survey of Harrison et al. (2014) does include gullies on the floor of Hellas; Fig. 20 shows an example of gullies within the basin on rare steep slopes at −6.8 km elevation, so this is not a limit caused by the formation process. The paucity of gullies in the Thaumasia region matches a longitude zone where Vincendon et al. (2010b) observed no low-latitude CO_2 frost.

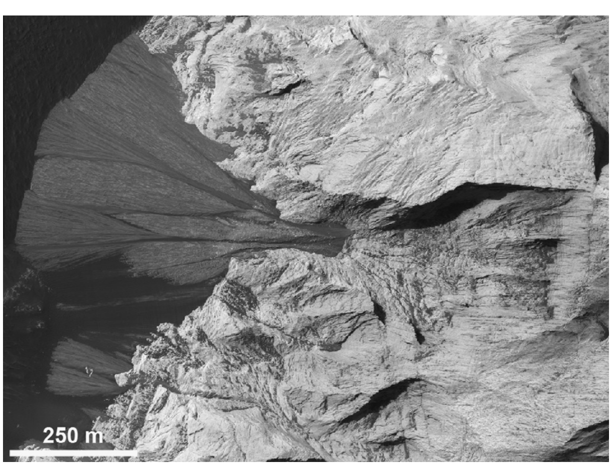

Fig. 21. Equatorial gully landform developed in light-toned layered deposits in Ganges Chasma. (HiRISE image ESP_018518_1715, located at 8.4°S, 313.3°E. Illumination from upper left.)

4.5. Equatorial gullies

Most gully studies consider only the classic mid-latitude gullies of Malin and Edgett (2000). However, Treiman (2003) noted some gully-like landforms in the calderas of equatorial volcanoes. Gullies on the Interior Layered Deposits of Valles Marineris have previously been mentioned (e.g., Chapman, 2005), but have not been compared in detail with classic mid-latitude gullies. Auld and Dixon (2014) also report equatorial gullies, although their survey includes landforms without channels. We have also observed landforms resembling classic gullies in equatorial regions (Fig. 21). The alcoves and fans of these equatorial gully landforms are typically not as well-developed as those in the mid-latitudes (Fig. 21 shows an especially prominent example). The gully in Fig. 21 does appear to show boulder movement and dark flows (Supplementary Animation 4). Activity at this latitude is very unlikely to be the result of CO_2 frost; while the timing of mid-latitude changes indicates the importance of seasonal frost, this location suggests that it is not the sole process active today. In general, equatorial gullies could reflect the effects of RSL (McEwen et al., 2014), trace water frost (cf. Landis et al., 2007) or purely dry flows (Treiman, 2003; Shinbrot et al., 2004), but the relative rarity and poor development compared to mid-latitude slopes serves to emphasize that those processes alone are normally inadequate to produce larger classic gully landforms. Neither equatorial gullies nor their activity have been comprehensively surveyed, so the significance of this single example is not yet clear.

4.6. Implications for planetary climate and liquid water

It is known that Mars' orbit and axial tilt have varied over time; the physics of this evolution is understood and the history over the past 20 Myr has been calculated in detail (e.g., Laskar et al., 2004). A straightforward consequence of this variation is that the distribution of insolation on the surface also varies, which must influence the climate (e.g., Murray et al., 1973; Ward, 1973; Pollack and Toon, 1982; Jakosky and Carr, 1985). Radar evidence suggests that CO_2 ice equivalent to a significant fraction of the current atmosphere has been sequestered at the south pole within the last million years, which would undoubtedly affect the climate (Phillips et al., 2011). However, the details of the climate history are not yet well-understood.

Gullies have commonly been taken as evidence of conditions favorable for melting and liquid runoff from either snow or ground ice, placing a constraint on the climate at the time of gully formation and rendering gullies high-priority targets for astrobiological investigations (e.g., Costard et al., 2002; Christensen, 2003; Mangold and Costard, 2003; Balme et al., 2006; Bridges and Lackner, 2006; Dickson et al., 2007; Dickson and Head, 2009; Schon et al., 2009; Williams et al., 2009; Kneissl et al., 2010; Lanza et al., 2010; Levy et al., 2010; Morgan et al., 2010; Schon and Head, 2011; Okubo et al., 2011; Jouannic et al., 2012; Raack et al., 2012). Meltwater amounts in gullies in the present climate are probably very small, unlikely to cause the large mass movements observed in gullies, and restricted to conditions of sudden heating (Hecht, 2002; Hecht and Bridges, 2003). It is impossible to prove that substantial melting did not occur in gullies in the past, but in light of the nature and rate of current activity, it is not necessary to invoke it. Furthermore, the rate of current change is such that most morphologies dating from the last high-obliquity period have probably been reworked. Changes in Mars' orbit have surely influenced the climate, but the simplest explanation for gully formation is by continuation of current processes, although the rates have likely varied in time and space. Models for past climates that produce widespread melting snow or ground ice are not needed to account for gullies. If CO_2 frost is the key volatile, the possibility that martian gully landforms were habitats for life or that they preserve evidence for subsurface life is reduced.

Although the evidence suggests that current processes are sufficient to form gullies, melting and liquid runoff at high obliquity could have occurred, and would have contributed to gully morphology if they did occur. Moreover, RSL in the present climate are often associated with small channels and could be the cause of their formation. (The source of liquid water in present-day RSL remains a puzzle; McEwen et al. (2011, 2014) considered groundwater or deliquescence but did not draw strong conclusions, and were unable to exclude some enigmatic dry process.) We do not rule out a role for liquid water in gully formation; however, the evidence from current activity indicates that most or all martian "gully" morphologies can be produced in the present climate with little or no liquid water, although RSL may contribute to the formation of fine channels.

The occurrence of gully-like landforms on Vesta has been taken as evidence for liquid water there (Scully et al., 2013, 2014). However, poorly developed gully-like features have also been observed in equatorial regions on the Moon, where significant water is not plausible (Bart, 2007; Kumar et al., 2013). These are best explained by flow of impact melt (Bray et al., 2010; cf. Denevi et al., 2012) or dry flow (Bart, 2007; Kumar et al., 2013). In light of these observations and the evidence on the origin of martian gullies discussed above, the idea that Vestan gullies necessarily indicate liquid water must be tested thoroughly.

5. Conclusions

Changes in classic alcove–channel–apron gully landforms are common under present-day conditions on Mars. A substantial fraction of gullies in the southern hemisphere are active today, and the active locations show little distinguishable difference from others, except that degraded-looking gullies show few changes and the polar pit gullies are particularly active. These observations imply that current processes are forming gullies in the southern hemisphere and that similar activity could occur within most gullies given a sufficiently long monitoring interval. Gullies in the northern hemisphere are currently far less active than those in the south, possibly due to the seasonal asymmetry caused by the occurrence of perihelion in late southern spring. The pace of activity is high enough to form the current population of southern-hemisphere gullies on timescales of Myrs, although it is likely that the rate has varied over time.

All of these observations may be explained by a model in which gullies form entirely by currently active processes, likely driven primarily by CO_2 frost. Recurring Slope Lineae (RSL) may contribute to the formation of fine channels, but in most cases they do not appear connected to the larger martian landforms usually referred to as gullies. This model is consistent not only with ongoing changes but also with a host of previously reported morphological constraints. Although it is impossible to rule out past liquid water in gullies or even present-day liquid water in rare cases or small volumes, we suggest that it does not need to be invoked as the major explanation of gully formation. Models for geologically recent martian climates do not need to produce widespread melting snow or ground ice.

Acknowledgments

We thank the HiRISE operations team for their work in acquiring the data used in this study, and the CTX team for suggesting several sites of possible activity for HiRISE imaging. Shane Byrne, Candy Hansen, Robin Fergason and Justin Hagerty provided helpful comments and suggestions on early drafts. We also thank Jay Dickson and an anonymous referee for helpful review comments. CMD was funded by NASA Mars Data Analysis Program Grant NNH13AV85I. ASM was funded by the MRO Project.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.icarus.2014.05.013.

References

Auld, K.S., Dixon, J.C., 2014. Classification of martian gullies from HiRISE imagery. Lunar Planet. Sci. 45. Abstract #1270.
Balme, M. et al., 2006. Orientation and distribution of recent gullies in the southern hemisphere of Mars: Observations from High Resolution Stereo Camera/Mars Express (HRSC/MEX) and Mars Orbiter Camera/Mars Global Surveyor (MOC/MGS) data. J. Geophys. Res. 111, E05001. http://dx.doi.org/10.1029/2005JE002607.
Bart, G., 2007. Comparison of small lunar landslides and martian gullies. Icarus 187, 417–421.
Bray, V.J. et al., 2010. New insight into lunar impact melt mobility from the LRO camera. Geophys. Res. Lett. 37, L21202. http://dx.doi.org/10.1029/2010GL044666.
Bridges, N.T., Lackner, C.N., 2006. Northern hemisphere martian gullies and mantled terrain: Implications for near-surface water migration in Mars' recent past. J. Geophys. Res. 111, E09014. http://dx.doi.org/10.1029/2006JE002702.
Bridges, N.T., Herkenhoff, K.E., Titus, T.N., Kieffer, H.H., 2001. Ephemeral dark spots associated with martian gullies. Lunar Planet. Sci. XXXII. Abstract #2126.
Bridges, N.T. et al., 2012. Planet-wide sand motion on Mars. Geology 40, 31–34.
Cedillo-Flores, Y., Treiman, A.H., Lasue, J., Clifford, S.M., 2011. CO_2 gas fluidization in the initiation and formation of martian polar gullies. Geophys. Res. Lett. 38, L21202. http://dx.doi.org/10.1029/2011GL049403.
Chapman, M.R., 2005. Volcanism and fluvio-glacial processes on the Interior Layered Deposits of Valles Marineris, Mars? American Geophysical Union (Fall). Abstract #P23B-0190.
Christensen, P.R., 2003. Formation of recent martian gullies through melting of extensive water-rich snow deposits. Nature 422, 45–48.
Christensen, P.R. et al., 2001. Mars Global Surveyor Thermal Emission Spectrometer experiment: Investigation description and surface science results. J. Geophys. Res. 106, 23823–23871.
Clancy, R.T. et al., 2000. An intercomparison of groundbased millimeter, MGS TES, and Viking atmospheric temperature measurements: Seasonal and interannual variability of temperatures and dust loading in the global Mars atmosphere. J. Geophys. Res. 105, 9553–9572. http://dx.doi.org/10.1029/1999JE001089.
Costard, F., Forget, F., Mangold, N., Peulvast, J.P., 2002. Formation of recent martian debris flows by melting of near-surface ground ice at high obliquity. Science 295, 110–113. http://dx.doi.org/10.1126/science.1066698.
De Haas, T., Hauber, E., Kleinhans, M.G., 2013. Local late Amazonian boulder breakdown and denudation rate on Mars. Geophys. Res. Lett. 40. http://dx.doi.org/10.1002/grl.50726.
Denevi, B.W., Koeber, S.D., Robinson, M.S., Garry, W.B., Hawke, B.R., Tran, T.N., Lawrence, S.J., Keszthelyi, L.P., Barnouin, O.S., Ernst, C.M., Tornabene, L.L., 2012. Physical constraints on impact melt properties from Lunar Reconnaissance Orbiter Camera images. Icarus 219, 665–675.
Di Achille, G., Silvestro, S., Ori, G.G., 2008. Defrosting processes on dark dunes: New insights from HiRISE images at Noachis and Aonia Terrae, Mars. Planetary Dunes Workshop: A Record of Climate Change. Abstract #7026.
Dickson, J.L., Head, J.W., 2009. The formation and evolution of youthful gullies on Mars: Gullies as the late-stage phase of Mars' most recent ice age. Icarus 204, 63–86.
Dickson, J.L., Head, J.W., Kreslavsky, M., 2007. Martian gullies in the southern mid-latitudes of Mars: Evidence for climate-controlled formation of young fluvial features based upon local and global topography. Icarus 188, 315–323.
Dickson, J.L., Head, J.W., Fassett, C.I., Levy, J.S., Morgan, G.A., 2010. The life cycle of young gullies on Mars: Gullies as a transient product of ice-rich mantle emplacement and removal. Lunar Planet. Sci. XLI. Abstract #1002.
Dickson, J.L., Head, J.W., Barbieri, L., 2013. Martian gullies as stratigraphic markers for latitude-dependent mantle emplacement and removal. Lunar Planet. Sci. XIV. Abstract #1012.
Diniega, S., Byrne, S., Bridges, N.T., Dundas, C.M., McEwen, A.S., 2010. Seasonality of present-day martian dune-gully activity. Geology 38, 1047–1050. http://dx.doi.org/10.1130/G31287.1.

Diniega, S., Hansen, C.J., McElwaine, J.N., Hugenholtz, C.H., Dundas, C.M., McEwen, A.S., Bourke, M.C., 2013. A new dry hypothesis for the formation of martian linear gullies. Icarus 225, 526–537.

Dundas, C.M., McEwen, A.S., Diniega, S., Byrne, S., Martinez-Alonso, S., 2010. New and recent gully activity on Mars as seen by HiRISE. Geophys. Res. Lett. 37, L07202. http://dx.doi.org/10.1029/2009GL041351.

Dundas, C.M., Diniega, S., Hansen, C.J., Byrne, S., McEwen, A.S., 2012. Seasonal activity and morphological changes in martian gullies. Icarus 220, 124–143.

Gaidos, E.J., 2001. Cryovolcanism and the recent flow of liquid water on Mars. Icarus 153, 218–223.

Gardin, E., Allemand, P., Quantin, C., Thollot, P., 2010. Defrosting, dark flow features, and dune activity on Mars: Example in Russell crater. J. Geophys. Res. 115, E06016. http://dx.doi.org/10.1029/2009JE003515.

Goldspiel, J.M., Squyres, S.W., 2011. Groundwater discharge and gully formation on martian slopes. Icarus 211, 238–258.

Haberle, R.M., Murphy, J.R., Schaeffer, J., 2003. Orbital change experiments with a Mars general circulation model. Icarus 161, 66–89.

Hansen, C.J. et al., 2007. HiRISE views of the sublimation of Mars' southern seasonal cap. In: 7th Int. Conf. Mars. Abstract #3364.

Hansen, C.J. et al., 2011. Seasonal erosion and restoration of Mars' northern polar dunes. Science 331, 575–578. http://dx.doi.org/10.1126/science.1197636.

Hansen, C.J., Byrne, S., Portyankina, G., Bourke, M., Dundas, C., McEwen, A., Mellon, M., Pommerol, A., Thomas, N., 2013. Observations of the northern seasonal polar cap on Mars: I. Spring sublimation activity and process. Icarus 225, 881–897.

Harrison, T.N., Malin, M.C., Edgett, K.S., 2009. Liquid water on the surface of Mars today: Present gully activity observed by the Mars Reconnaissance Orbiter (MRO) and Mars Global Surveyor (MGS) and direction for future missions. American Geophysical Union (Fall). Abstract #P43D-1454.

Harrison, T.N., Osinski, G.R., Tornabene, L.L., 2014. Global documentation of gullies with the Mars Reconnaissance Orbiter Context Camera (CTX) and implications for their formation. Lunar Planet. Sci. 45. Abstract #2124.

Hartmann, W.K., 2001. Martian seeps and their relation to youthful geothermal activity. Space Sci. Rev. 96, 405–410.

Head, J.W., Mustard, J.F., Kreslavsky, M.A., Milliken, R.E., Marchant, D.R., 2003. Recent ice ages on Mars. Nature 426, 797–802.

Hecht, M.H., 2002. Metastability of liquid water on Mars. Icarus 156, 373–386.

Hecht, M.H., Bridges, N.T., 2003. A mechanism for recent production of liquid water on Mars. Lunar Planet. Sci. 34. Abstract #2073.

Heldmann, J.L., Mellon, M.T., 2004. Observations of martian gullies and constraints on potential formation mechanisms. Icarus 168, 285–304. http://dx.doi.org/10.1016/j.icarus.2003.11.024.

Heldmann, J.L., Carlsson, E., Johansson, H., Mellon, M.T., Toon, O.B., 2007. Observations of martian gullies and constraints on potential formation mechanisms: II. The northern hemisphere. Icarus 188, 324–344. http://dx.doi.org/10.1016/j.icarus.2006.12.010.

Heldmann, J.L., Conley, C.A., Brown, A.J., Fletcher, L., Bishop, J.L., McKay, C.P., 2010. Possible liquid water origin for Atacama Desert mudflow and recent gully deposits on Mars. Icarus 206, 685–690.

Hoffman, N., 2002. Active polar gullies on Mars and the role of carbon dioxide. Astrobiology 2, 313–323. http://dx.doi.org/10.1089/153110702762027899.

Hugenholtz, C.H., 2008. Frosted granular flow: A new hypothesis for mass wasting in martian gullies. Icarus 197, 65–72. http://dx.doi.org/10.1016/j.icarus.2008.04.010.

Ishii, T., Sasaki, S., 2004. Formation of recent martian gullies by avalanches of CO_2 frost. Lunar Planet. Sci. XXXV. Abstract #1556.

Ito, G., Sylvest, M., Dixon, J.C., 2013. Understanding the role of CO_2 frost sublimation on martian gullies. Lunar Planet. Sci. XLIV. Abstract #2144.

Jakosky, B.M., Carr, M.H., 1985. Possible precipitation of ice at low latitudes of Mars during periods of high obliquity. Nature 315, 559–561.

Jouannic, G. et al., 2012. Morphological and mechanical characterization of gullies in a periglacial environment: The case of the Russell crater dune (Mars). Planet. Space Sci. 71, 38–54.

Kneissl, T., Reiss, D., van Gasselt, S., Neukum, G., 2010. Distribution and orientation of northern-hemisphere gullies on Mars from the evaluation of HRSC and MOC-NA data. Earth Planet. Sci. Lett. 294, 357–367.

Kolb, K.J., Pelletier, J.D., McEwen, A.S., 2010a. Modeling the formation of bright slope deposits associated with gullies in Hale crater, Mars: Implications for recent liquid water. Icarus 205, 113–137. http://dx.doi.org/10.1016/j.icarus.2009.09.009.

Kolb, K.J., Pelletier, J.D., McEwen, A.S., 2010b. Investigating gully flow emplacement mechanisms using apex slopes. Icarus 208, 132–142. http://dx.doi.org/10.1016/j.icarus.2010.01.007.

Kossacki, K.J., Markiewicz, W.J., 2004. Seasonal melting of surface water ice condensing in martian gullies. Icarus 171, 272–283.

Kreslavsky, M.A., Head, J.W., 2000. Kilometer-scale roughness of Mars: Results from MOLA data analysis. J. Geophys. Res. 105, 26695–26711.

Kumar, P.S. et al., 2013. Gullies and landslides on the Moon: Evidence for dry-granular flows. J. Geophys. Res. 118. http://dx.doi.org/10.1002/jgre.20043.

Landis, G.A., and the MER Athena Science Team, 2007. Observation of frost at the equator of Mars by the Opportunity rover. Lunar Planet. Sci. XXXVIII. Abstract #2423.

Lanza, N.L., Meyer, G.A., Okubo, C.H., Newsom, H.E., Wiens, R.C., 2010. Evidence for debris flow gully formation initiated by shallow subsurface water on Mars. Icarus 205, 103–112.

Laskar, J., Correia, A.C.M., Gastineau, M., Joutel, F., Levrard, B., Robutel, P., 2004. Long term evolution and chaotic diffusion of the insolation quantities of Mars. Icarus 170, 343–364.

Levy, J.S., Head, J.W., Marchant, D., 2009. Thermal contraction crack polygons on Mars: Classification, distribution, and climate implications from HiRISE observations. J. Geophys. Res. 114, E01007. http://dx.doi.org/10.1029/2008JE003273.

Levy, J.S., Head, J.W., Dickson, J.L., Fassett, C.I., Morgan, G.A., Schon, S.C., 2010. Identification of gully debris flow deposits in Protonilus Mensae, Mars: Characterization of a water-bearing, energetic gully-forming process. Earth Planet. Sci. Lett. 294, 368–377.

Malin, M.C., Edgett, K.S., 2000. Evidence for recent groundwater seepage and surface runoff on Mars. Science 288, 2330–2335. http://dx.doi.org/10.1126/science.288.5475.2330.

Malin, M.C. et al., 1992. Mars Observer Camera. J. Geophys. Res. 97, 7699–7718.

Malin, M.C., Edgett, K.S., Posiolova, L.V., McColley, S.M., Dobrea, E.Z.N., 2006. Present-day impact cratering rate and contemporary gully activity on Mars. Science 314, 1573–1577. http://dx.doi.org/10.1126/science.1135156.

Malin, M.C. et al., 2007. Context Camera investigation on board the Mars Reconnaissance Orbiter. J. Geophys. Res. 112, E05S04. http://dx.doi.org/10.1029/2006JE002808.

Malin, M.C. et al., 2010. An overview of the 1985–2006 Mars Orbiter Camera science investigation. Int. J. Mars Sci. Expl. 5, 1–60.

Mangold, N., Costard, F., Forget, F., 2003. Debris flows over sand dunes on Mars: Evidence for liquid water. J. Geophys. Res. 108, 5027. http://dx.doi.org/10.1029/2002JE001958.

Mangold, N., Baratoux, D., Costard, F., Forget, F., 2008. Current gullies activity: Dry avalanches observed over seasonal frost as seen on HiRISE images. Workshop on Martian Gullies: Theories and Tests. Abstract #8005.

Mangold, N. et al., 2010. Sinuous gullies on Mars: Frequency, distribution, and implications for flow properties. J. Geophys. Res. 115. http://dx.doi.org/10.1029/2009JE003540.

McEwen, A.S. et al., 2007a. Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). J. Geophys. Res. 112, E05S02. http://dx.doi.org/10.1029/2005JE002605.

McEwen, A.S. et al., 2007b. A closer look at water-related geologic activity on Mars. Science 317, 1706–1708. http://dx.doi.org/10.1126/science.1143987.

McEwen, A.S. et al., 2011. Seasonal flows on warm martian slopes. Science 333, 740–743. http://dx.doi.org/10.1125/science.1204816.

McEwen, A.S. et al., 2014. Recurring Slope Lineae in equatorial regions of Mars. Nat. Geosci. 7, 53–58.

Mellon, M.T., Phillips, R.J., 2001. Recent gullies on Mars and the source of liquid water. J. Geophys. Res. 106, 23165–23180.

Mellon, M.T. et al., 2009. The periglacial landscape and the Phoenix landing site. J. Geophys. Res. 114. http://dx.doi.org/10.1029/2009JE003418.

Morgan, G.A., Head, J.W., Forget, F., Madeleine, J.-B., Spiga, A., 2010. Gully formation on Mars: Two recent phases of formation suggested by links between morphology, slope orientation and insolation history. Icarus 208, 658–666.

Murray, B.C., Ward, W.R., Yeung, S.C., 1973. Periodic insolation variations on Mars. Science 180, 638–640.

Musselwhite, D.S., Swindle, T.D., Lunine, J.I., 2001. Liquid CO_2 breakout and the formation of recent small gullies on Mars. Geophys. Res. Lett. 28, 1283–1285.

Mustard, J.F., Cooper, C.D., Rifkin, M.A., 2001. Evidence for recent climate change on Mars from the identification of youthful near-surface ground ice. Nature 412, 411–414.

Neuendorf, K.K.E., Mehl, J.P., Jackson, J.A. (Eds.), 2005. Glossary of Geology, fifth ed. American Geological Institute, p. 779.

Neukum, G., Jaumann, R., The HRSC Co-Investigator Team, 2004. HRSC: The High-Resolution Stereo Camera of Mars Express. ESA Spec. Publ. 1240, 1–19.

Nunez, J.I. et al., 2013. Insight into gully formation on Mars with CRISM on the Mars Reconnaissance Orbiter. American Geophysical Union (Fall). Abstract #P41A-1907.

Ojha, L., McEwen, A., Dundas, C., Byrne, S., Mattson, S., Wray, J., Masse, M., Schaefer, E., 2014. HiRISE observations of Recurring Slope Lineae (RSL) during southern summer on Mars. Icarus 231, 365–376.

Okubo, C.H., Tornabene, L.L., Lanza, N.L., 2011. Constraints on mechanisms for the growth of gully alcoves in Gasa crater, Mars, from two-dimensional stability assessments of rock slopes. Icarus 211, 207–221.

Pelletier, J.D., Kolb, K.J., Kirk, R.L., 2008. Recent bright gully deposits on Mars: Wet or dry flow? Geology 36, 211–214. http://dx.doi.org/10.1130/G24346A.1.

Phillips, R.J. et al., 2011. Massive CO_2 ice deposits sequestered in the south polar layered deposits of Mars. Science 332, 838–841.

Pollack, J.B., Toon, O.B., 1982. Quasi-periodic climate changes on Mars: A review. Icarus 50, 259–287.

Putzig, N.E., Mellon, M.T., 2007. Apparent thermal inertia and the surface heterogeneity of Mars. Icarus 191, 68–94.

Raack, J., Reiss, D., Hiesinger, H., 2012. Gullies and their relationships to the dust-ice mantle in the northwestern Argyre Basin, Mars. Icarus 219, 129–141.

Raack, J., Reiss, D., Appéré, T., Vincendon, M., Ruesch, O., Hiesinger, H., 2015. Present-day seasonal gully activity in a south polar pit (Sisyphi Cavi) on Mars. Icarus 251, 226–243.

Reiss, D., Jaumann, R., 2003. Recent debris flows on Mars: Seasonal observations of the Russell crater dune field. Geophys. Res. Lett. 30. http://dx.doi.org/10.1029/2002GJ016704.

Reiss, D., van Gasselt, S., Neukum, G., Jaumann, R., 2004. Absolute dune ages and implications for the time of formation of gullies in Nirgal Vallis, Mars. J. Geophys. Res. 109. http://dx.doi.org/10.1029/2004JE002251.
Reiss, D., Jaumann, R., Kereszturi, A., Sik, A., Neukum, G., 2007. Gullies and avalanche scars on martian dark dunes. Lunar Planet. Sci. XXXVIII. Abstract #1993.
Reiss, D., Erkeling, G., Bauch, K.E., Hiesinger, H., 2010. Evidence for present day gully activity on the Russell crater dune field, Mars. Geophys. Res. Lett. 37, L06203. http://dx.doi.org/10.1029/2009GL042192.
Ross, S.M., 2000. Introduction to Probability and Statistics for Scientists and Engineers, second ed. Harcourt Academic Press.
Schon, S.C., Head, J.W., 2011. Keys to gully formation processes on Mars: Relation to climate cycles and sources of meltwater. Icarus 213, 428–432. http://dx.doi.org/10.1016/j.icarus.2011.02.020.
Schon, S.C., Head, J.W., 2012. Gasa impact crater, Mars: Very young gullies formed from impact into latitude-dependent mantle and debris-covered glacier deposits? Icarus 218, 459–477.
Schon, S.C., Head, J.W., Fassett, C.I., 2009. Unique chronostratigraphic marker in depositional fan stratigraphy on Mars: Evidence for ca. 1.25 Ma gully activity and surficial meltwater origin. Geology 37, 207–210. http://dx.doi.org/10.1130/G25398A.1.
Schon, S.C., Head, J.W., Fassett, C.I., 2012. Recent high-latitude resurfacing by a climate-related latitude-dependent mantle: Constraining age of emplacement from counts of small craters. Planet. Space Sci. 69, 49–61.
Schorghofer, N., Edgett, K.S., 2006. Seasonal surface frost at low latitudes on Mars. Icarus 180, 321–334. http://dx.doi.org/10.1016/j.icarus.2005.08.022.
Scully, J.E.C. et al., 2013. Gullies on Vesta, related geologic features and possible formation mechanisms. Lunar Planet. Sci. XLIV. Abstract #1578.
Scully, J.E.C. et al., 2014. Sub-curvilinear gullies interpreted as evidence for transient water flow on Vesta. Lunar Planet. Sci. 45. Abstract #1796.
Searls, M.L., Mellon, M.T., Martinez-Alonso, S., 2008. Slope analysis and ice stability of the mid-latitude dissected terrain on Mars. Lunar Planet. Sci. XXXIX. Abstract #2376.
Shinbrot, T., Duong, N.-H., Kwan, L., Alvarez, M.M., 2004. Dry granular flows can generate surface features resembling those seen in martian gullies. Proc. Natl. Acad. Sci. 101, 8542–8546.
Treiman, A.H., 2003. Geologic settings of martian gullies: Implications for their origins. J. Geophys. Res. 108, 8031–8042. http://dx.doi.org/10.1029/2002JE001900.
Vedie, E., Costard, F., Font, M., Lagarde, J.L., 2008. Laboratory simulations of martian gullies on sand dunes. Geophys. Res. Lett. 35, L21501. http://dx.doi.org/10.1029/2008GL035638.
Vincendon, M., Forget, F., Mustard, J., 2010a. Water ice at low to midlatitudes on Mars. J. Geophys. Res. 115, E10001. http://dx.doi.org/10.1029/2010JE003584.
Vincendon, M. et al., 2010b. Near-tropical subsurface ice on Mars. Geophys. Res. Lett. 37, L01202. http://dx.doi.org/10.1029/2009GL041426.
Ward, W.R., 1973. Large-scale variations in the obliquity of Mars. Science 181, 260–262.
Williams, K.E., Toon, O.B., Heldmann, J.L., 2007. Modeling water ice lifetimes at recent martian gully locations. Geophys. Res. Lett. 34, L09204. http://dx.doi.org/10.1029/2007GL029507.
Williams, K.E., Toon, O.B., Heldmann, J.L., Mellon, M.T., 2009. Ancient melting of mid-latitude snowpacks on Mars as a water source for gullies. Icarus 200, 418–425.
Zurek, R.W., Smrekar, S.E., 2007. An overview of the Mars Reconnaissance Orbiter (MRO) science mission. J. Geophys. Res. 112, E05S01. http://dx.doi.org/10.1029/2006JE002701.