The Formation of Gullies on Mars Today

Colin M. Dundas[a] *

Alfred S. McEwen[b]

Serina Diniega[c]

Candice J. Hansen[d]

Shane Byrne[b]

Jim N. McElwaine[e, f]

[a]Astrogeology Science Center, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001, USA (cdundas@usgs.gov).

[b]Lunar and Planetary Laboratory, The University of Arizona, Tucson, AZ 85721, USA.

[c]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA.

[d]Planetary Science Institute, St. George, UT 84770, USA.

[e]Planetary Science Institute, 1700 E. Fort Lowell, Tucson, AZ 85719, USA.

[f]Durham University, Department of Earth Sciences, Durham, UK.

*Corresponding author.

Abstract

A decade of high-resolution monitoring has revealed extensive activity in fresh Martian gullies. Flows within the gullies are diverse: they can be relatively light, neutral, or dark, colorful or bland, and range from superficial deposits to 10-meter-scale topographic changes. We observed erosion and transport of material within gullies, new terraces, freshly eroded channel segments, migrating sinuous curves, channel abandonment, and lobate deposits. We also observed early stages of gully initiation, demonstrating that these processes are not merely modifying pre-existing landforms. The timing of activity closely correlates with the presence of seasonal CO_2 frost, so the current changes must be part of ongoing gully formation that is driven largely by its presence. We suggest that the cumulative effect of many flows erodes alcoves and channels and builds lobate aprons, with no involvement of liquid water. Instead, flows may be fluidized by sublimation of entrained CO_2 ice or other mechanisms. The frequent activity has likely erased any features dating from high-obliquity periods, so fresh gully geomorphology at middle and high latitudes is not evidence for past liquid water. CO_2 ice-driven processes may have been important throughout Martian geologic history, and their deposits could exist in the rock record, perhaps resembling debris-flow sediments.

Gully landforms on Mars resemble water-formed features on Earth, with channels transporting material from an alcove to a depositional apron. From their discovery (Malin and Edgett, 2000), they have generally been interpreted as evidence for wet debris flows or flowing liquid water (e.g., Carr, 2006). Such liquid would have major implications for Martian climate, geology, the possibility of life, and the definition of Special Regions for planetary protection (Rummel et al., 2014). Understanding the formation of gullies has thus been a major focus of recent Mars science, as shown by the work in this volume.

Numerous hypotheses for gully formation have been considered. Martian surface conditions are not favorable for the existence of liquid water, so initial models focused on release of groundwater from shallow or deep aquifers (Malin and Edgett, 2000; Mellon and Phillips, 2001; Gaidos, 2001), possibly aided by geothermal heating melting permafrost (Hartmann, 2001; Hartmann et al., 2003) or the occurrence of brines (Knauth and Burt, 2002). However, the occurrence of gullies on sand dunes and isolated peaks argued against significant input from aquifers, and led to the development of models based on insolation-driven melting of snow or shallow permafrost at times when the obliquity of Mars was high (Lee et al., 2001; Costard et al., 2002; Gilmore and Phillips, 2002; Hecht, 2002; Christensen, 2003; Hartmann et al., 2003; Williams et al., 2009). Alternative processes were considered, such as release of liquid CO_2 from the subsurface (Musselwhite et al., 2001), various CO_2 frost-based hypotheses (e.g., Hoffman, 2002; Ishii and Sasaki, 2004; Ishii et al., 2006), or purely dry flow with no volatile involved (Treiman, 2003; Shinbrot et al., 2004), but were generally considered unlikely due to the morphologic similarity between Martian gullies and water-formed terrestrial features.

New flows were discovered in gullies by the Mars Orbiter Camera (MOC) on the Mars Global Surveyor mission (Malin et al., 2006). Later observations showed that the activity is seasonal (Harrison et al., 2009; Dundas et al., 2010), and at several locations changes in gullies have been tightly constrained to occur around the time that seasonal frost is present, indicating that they are driven by the frost (Reiss et al., 2010; Diniega et al., 2010; Dundas et al., 2012; 2015b; Raack et al., 2015). Although seasonal melting of H_2O frost was noted as a possible cause of activity (Reiss et al., 2010), CO_2 frost is much more abundant on Mars (e.g., Leighton and Murray, 1966). In combination with the occurrence of assorted defrosting features in some gullies, this led Diniega et al. (2010) and Dundas et al. (2010; 2012; 2015b) to suggest that CO_2-driven processes were responsible for the current activity, a possibility foreshadowed by early reports of CO_2 defrosting and possible flow features in gullies (Bridges et al., 2001; Hoffman, 2002; Hansen et al., 2007; Mangold et al., 2008). In a captioned image release, Malin and Edgett (2005) also suggested that CO_2 frost could be involved in an early example of dune gully activity. Diniega et al. (2010) and Dundas et al. (2012; 2015b) argued that the current activity could be actively forming dune gullies and "classic" Martian gullies, and not merely modifying older water-formed features.

Seasonal frost deposits are prominent at middle and high latitudes on Mars. The CO_2 caps extend only to around ±50° latitude (e.g., Piqueux et al., 2015), poleward of many gullies. However, localized frost on slopes occurs closer to the equator, at latitudes where gullies are common. Recent mid-latitude surveys include examinations of Mars Orbiter Camera (MOC) images by Schorghofer and Edgett (2006), and of near-IR spectral data by Vincendon et al. (2010a, 2010b). Schorghofer and Edgett (2006) observed frost at latitudes as low as 24°S, which they interpreted as CO_2, although visible-wavelength images cannot distinguish composition. Vincendon et al. (2010a, 2010b) reported detections of CO_2 frost at latitudes as low as 34° S, and water frost reaching 13°S and 32°N. This hemispheric asymmetry in the occurrence of low-latitude frost, also observed by Schorghofer and Edgett (2006), is caused by the occurrence of southern winter solstice near aphelion, which makes the winter longer and colder. Dundas et al. (2015b) reported a similar asymmetry in gully activity. Vincendon (2015) examined near-infrared spectra of active gullies, and found that most were consistent with the presence of CO_2 frost at the time of gully activity. However, the relatively-bright gully deposits were reported to form at times and places where H_2O ice was expected but CO_2 was less probable.

A variety of frost-driven hypotheses have been proposed to explain gully formation or activity. Hecht (2002) suggested that abrupt heating of water frost could enable it to melt before sublimating, providing a source of liquid. Kossacki and Markiewicz (2004) modeled this process and proposed that melting could occur at a given location on a single day of each Mars year, but only in trace amounts. CO_2-driven hypotheses have also been considered. Hoffman (2002) argued that basal sublimation beneath CO_2 could trigger mass movements, by avalanching and/or gas-lubricated flows. Ishii and Sasaki (2004) and Ishii et al. (2006) also proposed that CO_2 frost could avalanche, eroding the surface and forming gullies. They suggested that this was consistent with the orientations and global distribution of recent gullies, which closely matched models for seasonal CO_2 condensation. Hugenholtz (2008) suggested frosted granular flow, whereby a small amount of surface frost reduces friction and enables granular flows. Cedillo-Flores et al. (2011) argued that sublimating CO_2 could fluidize overlying material, although they did not address the initial burial of the ice. Diniega et al. (2013) suggested a model of sliding CO_2 blocks for "linear" gullies on sandy slopes. Pilorget and Forget (2016) modeled CO_2 ice on gully slopes, and suggested that the pressure rise from basal sublimation was capable of fracturing the ice and triggering mass movements.

We analyzed the distribution of seasonal frost in the mid-latitudes in high-resolution color images. This enables a meter-scale understanding of the behavior of the frost and its association with landforms. We compare these frost data with observations of gully activity and its morphological effects, expanding the survey of Dundas et al. (2015b). Finally, we discuss the implications of this work for the formation and evolution of gullies on Mars.

Following common practice, we use the term *gully* or *gully landform* for the alcove-channel-apron assemblages on Mars reported by Malin and Edgett (2000), although under terrestrial definitions (e.g., Neuendorf et al., 2005) "gulch" or "ravine" would be more accurate for many of these kilometer-scale features. Additionally, although terrestrial "debris flows" are commonly defined as wet flows with a wide range of grain sizes (e.g., Iverson, 1997; Turnbull et al., 2015), this usage is not always followed in planetary science, so we refer to "wet" or "aqueous" debris flows to emphasize this aspect. We use the Mars Year calendar defined by Clancy et al. (2000). Seasons are referred to by the areocentric longitude of the sun (L_S), where L_S=0° is the northern vernal equinox. Mars Year 0 (MY 0) began at L_S=0° on May 24, 1953.

Data and Methods

Data

The primary data set for this work was images acquired by the High Resolution Imaging Science Experiment (HiRISE; McEwen et al., 2007) on board the Mars Reconnaissance Orbiter (MRO) spacecraft (Zurek and Smrekar, 2007). HiRISE images are typically 5–6 km wide, with a central swath in three colors (red, blue-green (BG), and near-infrared) in the central 20% of the image, and a pixel scale of 25–60 cm. Delamere et al. (2010) provide more information about HiRISE color imaging. The Reduced Data Records (RDRs) used in this study are map-projected at a scale of 25 or 50 cm/pixel (or rarely 1 m/pixel). The Sun-synchronous MRO orbit constrains the local time for mid-latitude images to be near 3 PM. Incidence angles vary primarily with season.

Frost Survey

In order to survey mid-latitude frost, we selected a data set from HiRISE images acquired before L_S=0° of MY 33, roughly 4.5 MY after the start of the MRO mission. (Transition Orbit imaging occurred between L_S=114–116° of MY 28, and Primary Science Phase began at L_S=132°.) The images were chosen from the HiRISE "science themes" of Seasonal, Mass Wasting, Fluvial, and Impact Processes (McEwen et al., 2007). These themes were selected because they specifically target gullied locations and other steep slopes such as fresh craters with repeat coverage. Some gullies or steep slopes occur in other themes, but these constitute a sufficient sample. Images with significant atmospheric haze were discarded. We chose data from an envelope of latitude and L_S that encompasses the infrared observations of water frost by Vincendon et al. (2010a) for latitudes 25° - 60° in each hemisphere. This encompasses the range of most “classic” gullies, including those with well-studied activity. Water frost is also observed at lower southern latitudes (Vincendon et al., 2010a), and some equatorial gullies have been documented (e.g., McEwen et al., 2014; Auld and Dixon, 2016), but their activity has not been well studied. We focused on the mid-latitudes for the present study, and discuss the implications for equatorial gullies below. Frost is especially abundant in polar gullies.

We used only the color RDR observations, because frost can be indistinct in the red filter-only portion of the image (i.e., although it is often possible to determine that frost is present in the red-filter images, it is difficult to be confident that it is not present when not observed). With only three color bands, it is difficult to conduct an automated search for spectral features of H_2O or CO_2 frost in HiRISE data. Color ratios and brightnesses characteristic of frost in the BG bandpass may not be sufficiently unique for confident identification, especially in shadows or for small frost patches, which are some of the cases of most interest here. (An automated frost-detection algorithm developed by the HiRISE team for use in color adjustments is generally successful but commonly misses small frost patches or those in shadow.) The large size of the images also makes it impractical to manually search the entirety of every image at full resolution, even in our limited data set. Instead, we focused on the upper parts of steep slopes, particularly those with gullies as well as non-gullied slopes of a similar size and (apparent) steepness. Images lacking such slopes were ignored. We also excluded sites with excessively complex topography (such as certain rugged crater central peaks), because those sites are time-consuming to search, have ambiguous slope orientations when stereo data are not available, and may have unusual thermal environments due to complex slope interactions.

These considerations also led to the exclusion of dune field slopes. Impact craters less than 1 km in diameter were also omitted; frost and gullies do occur in such craters and on dunes, but this provided an objective cutoff and limited the data set to a manageable size. The resulting data set is dominated by impact crater slopes, with a few other significant scarps included.

Once these constraints were applied, we examined the remaining steep slope segments at the full RDR resolution to look for frost. Images were locally stretched as needed to enhance the color contrast, including in shadows. Although many cases are obvious, small patches of trace frost require some interpretation to rule out the presence of relatively-bright, relatively-blue lithic material. We interpreted as frost any surface material that appears distinctly “white” or bright “blue” in a stretched three-color HiRISE image (i.e., bright in all three bands or in the blue-green band), and that does not appear to be rock, sand, etc., based on morphology and geologic setting. (For instance, relatively-blue material dominating an equator-facing slope is unlikely to be frost except in cases where frost is ubiquitous. Sand deposits are likely to be rippled and relatively dark.) Frost commonly has very strong associations with small-scale topography, so bright material fringing topographic features or occupying particular slope facets is likely to be frost. For some uncertain cases where summer images were available, we compared the two. Features that persisted in summer images were assumed to be relatively-blue lithic material, although it is possible that in rare instances perennial ground ice could be exposed. Distinguishing diffuse frost from atmospheric haze can also be problematic, but the latter is indifferent to surface topography. In some cases, we interpret other coloration as frost based on context. The most common of these was in times and places where frost is very widespread, and may be translucent and/or dirty in the area of interest. In combination with a lack of defrosted surfaces for contrast, this can make frost coloration less distinctive. With only three broad color channels, it was not possible to distinguish between H_2O and CO_2 frost.

Slopes were divided into eight 45° octants and we recorded the presence or absence of frost on slopes in each octant in each image. We subdivided these observations into alcove and non-alcove slopes, where alcove slopes are the interiors of moderately- to well-developed gully or gully-like alcoves. Shallow alcoves and other slope irregularities were grouped with non-alcove slopes. Since high-resolution topography is only available for a small fraction of sites, slope direction was estimated from the RDR images. In cases where a slope was predominantly facing direction X but just barely curved into the next octant, only direction X was recorded. This ensured that those small slivers, which do not fully capture the frost conditions for their nominal slope orientation, would not be an excessive fraction of the data. The relevant direction is the downhill orientation of the slope on the scale at which gullies develop, because we are interested in the geomorphic evolution of gullies. For instance, a hollow with frost on a small southward slope facet of a generally east-facing slope was recorded as east-facing frost, because such frost could contribute to the formation of east-facing gullies. We also noted the presence of spots or flows superposing the frost, associated with active defrosting (cf. Kieffer, 2007; Hansen et al., 2010; Thomas et al., 2010).

Some of the seasonal ice that we classified as frost may actually have been deposited by precipitation, as snow. Snowfall contributes an estimated 3–20% of the mass of the CO_2 cap at 70–90°S latitude (Hayne et al., 2014). We have no reliable way to distinguish the two in HiRISE data, and refer to all seasonal ice as frost in order to distinguish it from ground ice, which is also likely present in the subsurface near many gullies.

Some frost was likely missed by this survey, for several reasons. Small frost patches or diffuse thin frosts might not produce distinct color and albedo changes, and dust could also reduce the contrast. Frost can also be transparent or translucent at visible wavelengths under some conditions. Additionally, frost in shadow can be more difficult to recognize due to illumination by scattered light only. We recorded frost as possible in cases where there were candidate patches but we were not confident of the interpretation. This most commonly occurred in shadows or small diffuse patches. If the image quality in shadow was too poor for any useful interpretation, the shadowed slope was excluded.

Gully Activity Survey

We updated the gully activity survey of Dundas et al. (2015b) with 1.5 Mars years of additional data, through MRO orbit 48999. This both added many new monitoring sites and extended the time record for many individual gullies. In a handful of cases, we have not used the most recent available image, generally because it was poorly illuminated. The methods follow those in Dundas et al. (2015b). Briefly, HiRISE images of the aprons and lower channels at a reduced resolution of 1 m/pixel were blink-compared to look for changes. Monitoring sites are those gully sites poleward of 25° latitude in each hemisphere with HiRISE image coverage separated by at least 4000 MRO orbits (roughly ten months). Images from each site were compared against the most similar older images to produce optimal comparisons spanning the full time interval for each site. Although in some instances the lighting and image geometry were significantly different, it is possible to detect changes even in non-ideal cases. However, some number of changes are missed. This is emphasized by the occasional observation of changes that can be dated with older images, but only after they are detected in more recent data with better conditions for comparison. This is an inherent limitation of the data and implies that the activity rates here are a lower bound. Thin, transient albedo changes with no meter-scale topographic effects are particularly likely to be missed, but more substantial changes may be unseen (or not considered confirmed) when the available images have dissimilar lighting or viewing geometry.

Martian gullies (Fig. 1) are often divided into dune gullies and non-dune gully landforms. Dune gullies have often been neglected in efforts to understand the formation of "classic" gullies (alcove-channel-apron morphology) on crater walls and other steep slopes. "Linear dune gullies" like those in Russell crater (Mangold et al., 2003; Reiss and Jaumann, 2003) do have a distinctive appearance in that they lack aprons and often have terminal pits (Fig. 1e), but many dune gullies have the classic alcove-channel-apron morphology (Fig. 1f). Additionally, dune and non-dune gullies are more gradational than commonly appreciated (Fig. 1b-d). Here we have included the gradational forms with the main survey. Both types of dune gully are commonly active, and due to the number of changes we did not attempt to catalog all events on the dunes. However, dune gullies with classic morphology likely form by the same processes as similar crater-wall gullies, so we document several examples with prominent morphologic changes.

Observations

Frost Survey

The southern-hemisphere seasonal frost distribution in HiRISE data (Fig. 2) is broadly consistent with the observations of water frost by Vincendon et al. (2010a). Those water frost observations approximately define the occurrence envelope of seasonal frost on Mars, because water ice has a broader spatial and temporal distribution (Schorghofer and Edgett, 2006; Vincendon et al., 2010a, b). However, CO_2 dominates the mass percentage of the frost except at the very fringes of CO_2 deposition (e.g., Leighton and Murray, 1966; Vincendon, 2015), as the minor atmospheric species H_2O forms only very thin deposits at any latitude. Some seasonal water frost occurs at lower latitudes than the 25°S cutoff in this study (Vincendon et al., 2010a). The relationship between frost and slope orientation is as expected: frost was most commonly observed on pole-facing slopes, and the spatial and temporal occurrence expands at higher latitudes. Frost is strongly affected by topography even at very small scales, occurring in the most-sheltered slope facets. Such local effects enable frost to occur even on broadly equator-facing slopes (Fig. 3).

We did not include the highest-latitude gullies in this survey because images are concentrated at only a few locations. However, those locations have been imaged frequently and demonstrate widespread defrosting spots and flows (Fig. 4; see also Dundas et al., 2012). Sublimation activity at particular locations is similar from year to year, but does not repeat exactly.

Defrosting spots and flows occur in the latter part of the frost season, as the frost is being removed. These sublimation features were most commonly observed at higher latitudes, and are rare equatorward of ~40°S. Defrosting spots and flows commonly show a strong concentration within alcoves and channels.

Data in the northern hemisphere were sparse due to the lower abundance of gullies and steep slopes on the northern plains. Frost was only observed poleward of ~35°N, consistent with near-infrared spectral observations of water frost by Vincendon et al. (2010a). Defrosting spots and flows are also rare.

Gully Change Survey

The extended change survey (Fig. 5) reveals that gully activity is common, particularly in gullies in the southern highlands. Over the full monitoring survey, 20% of gully sites south of 25°S have shown activity with before-and-after HiRISE coverage, compared with 5% north of 25°N, and multiple events at particular sites are more common in the south as well. The number of winter solstices spanned by HiRISE observations was 2.9 per site in the southern hemisphere, compared with 2.5 in the north, so northern activity may be slightly underrepresented but not by enough to explain this difference. These figures include gullies on sand-covered non-dune slopes, but not dune gullies. Monitoring sites are preferentially those with fresh gullies and steep slopes, which are likely to be the most active, but do include less pristine gullies as well. (Possible biases are discussed extensively in Dundas et al. (2015b); the expanded data set herein has the same general characteristics.) In addition to being more frequent, activity in the south is more geomorphically effective, as most of the observed changes in the north are superficial (little or no topographic change resolvable by HiRISE). Several sites and even individual gullies have experienced multiple flows (at least sixteen mass movements have occurred in Gasa crater over five Mars years), but the overall level of activity suggests that recurrence intervals in individual gullies are on the order of centuries. Dune gullies are particularly active, with annual changes in some cases, but numerous non-dune gully sites have also seen repeated changes. The timing of some flows can be constrained to within a few weeks, while other intervals span a Mars year or more. When well-constrained, gully activity is closely correlated with seasonal frost, particularly the latter part of the frosted season (Fig. 6).

The features of the various gully changes are diverse. The mass movements range from barely resolved to kilometers long, from superficial albedo changes to major erosion and deposition, and can be bright, dark, colorful, or neutral in tone. Here we describe flows from source to sink and the various morphological effects that occur, with the understanding that there are exceptions to most general statements. Additional examples of changes are shown in the following section.

The detectable sources of individual events are usually small and indistinct. We search for changes by making comparisons of the aprons and channels, where they are most visible. When events were traced up towards the source, the effects typically become more subtle, and may appear disconnected, although it is likely that there are simply unresolved changes uniting the flow, or the flow passed through with little effect. The typical plan form is best seen by examining flows that have covered or disturbed seasonal frost, which makes the entire shape of the flow distinct even where erosion and deposition are superficial (Fig. 7). These flows were virtually point-source features, which descended down channels before producing much larger terminal effects. Some flows do have larger, distributed source areas, although this could represent collapse propagating from a smaller initial failure.

Lower in the flow path, the morphological effects become more prominent. Changes in the channels are common. Some of these are obviously erosive or depositional, although in other cases there are distributed changes that have clearly altered the morphology but where the net local effect is not clear at HiRISE resolution. However, the formation of terminal deposits requires that material be eroded further up the slope, so the overall effect is to erode material from the alcoves and/or channels, resulting in net transport down the channel bed to the apron. Transport and deposition of meter-scale boulders is common in the larger events.

Deposition occurs in the lower reaches of the flows. Sometimes deposits end within existing channels; others reach beyond and onto the apron. The deposits are highly variable: some form thick lobate deposits, while others appear superficial at HiRISE resolution. The flows can deposit boulders or bury existing rocks in finer material, so boulder density is not necessarily an indicator of freshness or rock breakdown (as proposed by de Haas et al., 2013). Lobate features are not necessarily at the farthest point of the deposit, and disturbances and changes can reach beyond obvious lobate flows. The deposits can be brighter or darker than their surroundings, but can also be near-neutral in HiRISE red-filter images. Likewise, some deposits are distinct in color while others closely match the existing surface. Deposits that appear relatively-blue in HiRISE enhanced color are almost always darker than their surroundings in the red-filter images, while those that appear yellow are brighter.

Flows retain distinct color or albedo for varying lengths of time. For instance, the two bright deposits reported by Malin et al. (2006) formed no later than MY 27 and remained obvious in HiRISE images from MY 33. Other flows mostly fade within a Mars year, reflecting more effective local resurfacing, likely dust deposition. Some flows are only distinct while shadowed (Dundas et al., 2012; 2015b). These are demonstrably active events because the patterns change from year to year at individual sites, despite similar lighting. However, they have unresolvable effects on the color and relief of the surface. Other, similar flows are most distinct in winter shadow but produce very minor changes in well-lit images, demonstrating a gradation with more typical activity. Such flows may be minor activity that was distinct because of contrast with traces of frost, analogous to the more obvious flows over frost observed elsewhere (Fig. 7), but produce changes that are minimal at HiRISE resolution in well-illuminated images. Alternatively, they could be extremely thin flows that produced only short-term albedo differences. They may be under-reported because we have not searched for them in all shadowed images, as well as the inherent difficulty of observing features in deep shadow.

Although most of the changes occurred within defined gullies, some appear to be the initial stages of gully formation. A pair of flows in Raga crater followed a crease in the topography, which was so ill-defined in the earliest images of the site that it would likely have been omitted by gully surveys. After two events, the channel became notably more visible and connected (Fig. 8), progressing towards the appearance of better-defined gullies a short distance away. Both of these changes occurred in fall or winter, making them quite distinct from the Recurring Slope Lineae (RSL) found in the same crater in the warm seasons on more equator-facing slopes (McEwen et al., 2011).

Dune gullies appear to be the most active and experience the largest changes (Diniega et al., 2010). For example, a single large dune gully in Matara crater (Fig. 1f) has experienced major mass movements in every winter since the start of HiRISE observation. Such gullies can be fundamentally reworked within a few years. Fig. 9 shows a gully on a large dune west of the Argyre basin. Over three Mars years, the system transitioned from a degraded alcove and infilled channel to a sharp, fresh alcove feeding a 500-m-long, 20-m-wide, terraced channel.

Interpretation

Processes Causing Current Activity

The timing of numerous well-constrained gully events points to seasonal frost as the cause or trigger for current flows in gullies. Other possible seasonally-controlled drivers are inconsistent with the observed temporal behavior. Groundwater release could be seasonal, but should favor summer (Goldspiel and Squyres, 2011) and is extremely unlikely on sand dunes or isolated peaks. Aeolian processes are most active at maximum atmospheric pressure, during southern summer (Ayoub et al., 2014). RSL are most active in the warmest seasons (McEwen et al., 2011; 2014). These options are out of phase with the season of most observed gully flows. In contrast, the observed timing of activity is highly correlated with the presence of seasonal frost.

Fine details of the distribution of visible frost further support seasonal frost as the trigger for activity. Penticton crater has frost on a broadly equator-facing slope at an unusually low latitude (38.4°S), and a rare example of an equator-facing new gully deposit at that latitude (Fig. 3). This coincidence suggests that the frost could have been the trigger for the Penticton flow. The steep slopes and morphology of the deposit are considered consistent with dry flow (Pelletier et al., 2008), so a trigger by this small amount of frost is possible. If this is the case, the minimum frost amount required to trigger mass movements may be very low, but with only one example we cannot establish whether this flow was caused by frost or was simply a random volatile-free event. Volatile-free mass wasting must occur on Mars and a few likely examples have been observed outside of gullies, but the frequency is unknown.

Liquid flow due to melting water frost is excluded as the cause of current changes, for several reasons. First, melting is extremely difficult on present-day Mars. Ingersoll (1970) pointed out that the latent heat losses to sublimation are so high that insolation at the orbit of Mars is insufficient to melt ice. Even at temperatures below 273 K, the evaporative cooling removes more heat than can possibly be supplied by the Sun, precluding warming to the melting point. Hecht (2002) suggested that under certain circumstances (rapid heating, a lowered melting point, and low effective emissivity due to heat input from alcove walls), water ice could be melted. Kossacki and Markiewicz (2004) modeled such a scenario and suggested brief melting episodes during defrosting, producing <1 kg/m^2 of melt. However, their model significantly underestimates evaporative cooling since it included only forced-convection (wind-driven) sublimation. For the assumed wind speed of 5 m/s, free convection is a factor of 2–4 stronger at 270 K, depending on the atmospheric pressure (cf. Dundas and Byrne, 2010). This is likely to prevent even this limited melting. Second, the atmospheric pressure at many of the active locations is below the triple point pressure. Finally, the expected thickness of H_2O frost deposits is small, likely no more than a fraction of a millimeter (Vincendon et al., 2010b;

Vincendon, 2015). Such negligible amounts would not flow through or over a porous medium even if they melt somehow.

Boiling of small volumes of brine in the shallow subsurface (Massé et al., 2016) is possible, if the brine is present and does not evaporate. (Melting and boiling pure subsurface ice suffers from the same difficulties as surface frost.) Conditions for deliquescence to produce such brine occur on Mars (e.g., Gough et al., 2011), but if such brines form from deliquescence, the available volumes would be extremely limited because the Martian atmosphere is very dry, and in the winter H_2O will be cold-trapped at the surface rather than in the subsurface. If such a process occurs on Mars, it is likely to involve much less water than the flows generated in the laboratory by Massé et al. (2016), but could serve as a trigger for dry flows. However, it should not occur when CO_2 ice is present on the surface, which buffers the local temperature to the frost point; CO_2 was definitely present for some of the observed activity with the best time constraints. In sum, the strength of the deliquesced brine for realistic Martian conditions is unknown, and the seasonal timing of activity does not support this process in gullies. Instead, it is likely that activity is caused by processes with no melting or liquid present.

Pilorget and Forget (2016) modeled the possibility that basal sublimation and rising pressure beneath CO_2 ice trigger gully activity, developing an idea considered by Hoffman (2002) and Ishii et al. (2006); this is essentially the “Kieffer model” that produces high-latitude defrosting spots (e.g., Kieffer, 2000; 2007; Piqueux et al., 2003; Hansen et al., 2010; Thomas et al., 2010). However, gully activity is common between 30–40°S, where we rarely observed defrosting spots or flows. Does this contradict the basal sublimation model? It is possible that at lower latitudes, spots are small or shortlived and difficult to observe, particularly in the shadowed, rugged topography of gullies. It is also possible that gas ejection in gullies rarely moves silicate material—steep alcoves may have smaller amounts of loose fine material than the polar regions. In this case, gas ejection might have no tangible effect except when it triggers rare, stochastic, larger-scale failures leading to the observed mass movements. The model is supported in higher-latitude gullies, where spots and flows are common and recur every Mars year (Fig. 4; see also Dundas et al. (2012)). These flows can be considered bedload transport along a channel, albeit in unfamiliar form. The volumes transported annually may be small (the flows have no visible relief in HiRISE images), but the high frequency could make this a significant process in gully evolution where it occurs.

Although the basal sublimation model is consistent with activity in high-latitude gullies and can potentially cause lower-latitude activity, it is probably not the only significant frost process. The small abundances and patchy distribution of the lower-latitude frost are not conducive to gas trapping, and may prevent the CO_2 pressurization process from being as efficient as modeled. Additionally, Vincendon (2015) reported that some gullies with activity, particularly those with bright deposits, have H_2O frost but no detectable CO_2. CO_2 may yet be detected by future observations of those sites, occur at night (cf. Piqueux et al., 2016) or in unresolved patches, or be concealed by coatings of water frost. However, the occurrence of gully activity at locations where frost abundances are low suggests that other trigger mechanisms contribute to activity; these are not mutually exclusive. The point-source initiation of some flows that disturb frost (Fig. 7) suggests avalanching (cf. Hoffman, 2002; Ishii and Sasaki, 2004; Ishii et al., 2006). This could occur within granular frost without any gas pressure, although gas pressure would be an effective way to trigger avalanches (Hoffman, 2002; Ishii et al., 2006). Another possibility is frosted granular flow (Hugenholtz, 2008), although the morphology of terrestrial examples is a poor match for Martian gullies (Harrison, 2016). Slope failures might also be triggered by deposition and sublimation of small amounts of frost on steep alcove slopes, picking up material as they descend. Such a process would be more effective if any frost is deposited between the grains, so that sublimation can dislodge material (cf. Sylvest et al., 2016), and might be most effective in early or late winter when frost is patchy and has uneven effects on the surface.

Why do CO_2-triggered gully flows produce morphologies distinct from typical terrestrial mass wasting? One possibility is that terrestrial geomorphologies are dominated or overprinted by other processes. Another possibility is that gas fluidization from frost makes the flows more mobile than simple granular flow, as suggested by Hoffman (2002). Cedillo-Flores et al. (2011) showed that sand or dust superposed on top of CO_2 frost on Mars could be fluidized by sublimation driven by heat fluxes of tens of W/m^2, at which point the upward gas flow overcomes the weight of the particles. However, their model proposed that the mobilized material was aeolian sediment superposed on the frost and heated by the Sun. This resembles the behavior of defrosting flows creeping within some gullies (Fig. 4), but is unlike the observed point-source flows modifying bare frost (Fig. 7) and has no mechanism for erosion of the surface. To date, we have not observed any indication that aeolian processes are an important precursor to gully mass movements in general (as proposed by Treiman (2003)), although sand movement certainly affects dune gullies. Some flows clearly mobilize boulders, not just aeolian materials. Pilorget and Forget (2016) suggested that the gas generated by basal sublimation underneath frost could also serve to fluidize the flows, but there are few defrosting spots in the lower-latitude active gullies. Additionally, some activity occurs in early winter while CO_2 is condensing and gas pressure should be low.

We suggest a related alternative, in which gas generation occurs via two effects within a mix of sediment and CO_2 ice tumbling down a gully. First, the potential energy of falling material is initially converted to kinetic energy but must ultimately dissipate as heat (Iverson, 1997), or latent heat loss (sublimation) if buffered at the CO_2 frost point temperature. The available energy is 3.7 J/kg per meter of descent, for Martian gravity. For a typical vertical fall of 300 m, this amounts to 1100 J/kg. Second, eroded sediment from the shallow subsurface will be at least slightly warmer than the ice (especially if gas pressure has risen, causing a higher frost point), and could cause additional sublimation (Hoffman, 2002). Warmer material can also be entrained when flows pass into unfrosted areas. Mixing within the falling material will allow this heat to be transferred to the CO_2 frost, causing sublimation. Lithic material at only a few K above the frost point temperature could make several thousand J/kg available, and defrosted areas could be tens of degrees warmer. Hence, this is potentially even more important than the kinetic energy effect, and dramatically so in conditions where the flow is able to incorporate much warmer materials, although not all of the heat transfer need occur while the material is flowing. Thus, there is likely at least $\sim 10^3$ J/kg of energy to be dissipated in typical gully flows, or $\sim 10^6$ J/m^3 for a porous mixture of frost and lithic material. If the flow distance is 1 km at a velocity of 10 m/s (plausible values for gullies in Hale crater (Kolb et al., 2010a), which are now known to be active) then the heat used in gas generation could be up to 10^4 W/m^3, producing a vapor flux equivalent to 10^4 W/m^2 for a

1-m-thick flow if all spent on sublimation. This is a highly transient phenomenon, so this power is only generated briefly. The high energy dissipation in the gully flows is possible because it is distributed through the entire volume of the flow, and is not a radiant heat flux, but it is converted to per-area units here for comparison with the values from Cedillo-Flores et al. (2011). Since we are estimating the energy directed into sublimation, equal energy fluxes imply identical gas fluxes. If no CO_2 were present and this energy was expended on warming lithic material rather than sublimating frost, the temperature rise during the flow would be <2 K. Sublimation could occur within the flow, or at the base if it runs over frost. There is undoubtedly some efficiency factor since not all energy will be expended on sublimation: some energy will be lost to the surroundings, and some kinetic energy could warm the lithic component of the gully flow out of equilibrium with the CO_2 ice. (However, acting in the other direction, addition of energy from warmer rocks and sediment could increase the gas generation by an order of magnitude or more over these estimates.) Moreover, the values suggested by Cedillo-Flores et al. (2011) are lower bounds on the flux needed in this scenario, since some of the gas is generated within the flow, which would cause a range in fluidity with height. However, if even a few percent of this energy goes into frost sublimation, the fluxes indicated by Cedillo-Flores et al. (2011) are easily exceeded, so some amount of fluidization is likely.

Complete fluidization is not necessary to explain the Martian gully flows. The fan deposits of gullies are moderately steep and sometimes consistent with no gas fluidization (Kolb et al., 2010b), and it is likely that a spectrum of behaviors occurs even within individual gullies.

These processes represent a potential source of fluidization unknown in normal terrestrial mass movements, although they resemble processes that occur in ignimbrites and pyroclastic flows (cf. Branney and Kokelaar, 2002). We predict that, all else being equal, greater fluidization will correlate with thicker flows (greater gas flux per unit area, and gas escape timescales will follow the square of flow thickness per Darcy's Law), finer grain size (more effective transfer of heat from sediment to frost, greater ease of mobilization, and slower gas escape due to reduced permeability), flows that incorporate warm sediment well above the frost point (more likely later in the season), and flows with a greater vertical fall distance (more available energy per unit mass). Cohesion of dust and rapid cooling of small grains may reduce the effect of very fine grains (Cedillo-Flores et al., 2011). There may also be a correlation with a higher proportion of frost within the falling material, although if heat extraction from eroded material is important there might be an optimal ratio rather than a monotonic increase. High frost fractions could result in rapid (almost explosive) sublimation and high mobility similar to a suspension current, but might also result in swift gas loss causing the flow to stop. The frost/lithic ratio is not measurable with current data, but could correlate with latitude and season. Notably, of five gully sites studied by Kolb et al. (2010b), the highest-latitude site (at 46°S) had some of the most fluidized deposits. The efficiency factor is unknown and probably variable, depending on factors such as the grain sizes (also an important factor in the flux needed to cause fluidization) and the ratio of frost to lithic material. Experimental work is needed to determine how effective these processes would be under Martian conditions. Active fluidization during flow would have been difficult to observe in previous experiments on CO_2 frost flows (e.g., Sylvest et al., 2016), but those small-scale experiments demonstrate that sublimation of CO_2 within sand can trigger flows on slopes well below the dynamic angle of repose.

In light of these observations, we propose the following model for the relationship between frost and gully activity. Gully mass movements are initiated by seasonal frost through several mechanisms. Of these, the defrosting-pressurization model suggested by Hoffman (2002) and Pilorget and Forget (2016) is directly supported in higher-latitude gullies, but other mechanisms are probably also involved at lower latitudes. Point-source flows resemble the initiation of avalanches, and small amounts of frost may be enough to trigger some activity simply by dislodging grains. Frost blocks and dark halos observed in linear gullies (Pasquon et al., 2016) (Fig. 10) suggest that that distinctive morphology is produced by sliding slabs of ice (Diniega et al., 2013). In other gullies, the relative importance of the various processes is probably variable, particularly as a function of latitude and other local conditions that affect frost condensation, such as alcove topography. These processes result in flows with varying mixtures of frost and entrained regolith descending down a channel, eroding and depositing in accordance with the flow velocity and interactions with local topography and overall slope. If small amounts of frost are capable of triggering mass movements, H_2O frost may initiate flows in some cases, although not by melting. However, it would not be able to fluidize flows in the manner proposed for CO_2, so such flows would behave like volatile-free mass movements. The correlation between CO_2 frost and prominent gullies suggests that CO_2 is much more important. This is unsurprising, since CO_2 frost is typically several orders of magnitude more abundant than H_2O. Equatorial water frost does occur, as do equatorial gullies, but the latter are typically poorly developed and were not reported in a global survey of 6 m/pixel Context Camera images (Harrison et al., 2015). The concentration of prominent gullies on mid-latitude pole-facing slopes is consistent with CO_2 as the major driver of erosion and cause of fluidized gully flows.

One northern-hemisphere gully alcove (Fig. 11) showed a pattern of spots with brightness and color suggestive of frost or ice, sufficiently late in the spring that frost is unlikely. The pattern of spots varies somewhat from year to year and the spots become less distinct over the spring. The alcove is cut into mid-latitude mantle material interpreted to be ice-rich (Conway and Balme, 2014), so it is likely that these exposures are subsurface H_2O ice that is subsequently covered by a sublimation lag. This suggests that sublimation is an important secondary process in modifying some gully alcoves and liberating material for transport, as suggested by Forget et al. (2016). In such a process, a feedback between sublimation and CO_2-driven transport could occur: frost-driven flows strip dry lag material above the ground ice, which subsequently sublimates until another lag develops. Gully locations cut into such ice-rich mantle deposits would thus be a form of sublimation-thermokarst, related to scalloped depressions (cf. Dundas et al., 2015a).

Morphological Effects of Current Activity

Numerous morphologies observed in Martian gullies have been proposed to indicate that they are ultimately liquid water-formed features, regardless of the causes of current activity. These include sinuous, incised channels (Malin and Edgett, 2000; Mangold et al., 2010), braided or anastomosing channels (Malin and Edgett, 2000; Gallagher et al., 2011), terraces and longitudinal bars (Schon and Head, 2009), leveed lobate flows (Levy et al., 2010; Lanza et al., 2010; Johnsson et al., 2014; de Haas et al., 2015b), longitudinal profile characteristics (Conway et al., 2015), and statistical parameterization of three-dimensional topography (Conway and Balme, 2016). However, the purported diagnostic nature of all of these features depends on experience with terrestrial analogs. *A priori*, we do not know what morphologies should be produced by flows triggered or enhanced by CO_2 frost, especially at Mars' gravitational acceleration, because the details of the processes are incompletely understood and we have no clear terrestrial analogs. Therefore, it is essential to understand what morphologies can be produced within currently-active features, which must be produced by frost-driven processes. Dundas et al. (2015b) showed new examples of several of these morphologies. Here we describe additional examples of newly formed morphologies in order to show that they can be created via current Martian surface processes.

Channel incision commonly occurs, particularly in the form of local erosion and channel extension or widening. It is extremely frequent and large-scale in dune gullies. In non-dune gullies, some clear examples were seen, such as erosion of a 50-m-long breakout from a preexisting channel (Dundas et al., 2015b); more commonly, the erosion is more subtle. Fig. 12a-b shows an example of extension of a pre-existing channel. Flows passing down the channel occasionally destabilize the slope, causing wall collapse and liberating material for future transport (Fig. 12c-d). Channel sinuosity also develops over time. In several cases, sinuous curves were observed to migrate and become more sinuous. The process involves erosion of the down-slope outside bank, suggesting that energetic flows strike the outside of the curve and enhance the curves in the channel as they are deflected. This does not continue indefinitely—we have also observed cutoff of a sinuous curve (Fig. 13), analogous to the formation of an oxbow lake in a meandering stream.

Figure 14 shows an excellent example of current activity capable of producing complex, braided patterns. This location has a system of branching channels (Fig. 14a). These channels had faint bright material in an early HiRISE image (Fig. 14b), but in a later image have distinct bright deposits (Fig. 14c). A visible topographic change demonstrates that this is not simply a photometric effect. Instead, the older bright material represents a previous event following a similar pattern. The flows very likely had one source and branched downslope, although the source was not apparent. Within the lower reaches, the flows followed multiple channels, and broke out and branched in several places, likely due to the interaction of topographic irregularities and flow momentum.

Terraces form when channel erosion cuts through previously deposited material. As such, they indicate variations in the locations of erosion and deposition, but need not be caused by fluvial processes. We observed erosion of previous channel floors in several places. A clear example occurred in the large dune gully shown in Fig. 9, which developed a distinct cut-bank terrace as the channel evolved. Smaller examples were seen in non-dune gullies. Bar-like deposits were observed in many of the modified channels (Fig. 15). Like terraces, such bars are not diagnostic of flowing water, but simply indicate localized erosion and deposition by particular flows, with the gross dimensions of the gully likely set by the largest events.

Lobate flow deposits occur near the toes of many changes. Figure 16 shows an example formed in Istok crater (45.1°S, 274.2°E), likely in the winter of MY 33. The deposit resembles features in the same crater interpreted by Johnsson et al. (2014) and de Haas et al. (2015b) as aqueous debris flows. Boulder-rich levees also formed along segments of this flow. In general, levees are uncommon (or not resolved) in current flows, but they are also uncommon in gullies as a whole. Large, leveed lobate deposits have also been observed on equatorial sand dunes, so the formation of leveed flows in general is possible at present.

Conway et al. (2015) suggested that various measures of concavity of the longitudinal profile of gullies were diagnostic of aqueous processes. We examined the longitudinal profile of the major dune gully in eastern Matara crater (Fig. 17) using a high-resolution Digital Terrain Model. This gully (Fig. 1f) has shown annual large-scale activity sufficient to substantially rework the morphology within a decade, so it is unlikely to preserve morphologies not produced by current processes. This gully falls within the normal range of Martian gullies for several measures of concavity (Fig. 17), demonstrating that those parameters can be produced by current CO_2 ice processes.

The massive changes observed in some dune gullies (e.g., Fig. 9) demonstrate that gullies with the classic alcove-channel-apron morphology can be swiftly created or modified by current processes. It is not plausible that such gullies preserve morphologies established during a high-obliquity ice age while many thousands of cubic meters of sand are eroded and deposited annually. Although reworking on this scale has so far only been observed in dune gullies, the differences between activity in dune and non-dune gullies appear to be in scale rather than in kind (likely because sand is not very cohesive and easily mobilized). Furthermore, current activity appears capable of initiating gullies (Fig.

8), not merely modifying older features. Thus, our observations show that current processes are capable of creating the classic gully morphology.

A Dry Frost Model for Gully Formation and Evolution

This study of Martian gully activity yields several fundamental results. First, current activity is driven by seasonal frost, which is predominantly CO_2, and not by liquid water. Second, this present-day activity is extensive and could be observed in most gullies, given a sufficiently long observation period. Finally, diverse gully morphologies, including those sometimes considered diagnostic of liquid water, are forming today. Anything that does happen, can happen—and therefore, these observations demonstrate that gully formation is active, ongoing, and does not require significant volumes of liquid water. In light of these results, we propose that the fresh Martian gullies are not water-formed features, and that bulk volumes of liquid water were never present in the gullies. Instead, they form through dry, frost-driven processes.

In this model, individual gullies begin with events like the erosion seen in Raga crater (Fig. 8), localized by irregularities in the topography like the ill-defined partial channel at that site. Such irregularities also likely form the initiation points for alcoves. The concentration of frost activity in alcoves, combined with the locally steeper slopes, demonstrates that frost-driven processes can be concentrated within gullies in a positive feedback. Micro-topographic control of frost also enables the occurrence of ices on slopes where the overall orientation is not conducive to frost formation. Such topographic effects may control the locations of gullies, and likely explain the miscorrelations between model-predicted CO_2 frost and gully locations reported by Conway et al. (2016).

Many of these flows (tens to hundreds) build up a full-scale gully landform. The evolution is erratic, due to the variable size and erosive effects of the flows: channels form, low-energy flows result in local infill and deposition, energetic events break out to form new branches leading to channel abandonment, and sinuous curves develop and are cut off, while the alcove gradually expands. All of these phenomena have been observed and, integrated over many flows, will build the complex morphologies of well-developed gullies. The observed rate of activity in southern-hemisphere gullies implies hundreds of mass movements in individual gullies in a few Ma or less. Given the nature and extent of activity, it appears plausible for the observed gullies to form via current processes, with some variations in location and intensity over time due to climate variations, without melting or runoff. Table 1 summarizes a range of previous observations of gullies and their explanation in the seasonal frost model.

There is little to distinguish currently active gullies from most of those not (yet) known to be active. Dundas et al. (2015b) found that northern-hemisphere gullies were less active than those in the south, likely due to the current coincidence of aphelion and southern winter solstice, and this remains true in our larger data set. Dune gullies appear to be more active than those on non-sandy material, which likely reflects the ease of mobilizing loose sand. Degraded-appearing gullies appear less active or inactive (Dundas et al., 2015b), but it is very likely that most other gullies would show activity if monitored for decades or centuries. Certain locations like Gasa crater are particularly active at present, due to locally favorable frost conditions or especially steep or erodible material.

An important consequence of the frequent current activity is that it has reshaped most gullies and controls their morphology. This is most obvious in the complete reworking of large dune gullies within a decade (Fig. 9). However, there have probably been dozens or hundreds of flows in most fresh-looking gullies since the last high-obliquity period (Dundas et al., 2015b). Single flows can have significant geomorphic impacts, so the cumulative effects of many such events must have obliterated any features unique to high-obliquity conditions. In fact, an important question is why current processes have not degraded mid-latitude craters more thoroughly. There are two likely contributing factors (Dundas et al., 2015b). First, gully erosion may be most effective on steep, fresh slopes, especially at lower latitudes where slopes and shadowing are required for frost to accumulate. This would make it self-limiting as a geomorphic agent (cf. de Haas et al., 2015a). Consistent with this, the very young Gasa crater has already developed prominent gullies. (An important factor in the large Gasa crater gullies may be generation of the initial alcoves by landslides (Okubo et al., 2011), and the target materials may also be unusual (Schon and Head, 2012).) Second, mantling deposits from high-obliquity epochs fill and bury gullies, with gully erosion in many cases confined to the mantle (e.g., Christensen, 2003; Schon and Head, 2011; Aston et al., 2011; Raack et al., 2012; Conway and Balme, 2014; Dickson et al., 2015a), while erosion of bedrock alcoves occurs more slowly. This points to a model where gullies largely develop within unconsolidated material (sand and mantle deposits) and only slowly modify coherent rock. The likely formation timescale of fresh non-dune gullies by current processes is ~1–10 Ma based on rough estimation of mass fluxes (Dundas et al., 2015b). Consistent with this, upper bounds of one to several Ma have been reported for gully ages at several locations (Malin and Edgett, 2000; Reiss et al., 2004; Schon et al., 2009). Such upper bounds are consistent with ongoing formation and could allow older initiation, subsequently reworked. One possibility is that the current generation of gullies began forming around the transition to lower mean obliquity thought to have occurred at ~5 Ma (Levrard et al., 2004); perhaps mid-latitude mantle deposition competed with gully erosion more effectively at higher obliquities (cf. Madeleine et al., 2014). However, current flux estimates are not precise enough to prove such a connection.

Climate variations are permitted by this model, and should be expected. Changes in the orbital and axial parameters (Laskar et al., 2004) must affect mid-latitude and polar ices. There is evidence for a substantial mass of CO_2 stored in the south polar layered deposits, capable of doubling the surface pressure if it were all added to the atmosphere (Phillips et al., 2011; Bierson et al., 2016). These factors have likely caused variations in humidity (e.g., Mischna and Richardson, 2005), ground ice stability (e.g., Mellon and Jakosky, 1995; Chamberlain and Boynton, 2007; Schorghofer and Forget, 2012), and sublimation of surface ice and deposition of frost and snow (e.g., Levrard et al., 2004; 2007; Forget et al., 2006; Madeleine et al., 2009; 2014), among other variables. However, they may not have produced any significant amount of surface liquid water in the gullies. Pilorget and Forget (2016) demonstrated that the spatial distribution of CO_2 deposition and activity changes with obliquity. These variations, rather than variations in H_2O frost and snow, could account for formation of gullies that are currently inactive and cratered (cf. Morgan et al., 2010; Raack et al., 2012).

Climate variations could even have produced temperatures and pressures that were commonly above the triple point of water (e.g., Dickson et al., 2015b) without

generating runoff. There are two reasons for this. First, latent heat loss to sublimation makes it difficult for the temperature to ever rise to the melting point if water ice is present, as discussed above. Second, there is a difference between thermodynamic stability and stability against transport. Conditions above the triple point would make liquid water thermodynamically favored if H_2O were present. However, those same conditions would drive H_2O away and prevent condensation, because they cause a high mean vapor pressure which makes ice (and water) unstable (e.g., Leighton and Murray, 1966). Ice could be left over from cold climate conditions, but any ice transitioning towards conditions where melting temperatures might be possible would have a vapor pressure high enough to sublimate rapidly (Mellon and Phillips, 2001).
Counterintuitively, the existence of gullies cut into the ice-rich mid-latitude mantle is a strong argument that it has not melted—if local melting conditions were ever attained, the adjacent areas would have undergone massive losses to sublimation, destroying the mantle. The warm locations capable of exceeding the triple point are the locations where ice would be least likely to exist at all, and where ice exists, latent heat will buffer the temperature and make it difficult to reach the melting point. Some models do suggest that limited amounts of past snowmelt (few mm/year) could have occurred (Williams et al., 2009), but trace runoff typically does not produce large mass movements, while the CO_2 processes occurring at present clearly do so.

How long have such dry conditions prevailed on Mars? A generally dry climate may have prevailed for much of the Amazonian, as the atmospheric pressure has been low throughout (e.g., Lammer et al., 2013). Exceptions could have occurred in association with major transient events like impacts and volcanic eruptions. Richardson and Mischna (2005) argued that the middle period of Martian history may have been even less favorable to surface liquid than the present. Recurring Slope Lineae, the other leading candidate for current near-surface liquid water flow (McEwen et al., 2011) are not understood and have angle-of-repose slopes consistent with dry granular flow (Dundas et al., 2017). Forget et al. (2013) demonstrated that formation of extensive seasonal CO_2 ice is a likely consequence of many ancient climate scenarios with a thicker atmosphere, particularly for an atmospheric pressure $\leq$0.5 bars, so dry frost processes may have occurred through most of Mars' history. However, the evidence for ancient liquid water is diverse, although the climate remains poorly understood (Wordsworth, 2016). On early Mars, CO_2-driven processes may have been in competition with or secondary to runoff rather than the dominant process, transitioning as the planet grew colder and drier.

These gully processes could be recorded in Martian sediments dating from any location and epoch with a CO_2 frost cycle, and this possibility should be considered in interpreting Martian sediments, particularly at middle and high latitudes. The gully mass movements transport material ranging from fine grains (including sand and airfall dust) to meter-scale boulders. The morphological similarities between CO_2-driven activity and aqueous debris flows suggest that the deposits may also be similar, and CO_2-mobilized flows could have fluidization similar to wet debris flows, so such deposits on Mars should not be regarded as proof of liquid water. Diagnostic differences could exist, but none of the new Martian flows has yet been inspected in situ for comparison. (At the time of writing, the *Opportunity* rover is preparing to investigate a degraded gully-like feature in Meridiani Planum (Parker et al., 2017). The feature is poorly developed compared with many mid-latitude gullies, and the equatorial latitude (2.3°S) is less favorable for past CO_2 processes, but CO_2-driven formation should be considered a possible working hypothesis.) The most likely difference between aqueous and CO_2-driven mass movements is possible evidence for loss of ice that was mixed into the final deposit and later sublimated, which could manifest as voids or larger collapse or fluidization features, but the absence of such features would not necessarily rule out CO_2 frost. Sediments with evidence for sustained flow and deposition, such as bedform migration, are much more likely to be fluvial (or aeolian), although the deposition style of slowly creeping defrosting flows is unknown. Dune gully flows, if preserved in ancient sandstone, are presumably entirely sand, and linear-gully pits formed by sublimating blocks (Diniega et al., 2013) would disrupt existing bedding.

We emphasize several key points for further assessment of this hypothesis. Current Martian processes are carving sinuous channels, creating lobate flows, and producing other morphologies resembling water-formed terrestrial features. Arguments that particular liquid-free processes on Earth do not produce these morphologies are not convincing tests. Unless large volumes of liquid water are being regularly generated in individual gullies by some unknown mechanism and preferentially released in winter, some non-aqueous process is capable of making these features under Martian conditions. As we do not have terrestrial analogs for gullies formed by CO_2 frost, we do not know what their morphology and morphometry "should" be. The current formation of aqueous-like landforms on Mars suggests that they would resemble water-formed terrestrial features. It is difficult to categorically prove that runoff during some past high-obliquity climate did not contribute to gully formation, and we do not rule out the possibility of some surface liquid water in the geologically recent past. However, the essential argument for liquid water carving gullies is that their morphology is uniquely water-formed and has survived since the last period of high axial tilt. The nature and frequency of current activity in fresh gullies make that interpretation difficult to sustain.

Conclusions

Extensive activity is occurring in Martian gullies today, including formation of a host of geomorphic features often associated with water. However, the timing of activity, and the dry Martian climate, indicate that seasonal CO_2 frost is the cause. The flows seen within Martian gullies may resemble those produced by aqueous processes because they are fluidized to some extent, likely by gas generated from entrained CO_2 frost. Changes in gullies have significant geomorphic effects on all parts of the gully system. The extensive changes observed have likely erased and reworked any morphologies within these same gullies that formed during the last high-obliquity period, so gully geomorphology cannot be diagnostic of liquid water occurring only in a past climate. HiRISE observations indicate that Martian gullies are forming today. Liquid water is not necessary for the gullies, and may never have been involved in their formation. Such a dry scenario would mean that gullies need not be treated as potential naturally-occurring Special Regions, although the likely presence of shallow water ice on pole-facing slopes in the mid-latitudes would still make them potential induced Special Regions. CO_2 frost processes have likely been active for much of Mars' geologic history, with geomorphic and sedimentary consequences that are not yet understood.

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Supplementary Materials

Supporting materials for this article include a description and captions for the supplementary materials, Supplementary Figures 1–6, Supplementary Animations 1–3 (as separate files), and Supplementary Tables 1–2 (as separate files).

References

Aston, A. H., Conway, S. J., Balme, M. R., 2011. Identifying Martian gully evolution. In Martian Geomorphology (Balme, M. R., Bargery, A. S., Gallagher, C. J., & Gupta, S., eds.), Geological Society, London, Special Publication 356, 151-169, doi:10.1144/SP356.9.

Auld, K. S., Dixon, J. C., 2016. A classification of Martian gullies from HiRISE imagery. Planet. Space Sci., 131, 88-101, doi:10.1016/j.pss.2016.08.002.

Ayoub, F., Avouac, J.-P., Newman, C. E., Richardson, M. I., Lucas, A., Leprince, S., Bridges, N. T., 2014. Threshold for sand mobility on Mars calibrated from seasonal variations of sand flux. Nature Commun., 5:5096, doi:10.1038/ncomms6096.

Balme, M., Mangold, N., Baratoux, D., Costard, F., Gosselin, F., Masson, P., Pinet, P., Neukum, G., 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, doi:10.1029/2005JE002607.

Bart, G. D., 2007. Comparison of small lunar landslides and Martian gullies. Icarus, 187, 417-421, doi:10.1016/j.icarus.2006.11.004.

Bierson, C. J., Phillips, R. J., Smith, I. B., Wood, S. E., Putzig, N. E., Nunes, D., Byrne, S., 2016. Stratigraphy and evolution of the buried CO_2 deposit in the Martian south polar cap. Geophys. Res. Lett., 43, doi:10.1002/2016GL068457.

Branney, M. J., Kokelaar, P., 2002. Pyroclastic density currents and the sedimentation of ignimbrites. Geol. Soc. Memoir No. 27, Geological Society, London, 152 pp.

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, doi: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. Conf. 32, abstract #2126.

Carr, M. H., 2006. The Surface of Mars. Cambridge University Press, Cambridge, 307 p.

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, doi:10.1029/2011GL049403.

Chamberlain, M. A., Boynton, W. V., 2007. Response of Martian ground ice to orbit-induced climate change. J. Geophys. Res., 112, E06009, doi:10.1029/2006JE002801.

Christensen, P.R., 2003. Formation of recent Martian gullies through melting of extensive water-rich snow deposits. Nature, 422, 45-48, doi:10.1038/nature01436.

Clancy, R.T., Sandor, B.J., Wolff, M.J., Christensen, P.R., Smith, M.D., Pearl, J.C., Conrath, B.J., Wilson, R.J., 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, doi:10.1029/1999JE001089.

Conway, S. J., Balme, M. R., 2014. Decameter thick remnant glacial ice deposits on Mars. Geophys. Res. Lett., 41, 5402-5409, doi:10.1002/2014GL060314.

Conway, S. J., Balme, M. R., 2016. A novel topographic parameterization scheme indicates that Martian gullies display the signature of liquid water. Earth Planet. Sci. Lett., 454, 36-45, doi:10.1016/j.epsl.2016.08.031.

Conway, S. J., Balme, M. R., Kreslavsky, M. A., Murray, J. B., Towner, M. C., 2015. The comparison of topographic long profiles of gullies on Earth to gullies on Mars: A signal of water on Mars. Icarus, 253, 189-204, doi:10.1016/j.icarus.2015.03.009.

Conway, S. J., Harrison, T. N., Lewis, S. R., Soare, R. J., Balme, M. R., Britton, A., 2016. Martian gully orientation and slope used to test meltwater and carbon dioxide hypotheses. Lunar Planet. Sci. Conf. 47, abstract #1973.

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, doi: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, 3527-3531, doi:10.1002/grl.50726.

de Haas, T., Conway, S. J., Krautblatter, M., 2015a. Recent (Late Amazonian) enhanced backweathering rates on Mars: Paracratering evidence from gully alcoves. J. Geophys. Res. Planets, 120, doi:10.1002/2015JE004915.

de Haas, T., Hauber, E., Conway, S. J., van Steijn, H., Johnsson, A., Kleinhans, M. G., 2015b. Earth-like aqueous debris-flow activity on Mars at high orbital obliquity in the last million years. Nature Commun., 6:7543, doi:10.1038/ncomms8543.

de Haas, T., Ventra, D., Hauber, E., Conway, S. J., Kleinhans, M. G., 2015c. Sedimentological analyses of Martian gullies: The subsurface as the key to the surface. Icarus, 258, 92-108, doi:10.1016/j.icarus.2015.06.017.

Delamere, W. A., et al., 2010. Color imaging of Mars by the High Resolution Imaging Science Experiment (HiRISE). Icarus, 205, 38-52, doi:10.1016/j.icarus.2009.03.012.

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, doi:10.1016/j.icarus.2009.06.018.

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, doi:10.1016/j.icarus.2006.11.020.

Dickson, J. L., Head, J. W., Goudge, T. A., Barbieri, L., 2015a. Recent climate cycles on Mars: Stratigraphic relationships between multiple generations of gullies and the latitude-dependent mantle. Icarus, 252, 83-94, doi:10.1016/j.icarus.2014.12.035.

Dickson, J. L., Kerber, L., Fassett, C. I., Head, J. W., Forget, F., Madeleine, J.-B., 2015b. Formation of gullies on Mars by water at high obliquity: Quantitative integration of Global Climate Models and gully distribution. Lunar Planet. Sci. Conf. 46, abstract #1035.

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, doi: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, doi:10.1016/j.icarus.2013.04.006.

Dundas, C. M., Byrne, S., 2010. Modeling sublimation of ice exposed by new impacts in the Martian mid-latitudes. Icarus, 206, 716-728, doi:10.1016/j.icarus.2009.09.007.

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, doi: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, doi:10.1016/j.icarus.2012.04.005.

Dundas, C. M., Byrne, S., McEwen, A. S., 2015a. Modeling the development of Martian sublimation thermokarst landforms. Icarus, 262, 154-169, doi:10.1016/j.icarus.2015.07.033.

Dundas, C.M., Diniega, S., McEwen, A.S., 2015b. Long-term monitoring of Martian gully formation and evolution with MRO/HiRISE. Icarus, 251, 244-263, doi:10.1016/j.icarus.2014.05.013.

Dundas, C. M., McEwen, A. S., Chojnacki, M., Milazzo, M. P., Byrne, S., 2017. A granular flow model for Recurring Slope Lineae on Mars. Lunar Planet. Sci. Conf. 48, abstract #2399.

Forget, F., Haberle, R. M., Montmessin, F., Levrard, B., Head, J. W., 2006. Formation of glaciers on Mars by atmospheric precipitation at high obliquity. Science, 311, 368-371, doi:10.1126/science.1120335.

Forget, F., Wordsworth, R., Millour, E., Madeleine, J.-B., Kerber, L., Leconte, J., Marcq, E., Haberle, R. M., 2013. 3D modelling of the early Martian climate under a denser CO_2 atmosphere: Temperatures and CO_2 ice clouds. Icarus, 222, 81-99, doi:10.1016/j.icarus.2012.10.019.

Forget, F., Pilorget, C., Pottier, A., Meslin, P.-Y., 2016. Deep incision of the Latitude Dependent Mantle in Martian gullies formed by CO_2 sublimation processes. Unnumbered abstract presented at the Workshop on Martian Gullies and their Earth Analogs, June 20, 2016, London, UK.

Gaidos, E.J., 2001. Cryovolcanism and the recent flow of liquid water on Mars. Icarus, 153, 218-223, doi:10.1006/icar.2001.6649.

Gallagher, C., Balme, M. R., Conway, S. J., Grindrod, P. M., 2011. Sorted clastic stripes, lobes and associated gullies in high-latitude craters on Mars: Landforms indicative of very recent, polycyclic ground-ice thaw and liquid flows. Icarus, 211, 458-471, doi:10.1016/j.icarus.2010.09.010.

Gilmore, M. S., Phillips, E. L., 2002. Role of aquicludes in formation of Martian gullies. Geology, 30, 1107-1110, doi:10.1130/0091-7613(2002)030<1107:ROAIFO>2.0.CO;2.

Goldspiel, J. M., Squyres, S. W., 2011. Groundwater discharge and gully formation on Martian slopes. Icarus, 211, 238-258, doi:10.1016/j.icarus.2010.10.008.

Gough, R. V., Chevrier, V. F., Baustian, K. J., Wise, M. E., Tolbert, M. A., 2011. Laboratory studies of perchlorate phase transitions: Support for metastable aqueous perchlorate solutions on Mars. Earth Planet. Sci. Lett., 312, 371-377, doi:10.1016/j.epsl.2011.10.026.

Hansen, C. J., Okubo, C., McEwen, A., Byrne, S., DeJong, E., Herkenhoff, K., Mellon, M., Russell, P., Thomas, N., 2007. HiRISE views of the sublimation of Mars' southern seasonal cap. 7th Int. Conf. Mars, abstract #3364.

Hansen, C. J., Thomas, N., Portyankina, G., McEwen, A., Becker, T., Byrne, S., Herkenhoff, K., Kieffer, H., Mellon, M., 2010. HiRISE observations of gas sublimation-driven activity in Mars' southern polar regions: I. Erosion of the surface. Icarus, 205, 283-295, doi:10.1016/j.icarus.2009.07.021.

Hansen, C. J., Diniega, S., Bridges, N., Byrne, S., Dundas, C., McEwen, A., Portyankina, G., 2015. Agents of change on Mars' northern dunes: CO_2 ice and wind. Icarus, 251, 264-274, doi:10.1016/j.icarus.2014.11.015.

Harrison, T.N., 2016. Martian gully formation and evolution: Studies from the local to global scale. Ph.D. Dissertation, Western University.

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. AGU Fall Meeting, abstract #P43D-1454.

Harrison, T. N., Osinski, G. R., Tornabene, L. L., Jones, E., 2015. Global documentation of gullies with the Mars Reconnaissance Orbiter Context Camera and implications for their formation. Icarus, 252, 236-254, doi:10.1016/j.icarus.2015.01.022.

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

Hartmann, W. K., Thorsteinsson, T., Sigurdsson, F., 2003. Martian hillside gullies and Icelandic analogs. Icarus, 162, 259-277, doi:10.1016/S0019-1035(02)00065-9.

Hayne, P. O., Paige, D. A., Heavens, N. G., and the Mars Climate Sounder Science Team, 2014. The role of snowfall in forming the seasonal ice caps of Mars: Models and constraints from the Mars Climate Sounder. Icarus, 231, 122-130, doi:10.1016/j.icarus.2013.10.020.

Hecht, M.H., 2002. Metastability of liquid water on Mars. Icarus, 156, 373-386, doi:10.1006/icar.2001.6794.

Heldmann, J. L., Mellon, M. T., 2004. Observations of Martian gullies and constraints on potential formation mechanisms. Icarus, 168, 285-304, doi: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, doi:10.1016/j.icarus.2006.12.010.

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

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

Ingersoll, A., 1970. Mars: Occurrence of liquid water. Science, 168, 972-973, doi:10.1126/science.168.3934.972.

Ishii, T., Sasaki, S., 2004. Formation of recent Martian gullies by avalanches of CO_2 Frost. Lunar Planet. Sci. Conf. 35, abstract #1556.

Ishii, T., Miyamoto, H., Sasaki, S., Tajika, E., 2006. Constraints on the formation of gullies on Mars: A possibility of the formation of gullies by avalanches of granular CO_2 ice particles. Lunar Planet. Sci. Conf. 37, abstract #1646.

Iverson, R. M., 1997. The physics of debris flows. Rev. Geophys., 35, 245-296, doi:10.1029/97RG00426.

Johnsson, A., Reiss, D., Hauber, E., Hiesinger, H., Zanetti, M., 2014. Evidence for very recent melt-water and debris flow activity in gullies in a young mid-latitude crater on Mars. Icarus, 235, 37-54, doi:10.1016/j.icarus.2014.03.005.

Kieffer, H. H., 2000. Annual punctuated CO_2 slab-ice and jets on Mars. Mars Polar Sci. Conf., abstract #4095.

Kieffer, H. H., 2007. Cold jets in the Martian polar caps. J. Geophys. Res., 112, E08005, doi:10.1029/2006JE002816.

Knauth, L. P., Burt, D. M., 2002. Eutectic brines on Mars: Origin and possible relation to young surface features. Icarus, 158, 267-271, doi:10.1006/icar.2002.6866.

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, doi:10.1016/j.epsl.2009.05.018.

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, doi: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, doi: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, doi:10.1016/j.icarus.2004.05.018.

Kumar, P. S., Keerthi, V., Kumar, A. S., Mustard, J., Krishna, B. G., Amitabh, Ostrach, L. R., Kring, D. A., Kumar, A. S. K., Goswami, J. N., 2013. Gullies and landslides on the Moon: Evidence for dry-granular flows. J. Geophys. Res., 118, doi:10.1002/jgre.20043.

Lammer, H., Chassefiére, E., Karatekin, O., Morschhauser, A., Niles, P. B., Mousis, O., Odert, P., Möstl, U. V., Breuer, D., Dehant, V., Grott, M., Gröller, H., Hauber, E., Pham, L. B. S., 2013. Outgassing history and escape of the Martian atmosphere and water inventory. Space Sci. Rev., 174, 113-154, doi:10.1007/s11214-012-9943-8.

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, doi:10.1016/j.icarus.2009.04.014.

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, doi:10.1016/j.icarus.2004.04.005.

Lee, P., Cockell, C. S., Marinova, M. M., McKay, C. P., Rice, J. W., 2001. Snow and ice melt flow features on Devon Island, Nunavut, Arctic Canada as possible analogs for recent slope flow features on Mars. Lunar Planet. Sci. Conf. 32, abstract #1809.

Leighton, R. B., Murray, B. C., 1966. Behavior of carbon dioxide and other volatiles on Mars. Science, 153, 136-144, doi:10.1126/science.153.3732.136.

Levrard, B., Forget, F., Montmessin, F., Laskar, J., 2004. Recent ice-rich deposits formed at high latitudes on Mars by sublimation of unstable equatorial ice during low obliquity. Nature, 431, 1072-1075, doi:10.1038/nature03055.

Levrard, B., Forget, F., Montmessin, F., Laskar, J., 2007. Recent formation and evolution of northern Martian polar layered deposits as inferred from a Global Climate Model. J. Geophys. Res., 112, E06012, doi:10.1029/2006JE002772.

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, doi:10.1016/j.epsl.2009.08.002.

Madeleine, J.-B., Forget, F., Head, J. W., Levrard, B., Montmessin, F., Millour, E., 2009. Amazonian northern mid-latitude glaciation on Mars: A proposed climate scenario. Icarus, 203, 390-405, doi:10.1016/j.icarus.2009.04.037.

Madeleine, J.-B., Head, J. W., Forget, F., Navarro, T., Millour, E., Spiga, A., Colaïtis, A., Määttänen, A., Montmessin, F., Dickson, J. L., 2014. Recent Ice Ages on Mars: The role of radiatively active clouds and cloud microphysics. Geophys. Res. Lett., 41, 4873-4879, doi:10.1002/2014GL059861.

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

Malin, M. C., Edgett, K. S., 2005. 8 years at Mars #1: New dune gullies, Malin Space Science Systems captioned image release, MOC2-1220, NASA/JPL Planetary Photojournal, http://photojournal.jpl.nasa.gov/, catalog number PIA04290.

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, doi:10.1126/science.1135156.

Mangold, N., Costard, F., 2003. Debris flows over sand dunes on Mars: Evidence for liquid water. J. Geophys. Res., 108, 5027, doi: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., Mangeney, A., Migeon, V., Ansan, V., Lucas, A., Baratoux, D., Bouchut, F., 2010. Sinuous gullies on Mars: Frequency, distribution, and implications for flow properties. J. Geophys. Res., 115, E11001, doi:10.1029/2009JE003540.

Massé, M., Conway, S. J., Gargani, J., Patel, M. R., Pasquon, K., McEwen, A., Carpy, S., Chevrier, V., Balme, M. R., Ojha, L., Vincendon, M., Poulet, F., Costard, F., Jouannic, G., 2016. Transport processes induced by metastable boiling water under Martian surface conditions. Nature Geosci., 9, 425-428, doi:10.1038/NGEO2706.

McEwen, A.S., Eliason, E.M., Bergstrom, J.W., Bridges, N.T., Hansen, C.J., Delamere, W.A., Grant, J.A., Gulick, V.C., Herkenhoff, K.E., Keszthelyi, L., Kirk, R.L., Mellon, M.T., Squyres, S.W., Thomas, N., Weitz, C.M., 2007a. Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). J. Geophys. Res., 112, E05S02, doi:10.1029/2005JE002605.

McEwen, A. S., Ojha, L., Dundas, C. M., Mattson, S. S., Byrne, S., Wray, J. J., Cull, S. C., Murchie, S. L., Thomas, N., Gulick, V. C., 2011. Seasonal flows on warm Martian slopes. Science, 333, 740-743, doi:10.1126/science.1204816.

McEwen, A. S., Dundas, C. M., Mattson, S. S., Toigo, A. D., Ojha, L., Wray, J. J., Chojnacki, M., Byrne, S., Murchie, S. L., Thomas, N., 2014. Recurring slope lineae in equatorial regions of Mars. Nat. Geosci., 7, 53-58, doi:10.1038/ngeo2014.

McEwen, A. S., Dundas, C. M., Chojnacki, M., Massé, M., 2016. Small Martian gullies associated with Recurring Slope Lineae. Unnumbered abstract presented at the Workshop on Martian Gullies and their Earth Analogs, June 20, 2016, London, UK.

Mellon, M. T., Jakosky, B. A., 1995. The distribution and behavior of Martian ground ice during past and present epochs. J. Geophys. Res., 100, 11781-11799, doi:10.1029/95JE01027.

Mellon, M.T., Phillips, R.J., 2001. Recent gullies on Mars and the source of liquid water. J. Geophys. Res., 106, 23,165-23,180, doi:10.1029/2000JE001424.

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, doi:10.1016/j.icarus.2010.02.019.

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, doi:10.1029/2000GL012496.

Neuendorf, K.K.E., Mehl, J.P., Jackson, J.A. (eds.), 2005. Glossary of Geology, 5th Edition, American Geological Institute, 779 pp.

Núñez, J. I., Barnouin, O. S., Murchie, S. L., Seelos, F. P., McGovern, J. A., Seelos, K. D., Buczkowski, D. L., 2016. New insights into gully formation on Mars: Constraints from composition as seen by MRO/CRISM. Geophys. Res. Lett., 43, 8893-8902, doi:10.1002/2016GL068956

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, doi:10.1016/j.icarus.2010.09.025.

Parker, T. J., Golombek, M. P., Lamb, M., Palucis, M. C., Athena Science Team, 2017. An opportunity to inspect a Martian gully up close. Lunar Planet. Sci. Conf. 48, abstract #2468.

Pasquon, K., Gargani, J., Massé, M., Conway, S. J., 2016. Present-day formation and seasonal evolution of linear dune gullies on Mars. Icarus, 274, 195-210, doi:10.1016/j.icarus.2016.03.024.

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

Phillips, R.J., Davis, B.J., Tanaka, K.L., Byrne, S., Mellon, M.T., Putzig, N.E., Haberle, R.M., Kahre, M.A., Campbell, B.C., Carter, L.M., Smith, I.B., Holt, J.W., Smrekar, S.E., Nunes, D.C., Plaut, J.J., Egan, A.F., Titus, T.N., Seu, R., 2011. Massive CO_2 ice deposits sequestered in the South Polar Layered Deposits of Mars. Science, 332, 838-841, doi:10.1126/science.1203091.

Pilorget, C., Forget, F., 2016. Formation of gullies on Mars by debris flows triggered by CO_2 sublimation. Nature Geosci., 9, 65-69, doi:10.1038/ngeo2619.

Piqueux, S., Byrne, S., Richardson, M. I., 2003. Sublimation of Mars's southern seasonal CO_2 ice cap and the formation of spiders. J. Geophys. Res., 108, doi:10.1029/2002JE002007.

Piqueux, S., Kleinböhl, A., Hayne, P. O., Kass, D. M., Schofield, J. T., McCleese, D. J., 2015. Variability of the Martian seasonal CO_2 cap extent over eight Mars Years. Icarus, 251, 164-180, doi:10.1016/j.icarus.2014.10.045.

Piqueux, S., Kleinböhl, A., Hayne, P. O., Heavens, N. G., Kass, D. M., McCleese, D. J., Schofield, J. T., Shirley, J. H., 2016. Discovery of a widespread low-latitude diurnal CO_2 frost cycle on Mars. J. Geophys. Res. Planets, 121, doi:10.1002/2016JE005034.

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, doi:10.1016/j.icarus.2012.02.025.

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, doi:10.1016/j.icarus.2014.03.040.

Reiss, D., Jaumann, R., 2003. Recent debris flows on Mars: Seasonal observations of the Russell Crater dune field. Geophys. Res. Lett., 30, doi:10.1029/2002GL016704.

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, doi:10.1029/2004JE002251.

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, doi:10.1029/2009GL042192.

Richardson, M. I., Mischna, M. A., 2005. Long-term evolution of transient liquid water on Mars. J. Geophys. Res., 110, E03003, doi:10.1029/2004JE002367.

Rummel, J. D., and 24 coauthors, 2014. A new analysis of Mars "Special Regions": Findings of the Second MEPAG Special Regions Science Analysis Group (SR-SAG2). Astrobiology, 14, 887-968, doi:10.1089/ast.2014.1227.

Schon, S. C., Head, J. W., 2009. Terraced cutbanks and longitudinal bars in gully channels on Mars: Evidence for multiple episodes of fluvial transport. Lunar Planet. Sci. Conf. 40, abstract #1691.

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, doi: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, doi:10.1016/j.icarus.2012.01.002.

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, doi:10.1130/G25398A.1.

Schorghofer, N., Edgett, K.S., 2006. Seasonal surface frost at low latitudes on Mars. Icarus, 180, 321-334, doi:10.1016/j.icarus.2005.08.022.

Schorghofer, N., Forget, F., 2012. History and anatomy of subsurface ice on Mars. Icarus, 220, 1112-1120, doi:10.1016/j.icarus.2012.07.003.

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. Nat. Acad. Sci., 101, 8542-8546, doi:10.1073/pnas.0308251101.

Sylvest, M. S., Conway, S. J., Patel, M. R., Dixon, J. C., Barnes, A., 2016. Mass wasting triggered by seasonal CO_2 sublimation under Martian atmospheric conditions: Laboratory experiments. Geophys. Res. Lett., 43, 12,363-12,370, doi:10.1002/2016GL071022.

Thomas, N., Hansen, C. J., Portyankina, G., Russell, P. S., 2010. HiRISE observations of gas sublimation-driven activity in Mars' southern polar regions: II. Surficial deposits and their origins. Icarus, 205, 296-310, doi:10.1016/j.icarus.2009.05.030.

Treiman, A.H., 2003. Geologic settings of Martian gullies: Implications for their origins. J. Geophys. Res., 108, 8031-8042, doi:10.1029/2002JE001900.

Turnbull, B., Bowman, E. T., McElwaine, J. N., 2015. Debris flows: Experiments and modelling. Comp. Rend. Phys., 16, 86-96.

Vincendon, M., 2015. Identification of Mars gully activity types associated with ice composition. J. Geophys. Res. Planets, 120, doi:10.1002/2015JE004909.

Vincendon, M., Forget, F., Mustard, J., 2010a. Water ice at low to midlatitudes on Mars. J. Geophys. Res., 115, E10001, doi:10.1029/2010JE003584.

Vincendon, M., Mustard, J., Forget, F., Kreslavsky, M., Spiga, A., Murchie, S., Bibring, J.-P., 2010b. Near-tropical subsurface ice on Mars. Geophys. Res. Lett., 37, L01202, doi:10.1029/2009GL041426.

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, doi:10.1026/j.icarus.2008.12.013.

Wordsworth, R. D., 2016. The climate of early Mars. Annu. Rev. Earth Planet. Sci., 44, 381-408, doi:10.1146/annurev-earth-060115-012355.

Zurek, R.W., Smrekar, S.E., 2007. An overview of the Mars Reconnaissance Orbiter (MRO) science mission. J. Geophys. Res., 112, E05S01, doi:10.1029/2006JE002701.

Tables

Table 1. Comparison of Gully Observations and Dry Frost Model

Observation	Frost Model Interpretation
Widespread gully activity, consistent with all fresh gullies being active on timescales of centuries.	Key observation supporting frost model.
Current activity associated with seasonal frost, primarily CO_2.	Key observation supporting frost model.
Diverse aqueous-like (fluviatile or debris flow-like) morphologies in gullies.	Observed to form by current processes (see main text for further discussion).
Gullies concentrated in mid-latitudes, occasionally high latitude, and are relatively uncommon in Hellas basin and northern plains.*	Distribution represents overlap of frost abundance (minimal near equator) and topographic roughness/steep slopes (rare at high latitude and on plains).
Mid-latitude gullies face the pole.*	Consistent with observed frost distribution.
High-latitude gullies face equator or have no preference.*	Consistent with observed frost distribution.
Equatorial gullies exist, but are less developed (McEwen et al., 2016).	Due to minor frost and/or RSL; should show minimal fluidization beyond typical dry mass movements.
Gullies initiate on steep slopes.*	Steep slopes are less stable, more easily eroded; may also be required to permit frost accumulation at lower latitudes.
Gullies found at a wide range of elevations.*	CO_2 frost found at all elevations; frost point varies < 10 K over typical gully elevations.
Gullies found on sand dunes and isolated peaks.*	Consistent with frost deposited from atmosphere.
Gullies associated with low dust cover, low albedo, intermediate grain size at coarse scales (Harrison et al., 2015).	May be proxy for other favorable conditions; thermophysical classes correlate with latitude.
Gullies are not routinely associated with hydrated minerals (Núñez et al., 2016).	Consistent with no frequent or long-lived water-rock interactions.
Apparent reduction in gully fluidization in recent events (Kolb et al., 2010b).	Frost process intensity varies over time; alternatively, may represent local effects at the small number of sites.
Episodic formation by many events, with channel abandonment (Dickson and Head, 2009).	Current activity is the most recent generation of ongoing formative events. Channel abandonment observed.
Age ≤ ~1 Ma (e.g., Reiss et al., 2004; Schon et al., 2009; Raack et al., 2012).	Consistent with ongoing formation. Most gullies are un-cratered.
Northern hemisphere gullies appear more degraded/eroded than those in the south (Heldmann et al., 2007).	Lower current activity rate in northern gullies, due to occurrence of perihelion in northern fall.
Buried and/or inactive gullies exist (e.g.,	Due to variations in the distribution of

Morgan et al., 2010; Raack et al., 2012; Dickson et al., 2015a).	seasonal frost processes over time (cf. Pilorget and Forget, 2016).
Gullies commonly incised into mid-latitude mantle (e.g., Christensen, 2003).	Mantle readily eroded by frost processes when not ice-cemented. Bedrock is more resistant to erosion and mobilization.
Occasional association with bedrock layers (e.g., Malin and Edgett, 2000; Gilmore and Phillips, 2002).	Consistent with erosion of material up to resistant layers.
Gully fan outcrops expose boulders (de Haas et al., 2015c).	Current processes observed to transport and bury boulders within channels and on fans.
Small lunar mass-wasting features resemble poorly developed gullies with straight channels (Bart, 2007; Kumar et al., 2013).	Demonstrates that simple forms can develop with no volatile; larger, well-developed features require frost processes.

*Major surveys of the distribution and properties of gullies include Malin and Edgett (2000), Heldmann and Mellon (2004), Heldmann et al. (2007), Balme et al. (2006), Bridges and Lackner (2006), Dickson et al. (2007), Dickson and Head (2009), Kneissl et al. (2010), and Harrison et al. (2015).

Figure Captions

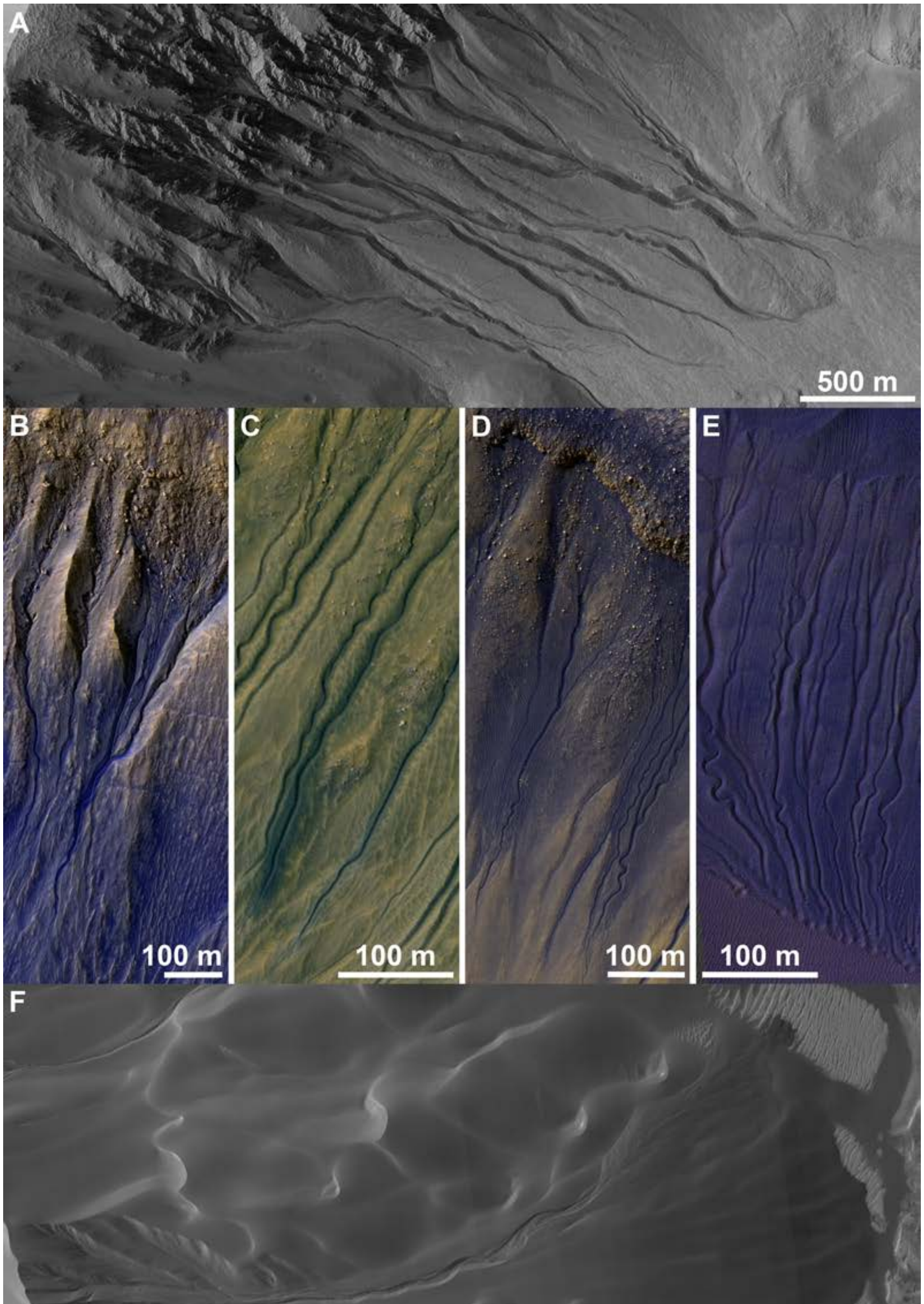


Figure 1. Examples of gully morphologies. A) Examples of classic alcove-channel-apron gullies cut into the wall of Triolet crater (37.1°S, 191.9°E). B–E show a gradation from

classic crater-wall gullies towards linear dune gullies. B) Alcove-channel-apron gullies cut into mid-latitude mantle material, but with minor sand coloration/infill. C) Gullies with distinct channels but minor alcoves and depositional aprons, cut into a substrate with some large ripples but without the coloration of sand. D) Gullies in crater-wall material that appears to be a mix of sand and other material. E) Linear dune gullies (channels with minimal alcoves or deposits, and common terminal pits) in sand, including sinuous examples. F) Large dune gully in Matara crater (49.5°S, 34.9°E) with classic alcove-channel-apron morphology. (A: HiRISE image PSP_003583_1425. B: ESP_046309_1425. C: ESP_040402_1410. D: ESP_024344_1325. E: ESP_029701_1295. F: ESP_038387_1300. Downhill is to the right in A and F and to the bottom in B–E. All image figures herein are sub-frames of HiRISE images (credit: NASA/JPL/University of Arizona) with north up and light from the left, and have been stretched to maximize local contrast. All original data are available via the Planetary Data System.)

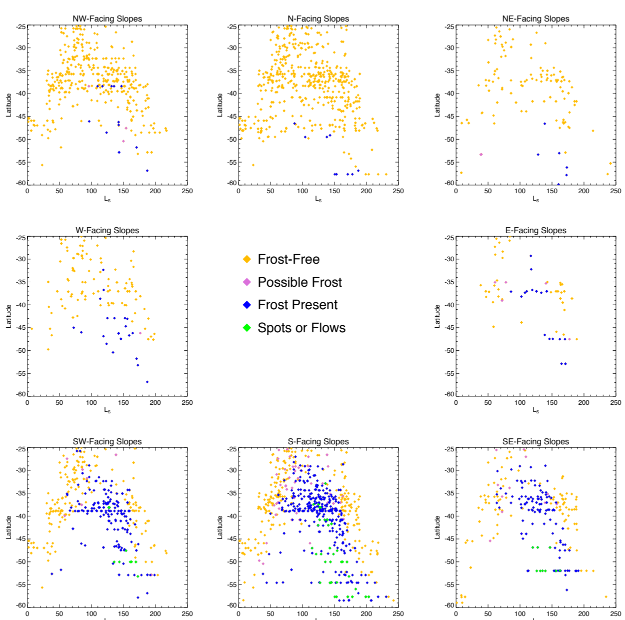


Figure 2. Seasonal frost (outside gully alcoves) in the southern hemisphere, as a function of season and slope orientation.

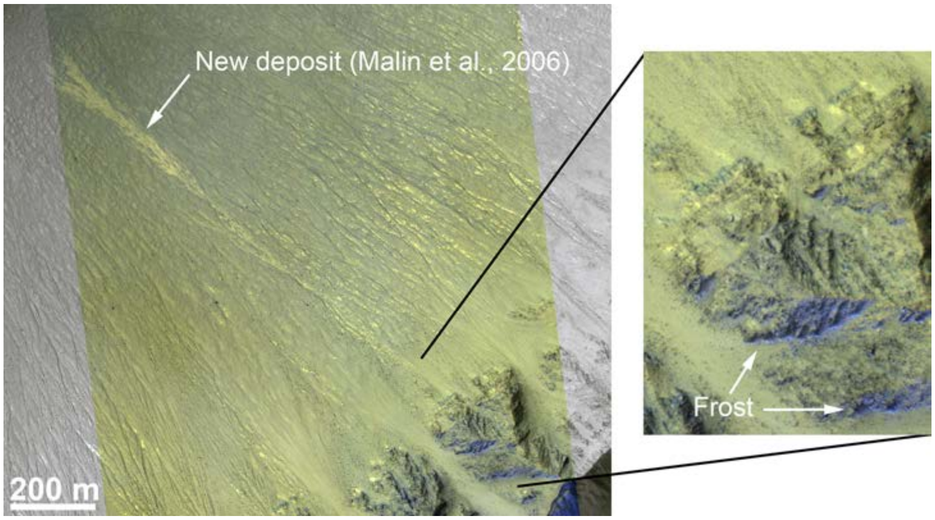


Figure 3. One of the few equator-facing mid-latitude gully flows correlates with an unusual small patch of frost. Local frost (blue-tinted material) occurred in hollows on a broadly equator-facing slope uphill (lower right) from a new gully deposit in Penticton crater (38.4°S, 96.8°E) at L_S=132°. (HiRISE image ESP_036578_1415.)

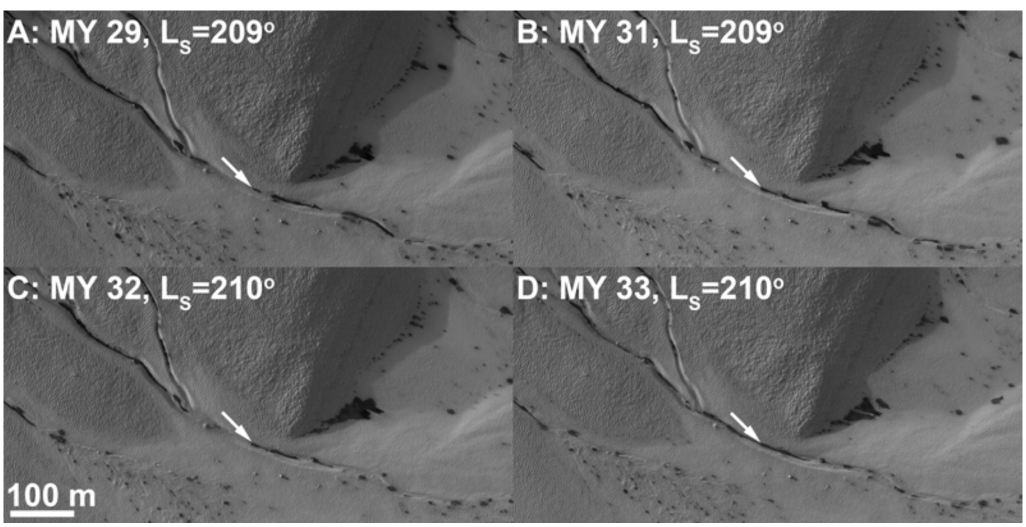


Figure 4. Example of defrosting flows in a polar pit gully (68.5°S, 1.3°E). Flows concentrate in channels, gradually advance, and approximately repeat from year to year. The flows are dark in contrast with the widespread frost and leave no resolvable sign in

albedo or topography once the frost is gone. Arrows indicate the source point of a flow for comparison between years. In (D), the flow is being overtaken by another flow initiating higher in the channel. (A: HiRISE image ESP_011963_1115. B: ESP_029580_1115. C: ESP_038428_1115. D: ESP_047250_1115. Downhill is to the lower right.)

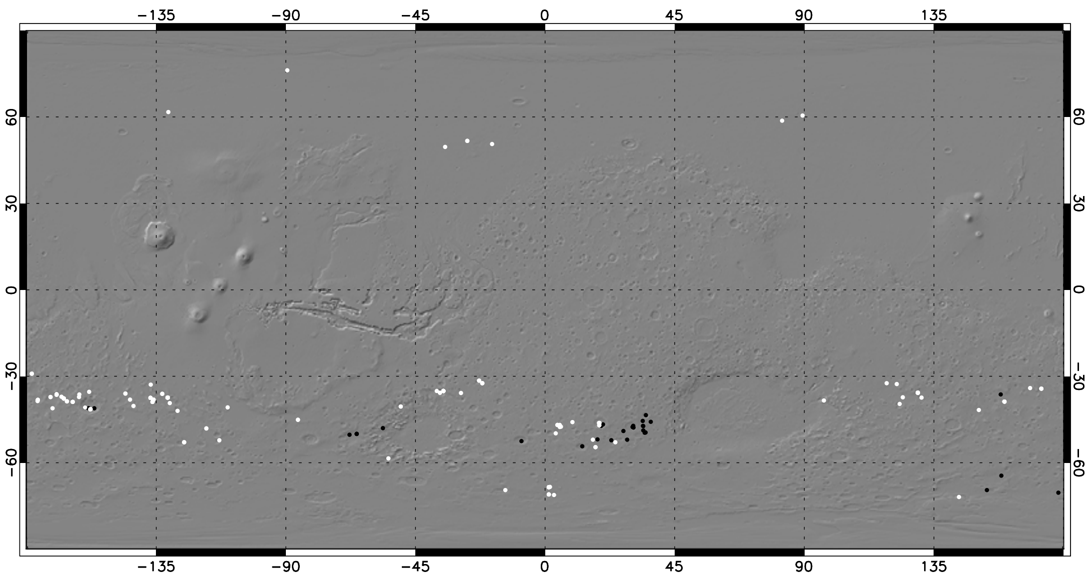


Figure 5. Map of observed active gullies (white symbols) and active dune or sandy-slope gullies (black). North polar dune alcoves (Hansen et al. 2015) and similar minor alcoves on other dunes are not included here.

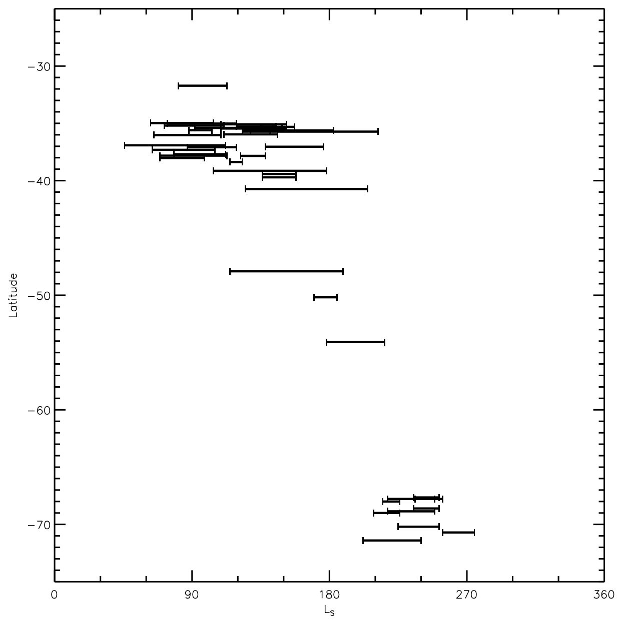


Figure 6. Timing of well-constrained gully changes in the southern hemisphere as a function of latitude. Only changes constrained to an interval <90° of L_S are shown. (Note that this is not quite a constant unit of time due to Mars' elliptical orbit.) Lines are offset in latitude by small amounts in order to separate overlapping intervals.

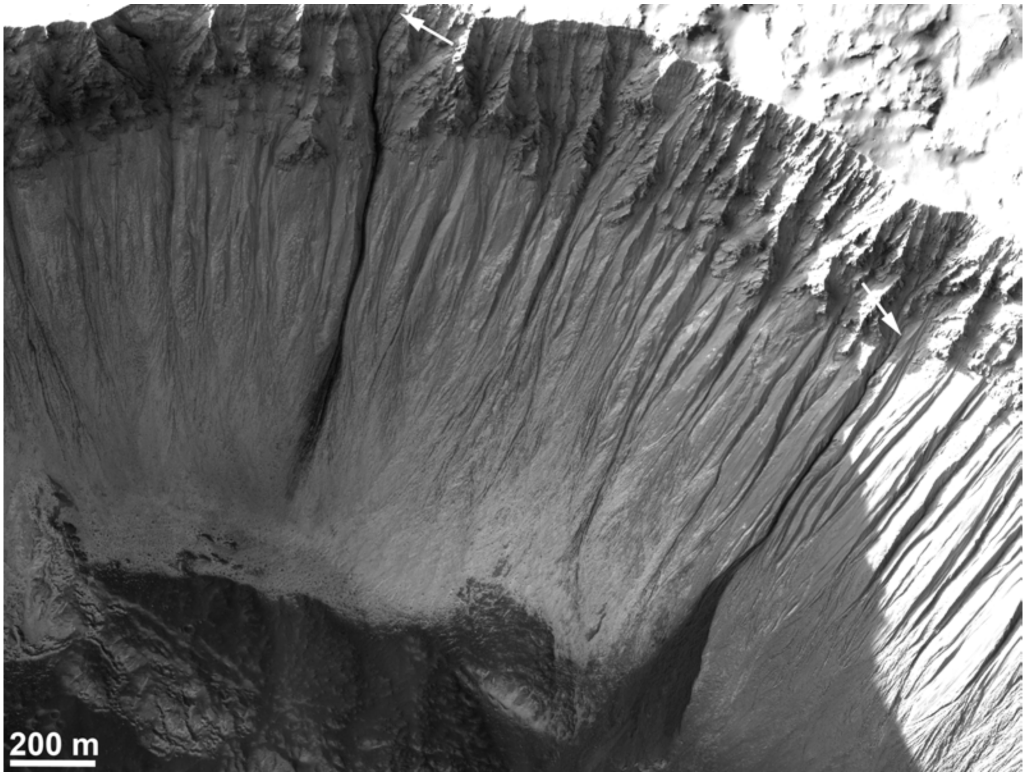


Figure 7. Gully flows in Selevac crater (37.4°S, 228.9°E). The flows bury or disrupt seasonal frost, allowing the shape of the entire mass movement to be seen. They begin at point sources (arrows), descend along channels, and terminate in extensive deposits. The image is in shadow and has been stretched to show detail, saturating the illuminated areas; original data available via the Planetary Data System. (HiRISE image ESP_045158_1425.)

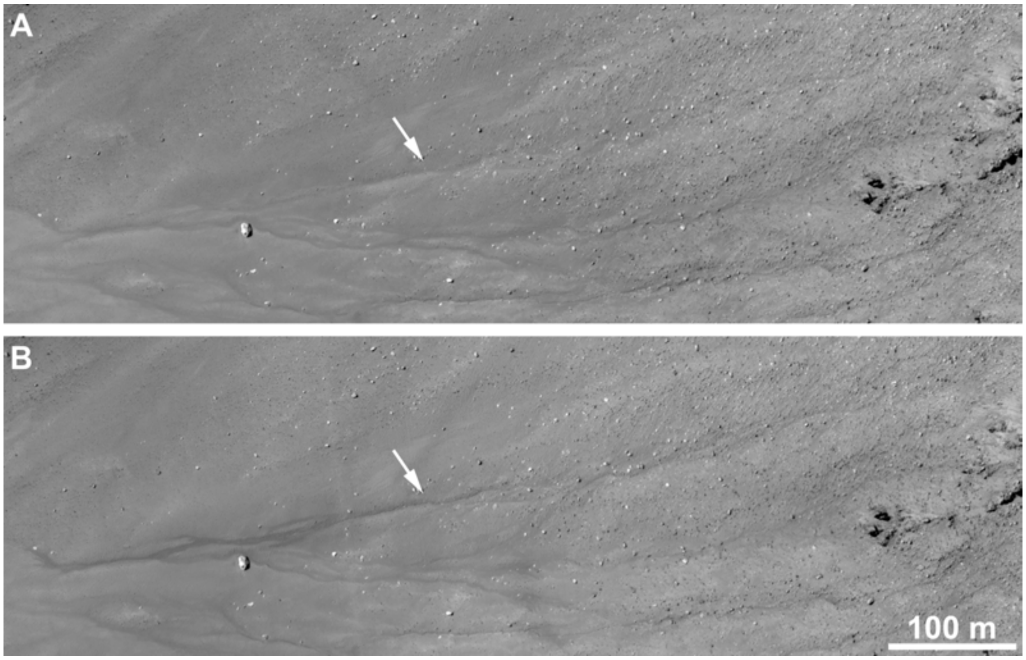


Figure 8. Activity in Raga crater (48.1°S, 242.4°E) showing gully formation. An ill-defined shallow trough or degraded gully seen in MY 29 (A) subsequently became active. Two flow events occurred, resulting in a much more sharply-defined channel system (B). (A: HiRISE image ESP_014011_1315. B: ESP_040239_1315. Downhill is to the left.)

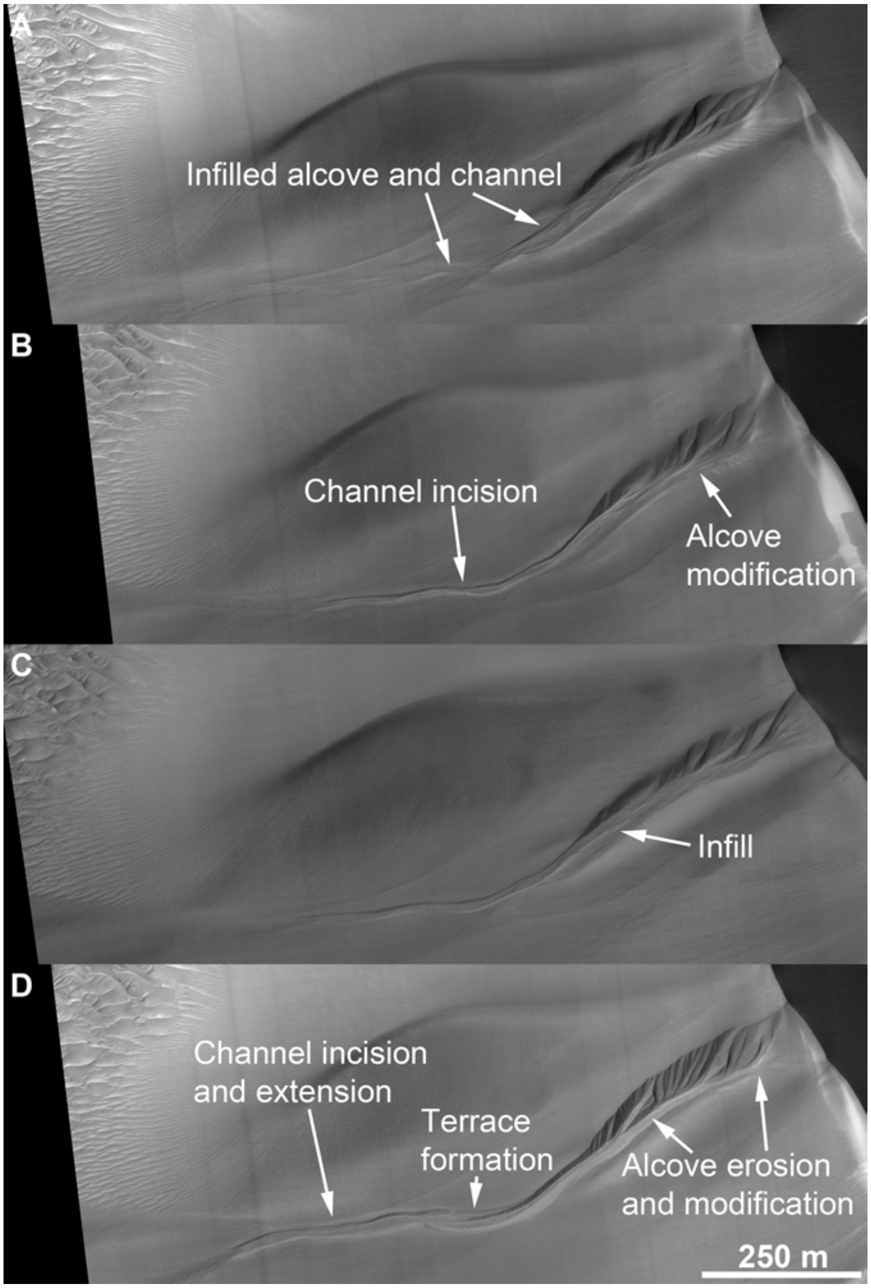


Figure 9. Major changes in a dune gully west of the Argyre basin (48°S, 303.7°E), progressing from a degraded alcove and obliterated apron (A) to a sharply defined system with a large, terraced channel (D). Panels B–C show incremental annual changes, which can each be dated to Martian winter. (A: HiRISE image ESP_023582_1315. B: ESP_030584_1315. C: ESP_038087_1315. D: ESP_047331_1315. Downhill is to the left.)

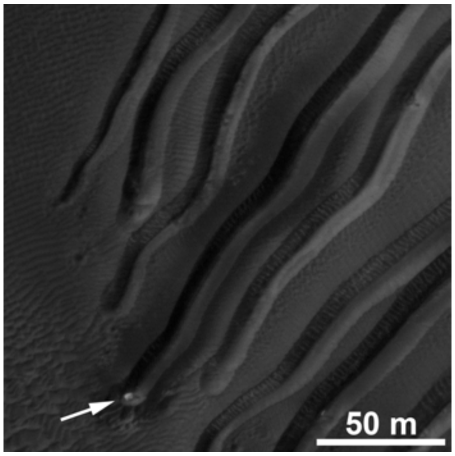


Figure 10. Ice slab and dark halo at the toe of a large linear dune gully in Russell crater (54.3°S, 12.9°E). The halo is interpreted to form via sand thrown out by the sliding ice block, maintaining and incising the channel (Diniega et al., 2013). (HiRISE image ESP_047078_1255. Downhill is to the lower left.)

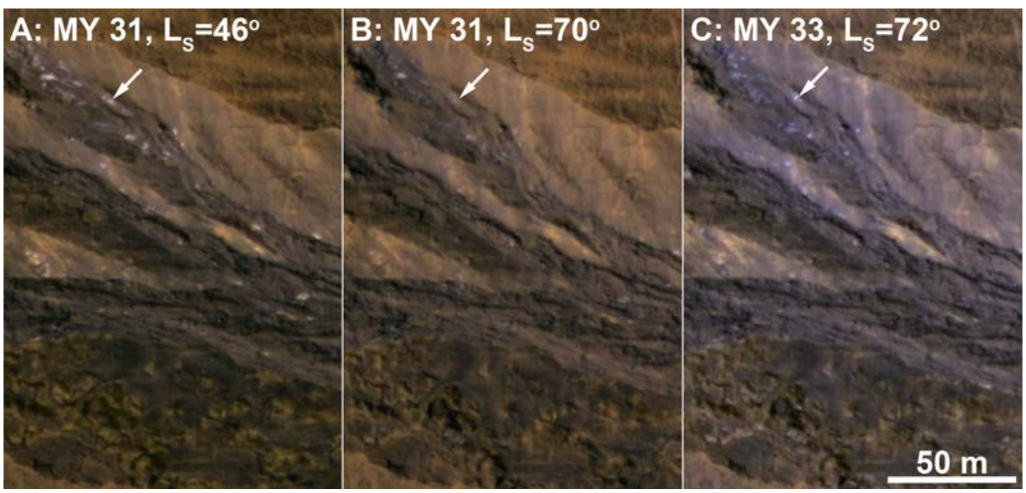


Figure 11. Likely ice exposure in mid-latitude mantle materials in a gully alcove (59.5°N, 302.2°E). Bright spots appeared prominent in mid-spring of MY 31 but faded over several months. They were again prominent, but with a different pattern, in MY 33. Arrow indicates an example of one of the spots. (A: HiRISE image ESP_025322_2400. B: ESP_026021_2400. C: ESP_043691_2400. Downhill is to the right.)

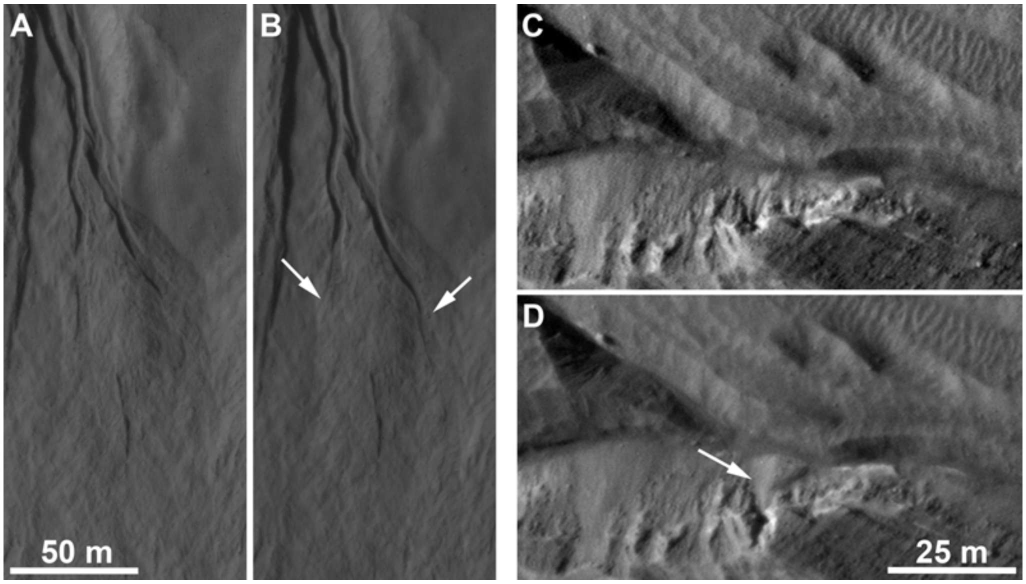


Figure 12. Examples of channel changes in gullies. A–B) A flow event in this gully in eastern Hale crater (35.1°S, 324.7°E) divided between two channels. The arrows indicate that in one (left), deposition obliterated part of the channel system, while in the other (right), the channel was extended. Distributed changes due to deposition occur throughout the bottom of the frames. C–D) A flow in Triolet crater (37.1°S, 191.9°E) disturbed material along the edge of the channel, causing a small hollow to collapse and form a small debris cone within the channel. (A: HiRISE image ESP_011819_1445. B: ESP_038218_1445. C: ESP_020751_1425. D: ESP_047190_1425. Downhill is to the bottom in A–B and to the right in C–D.)

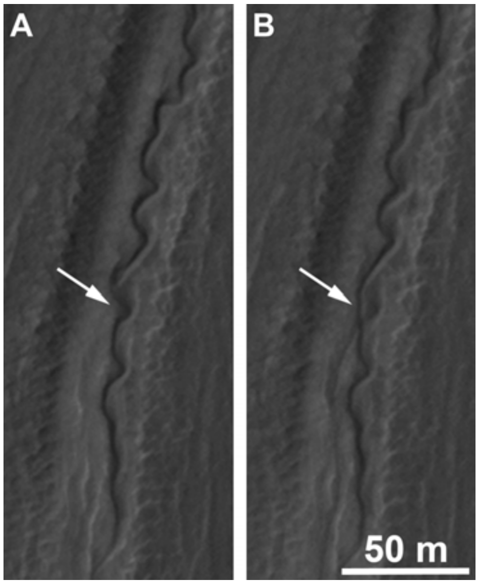


Figure 13. Cutoff of a sinuous curve (arrow) by a new incised segment in a gully channel within sandy fill in a crater-wall gully (38.9°S, 196°E). (A: HiRISE image ESP_029032_1410. B: ESP_046702_1410. Downhill is to the bottom.)

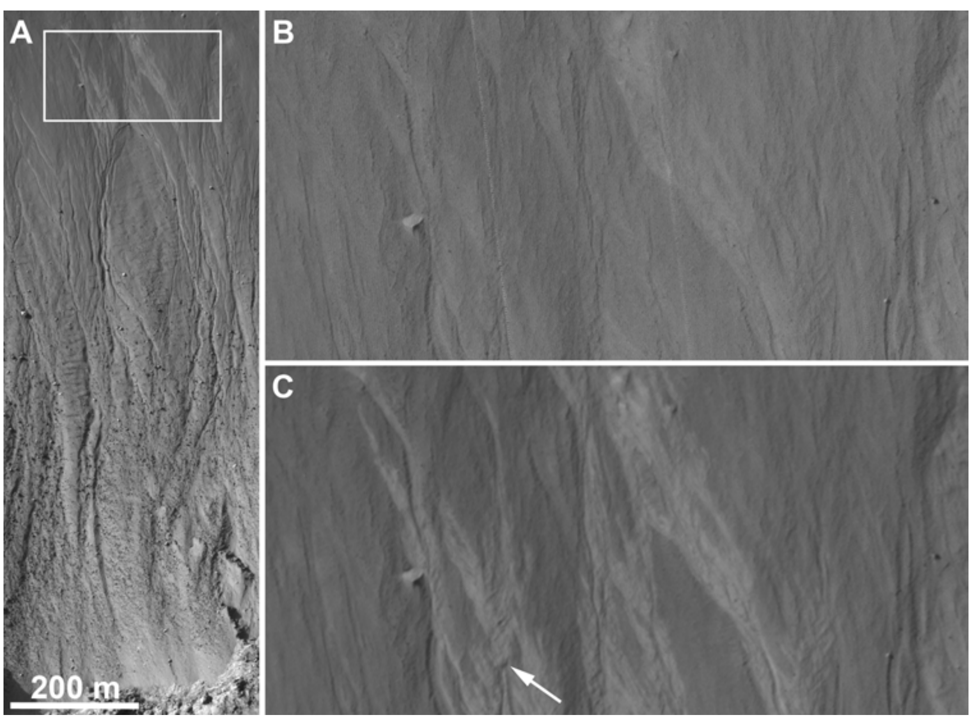


Figure 14. Example of branching flow producing activity in multiple channels, located in Asimov crater (46.8°S, 4.3°E). A) Overview of gully system, with complex channel

network. Box indicates location of panels B–C. B) “Before” image showing faint light material associated with some channels. C) “After” image with distinct bright deposits branching and occupying different channels, breaking out in some cases. Deposition producing a topographic change (arrow) demonstrates that this is real activity and not a photometric effect. (A, C: HiRISE image ESP_036977_1330. B: PSP_002179_1330. Downhill is to the top.)

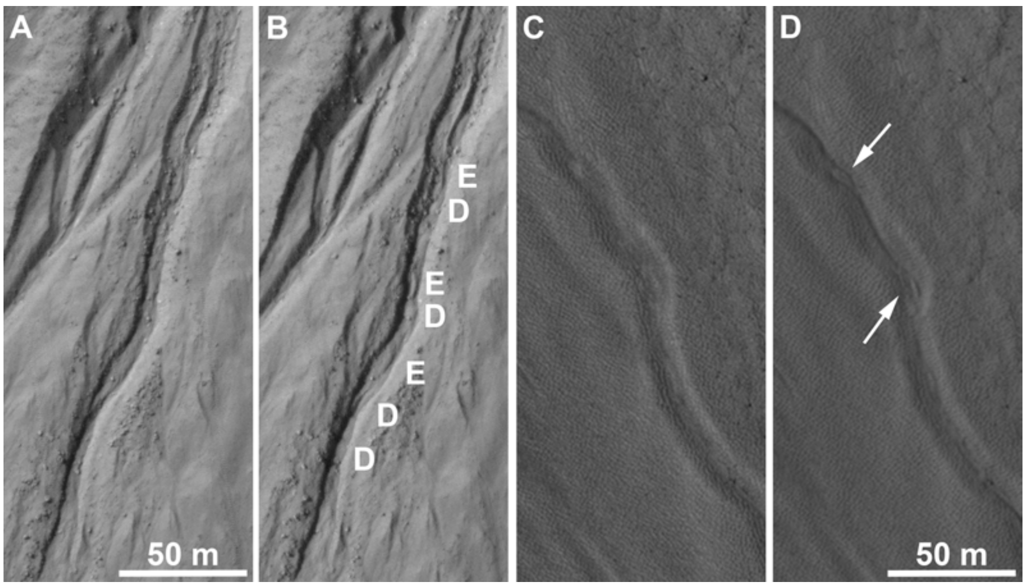


Figure 15. Examples of changes in channels. A–B) Alternating erosion and deposition (“E” and “D” annotations) produced by local conditions, resulting in small-scale bar-like landforms within the channel (38.1°S, 224°E). C–D) Incision within an older, larger channel (47.5°S, 5.5°E), resulting in formation or enhancement of an “island” (upper arrow) and a lobate bar-like feature (lower arrow). (A: HiRISE image ESP_023809_1415. B: ESP_047057_1415. C: ESP_013334_1320. D: ESP_047276_1320. Downhill is to the bottom in all panels.)

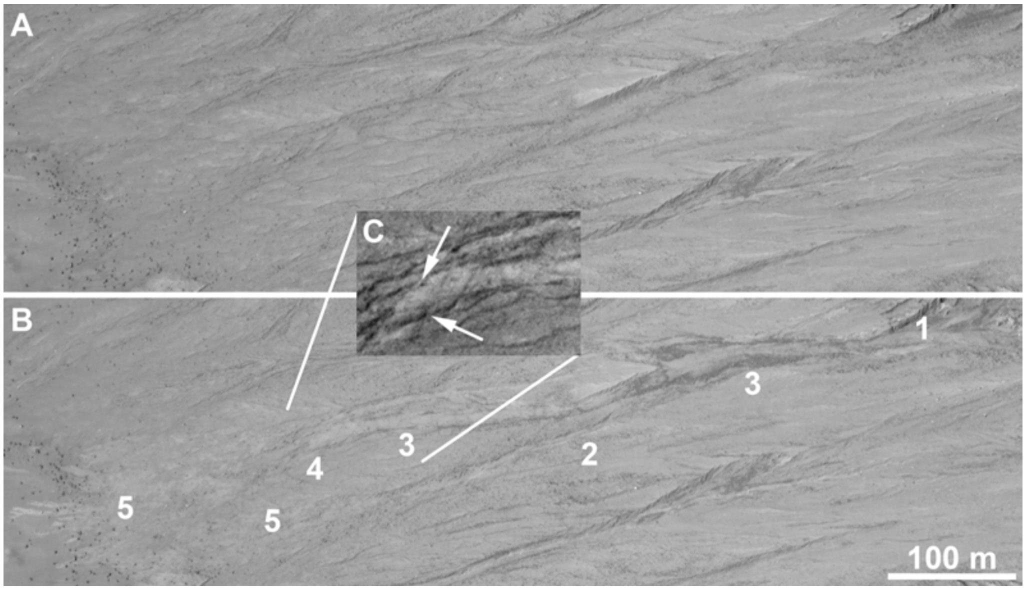


Figure 16. Changes within a gully system in Istok crater (45.1°S, 274.2°E), which either divided between two gullies or encompassed multiple events closely spaced in time. Numbers indicate source alcove (1), local scour of a channel segment (2), deposition of dark boulder-rich levees (3), formation of a lobate deposit snout (4), and distributed topographic changes (sufficient to move and/or bury rocks) (5). Note that the most distal deposits are small, relatively-bright toes, although the deposit mostly matches the tone of the upper slope and thus lacks contrast. Inset C) shows an enlarged view of the lobate snout (4) from a low-Sun image to emphasize topography with arrows indicating margins. (A: HiRISE image ESP_040251_1345. B: ESP_048255_1345. C: ESP_045842_1345. Downhill is to the left.)

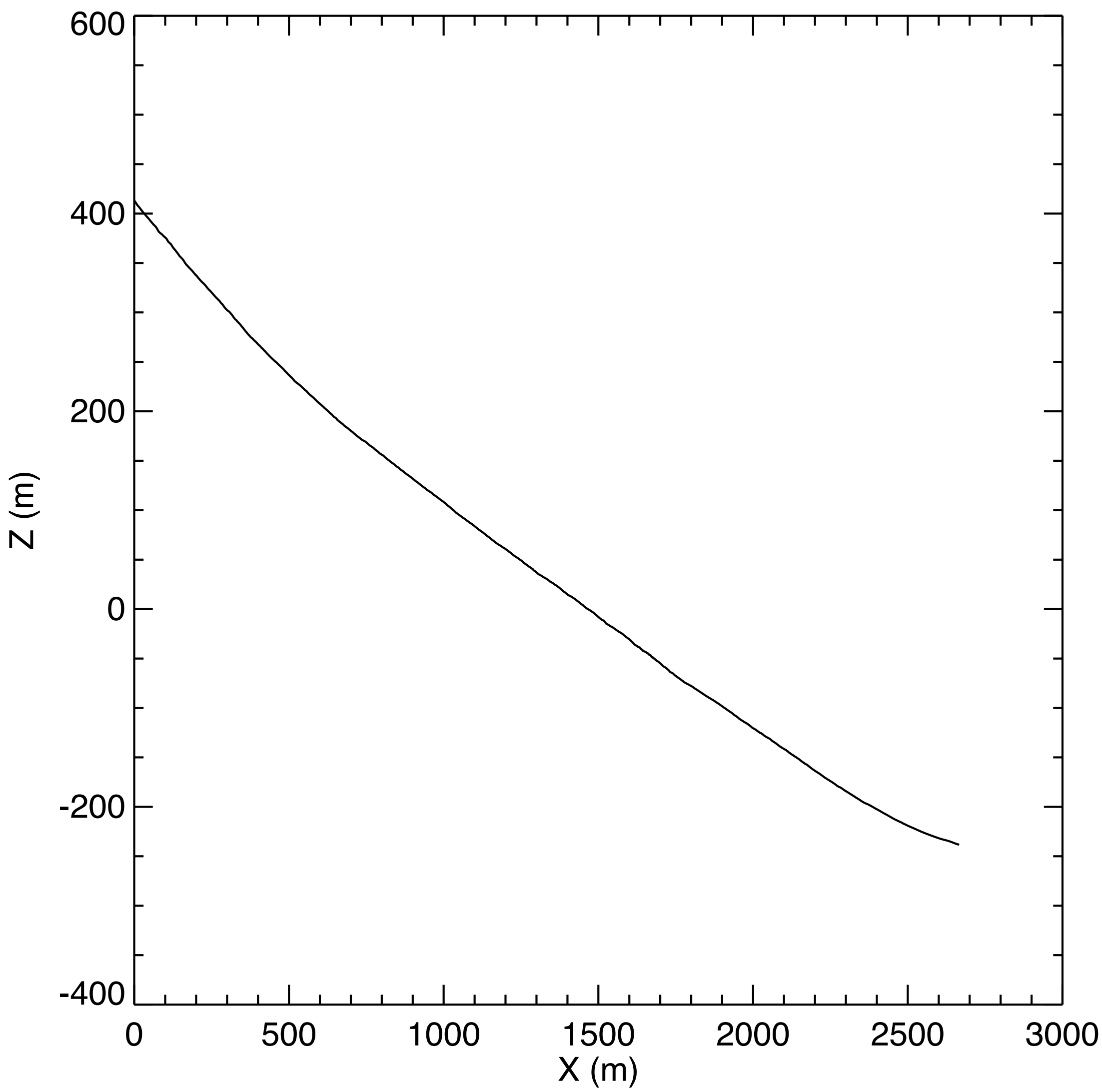


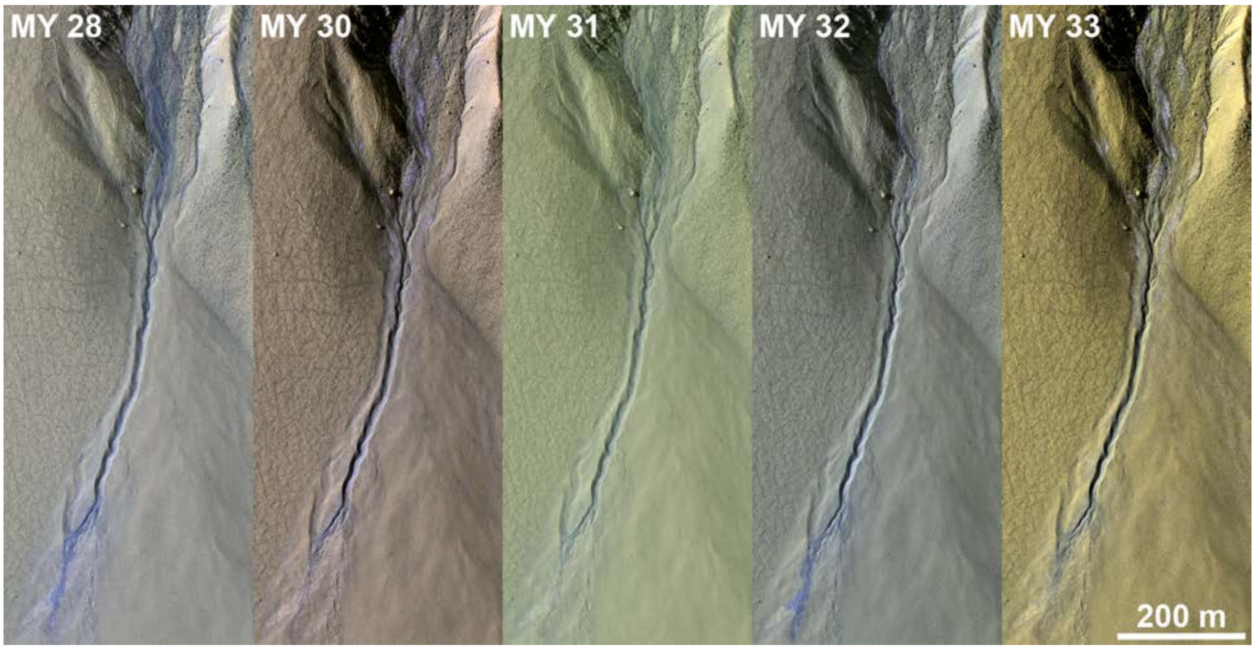
Figure 17. Longitudinal profile of the large alcove-channel-apron dune gully in Matara crater (Fig. 1f) derived from a HiRISE Digital Terrain Model (DTEEC_022115_1300_22392_1300_U01). Using definitions from Conway et al. (2015), this profile has concavity measures A_{ero}=0.14 (Mars gully range 0.02–0.77 from Conway et al. (2015), *Eq*=0.28 (Mars range 0.11–0.63), *CI*=0.07 (Mars range -0.16–0.3), and θ=-0.23 (Mars range -0.86–0.02). The slope is over 20° near the head of the gully

(and may be higher on alcove slopes above the thalweg) and below 10° near the flow termination.

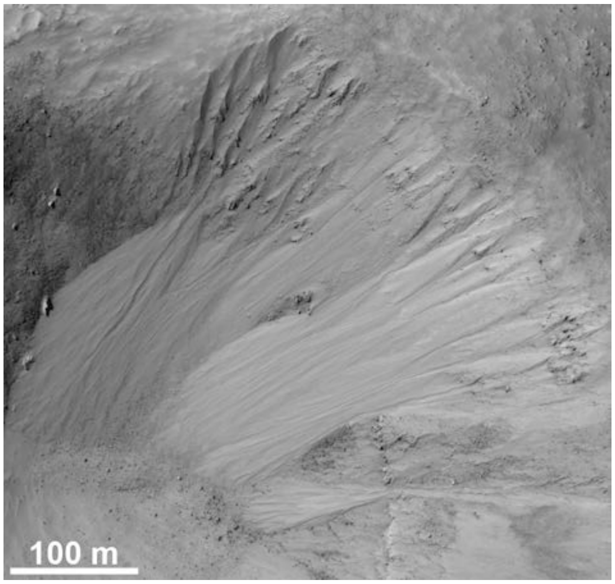
Supplementary Materials for "The Formation of Gullies on Mars Today"

The supplementary information for this report includes figures, animations, and a summary table describing details of known gully activity. Original HiRISE images are available via the Planetary Data System, including both raw spacecraft data and the Reduced Data Records used for these figures. Some images have been stretched to improve contrast.

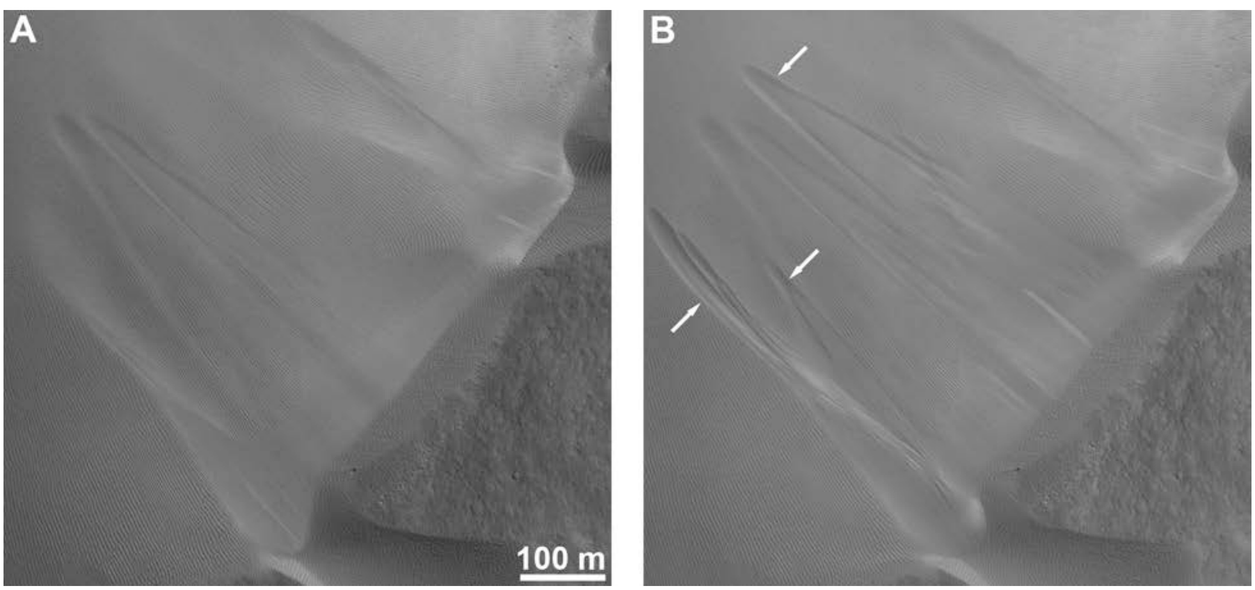
Supplementary Figures



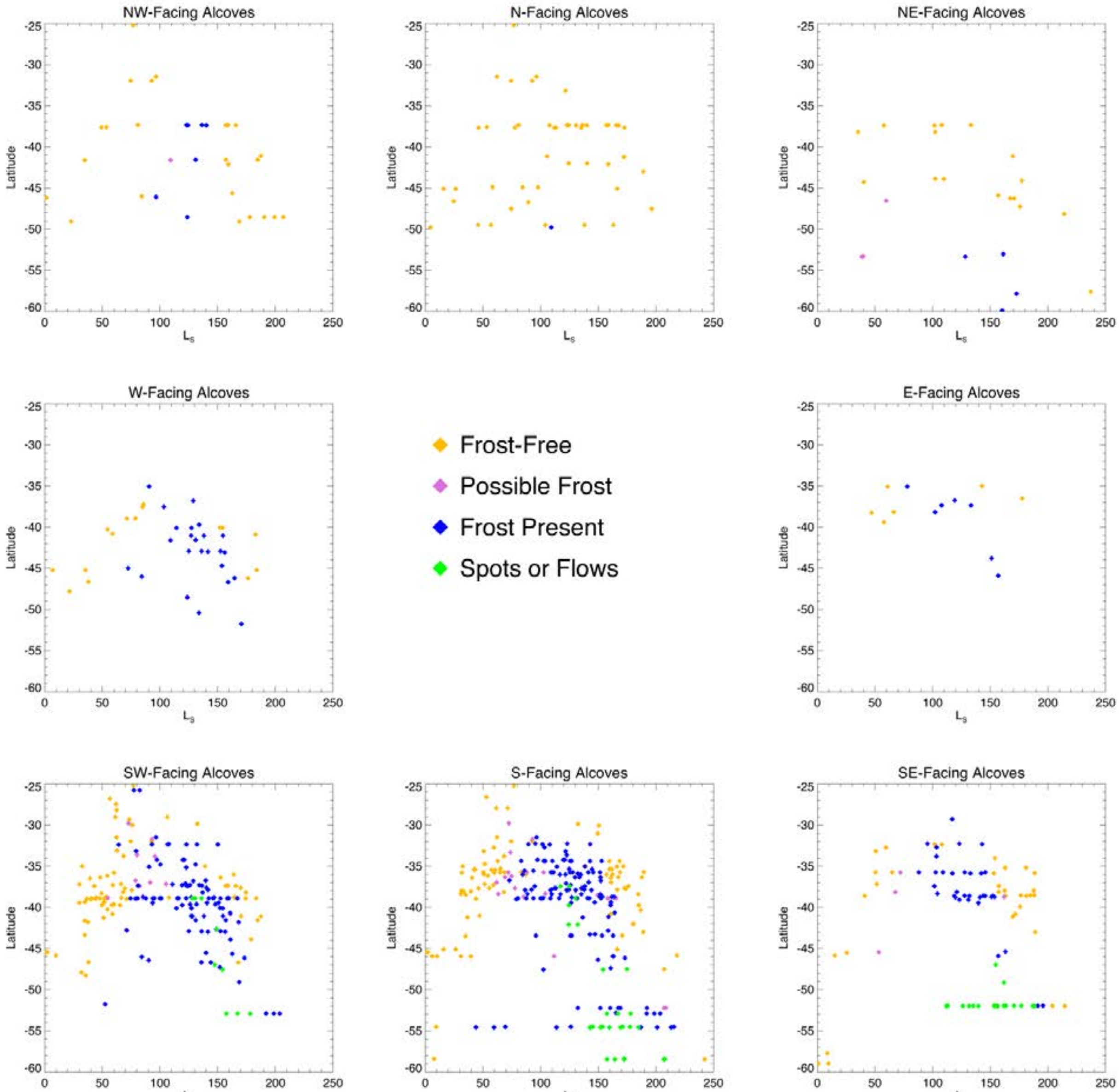
Supplementary Figure 1. Rapid changes in the appearance of deposits associated with a gully at 54.5°S. The deposit appeared fresh in MY 28, but was largely faded in MY 30–31. In MY 32, a new dark deposit formed, with accompanying morphologic changes including minor channel incision. This deposit had mostly faded by MY 33. This demonstrates that distinct deposits can fade on short timescales, and also that frequent activity can occur in individual gullies. (HiRISE color images PSP_003695_1250, ESP_020863_1250, ESP_030344_1250, ESP_038546_1250, and ESP_047302_1250. Images have relative stretch to maximize contrast despite variable frost, illumination, and atmospheric dust, so absolute color is not directly comparable across images.)



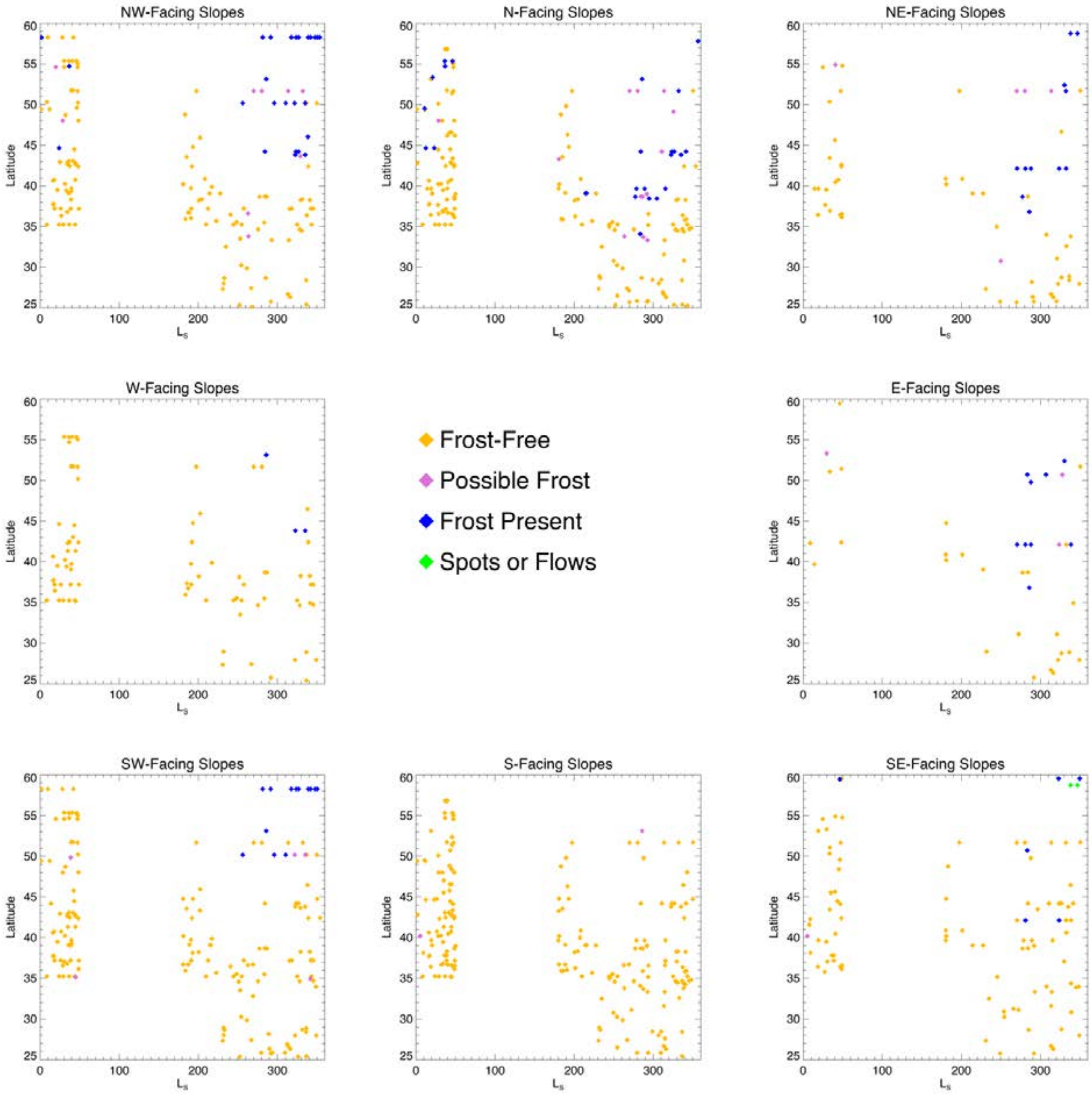
Supplementary Figure 2. Equatorial gully-like landforms (McEwen et al., 2016) in an unnamed crater at 2.6°N latitude. Water frost is observed at low latitudes in the southern hemisphere (Vincendon et al., 2010a) and perhaps traces are enough to occasionally trigger mass movements and gully formation. Nighttime CO_2 frost also occurs in low-thermal inertia regions at the equator (Piqueux et al., 2016), and H_2O frost has been observed on the *Opportunity* rover in the early morning (Landis et al., 2007). However, equatorial gullies have not been studied in sufficient detail to understand how they relate to the more prominent mid-latitude features. (HiRISE image ESP_034864_1825.)



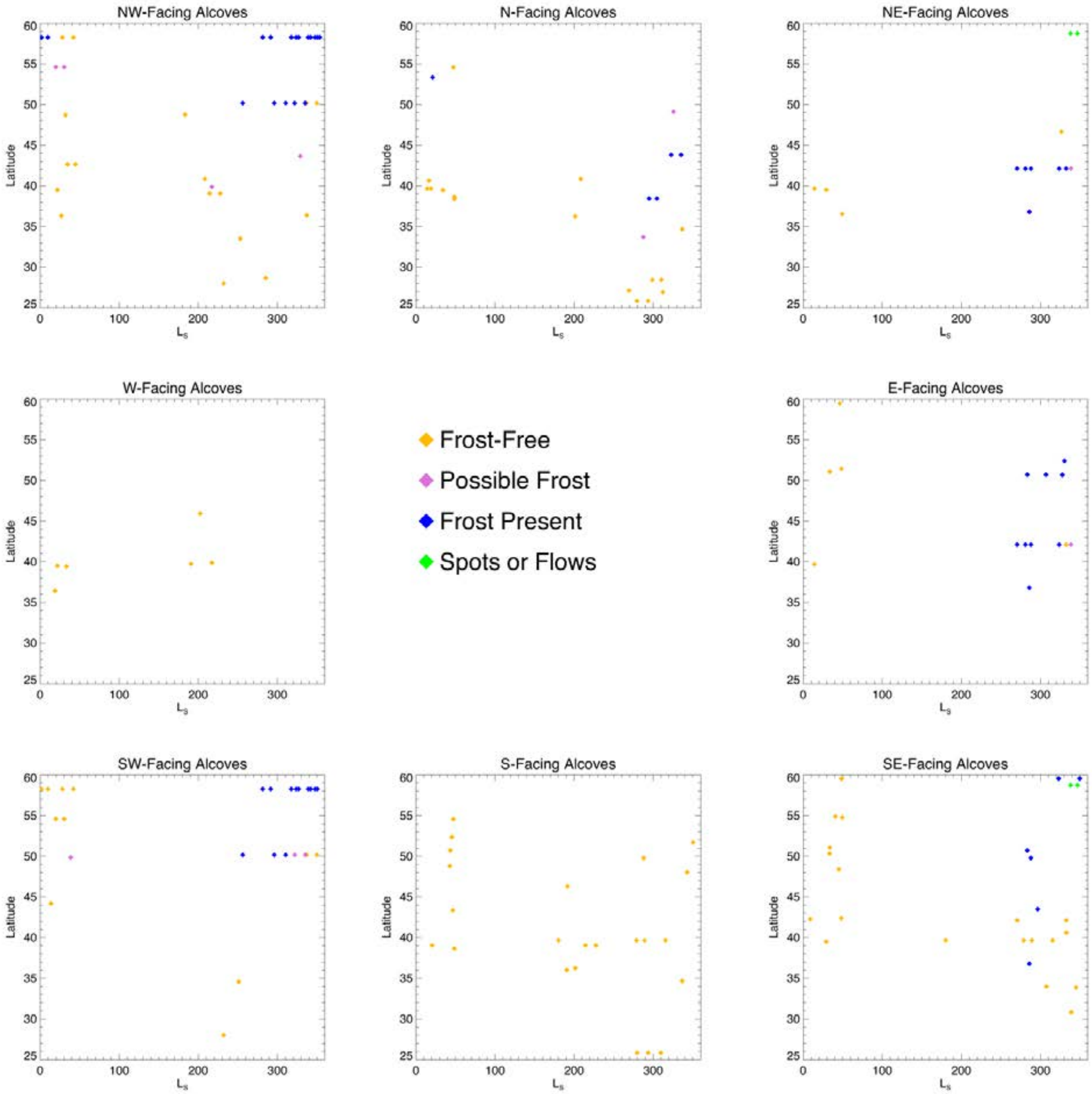
Supplementary Figure 3. Large-scale, leveed, lobate flows formed in sand covering an equatorial crater wall in Meroe Patera (7.2°N, 67.8°E), demonstrating that these morphologies can form with little or no volatiles (HiRISE images ESP_039388_1875 and ESP_040588_1875.)



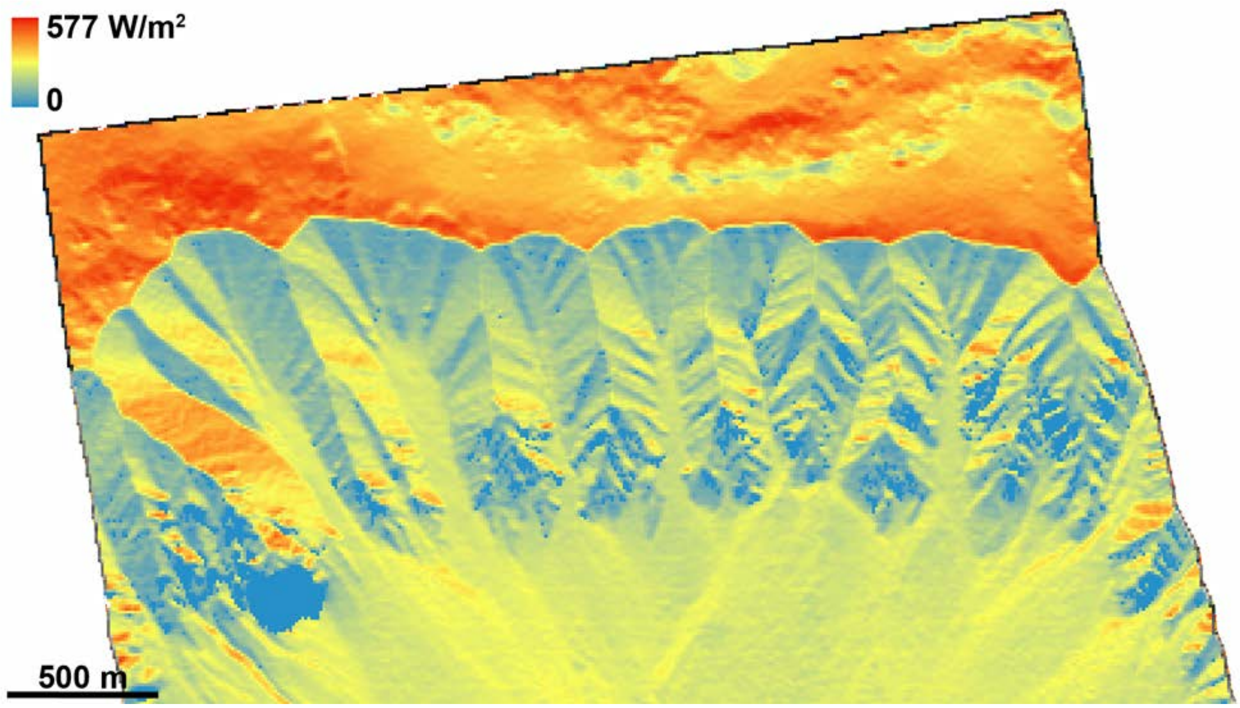
Supplementary Figure 4. Observations of frost within moderately to well-developed gully alcoves in the southern hemisphere (compare with main text Fig. 2, which shows non-gullied slopes and poorly developed, shallow alcoves).



Supplementary Figure 5. Observations of frost on non-gully slopes or in poorly developed alcoves in the northern hemisphere.



Supplementary Figure 6. Observations of frost within moderately to well-developed gully alcoves in the northern hemisphere.



Supplementary Figure 7: Modeled insolation in Gasa crater at noon at L_S=150° (late winter, after most activity has concluded), assuming a clear atmosphere. Insolation was modeled based on the slopes and aspects of a DTM resampled to 10 m/pix. The insolation in even the best-illuminated parts of the gully alcoves is just over 400 W/m^2. This heat input is far below the heat loss for H_2O ice approaching the melting temperature, so frost or ice cannot melt at the times and places of gully activity. For pure water frost, latent heat loss to sublimation alone exceeds this insolation at temperatures below the melting point (Ingersoll, 1970; Hecht, 2002). Additionally, radiative heat loss at 273 K is 315 W/m^2, which could be reduced by a factor of ~2 in these alcoves since roughly half of the sky is blocked by warmer ground, and conductive and convective heat losses also occur.

Supplementary Animations

The supplementary animations are time comparisons of selected changes which highlight important morphological effects. Images used in the animations are selected for similar illumination and viewing geometry, but are not orthorectified. (Orthorectified images are not always available, and entail some loss of detail due to resampling.) There is thus typically some distortion between the frames which appears as a stretch or twist of the surface, but the comparisons have been selected to minimize distortion and maximize visibility of the changes.

The animations are provided as separate animated gif files. Descriptions of each animation are below.

Supplementary Animation 1: Gully initiation in Raga crater (48.1°S, 242.5°E); compare with main text Fig. 8. Two separate events between the images resulted in formation of a well-defined channel following a pre-existing crease in the topography, possibly a degraded or infilled old channel. The images have near-identical illumination (ESP_014011_1315: incidence angle 41.9°, phase angle 43.4°, subsolar azimuth 208.1°; ESP_040239_1315: incidence angle 41.1°, phase angle 40.8°, subsolar azimuth 203.8°).

Supplementary Animation 2: Gully changes in Dunkassa crater (37.5°S, 222.9°E). Two separate events between the images resulted in channel abandonment and breakout, forming a new 50-meter channel and terminal deposit. Sinuous curves in the upper channel migrated downhill (arrows indicate outermost point of the bends). The images have near-identical illumination (ESP_013115_1420: incidence angle 41.2°, phase angle 47.1°, subsolar azimuth 183.6°; ESP_039488_1420: incidence angle 42.2°, phase angle 47.6°, subsolar azimuth 183.1°).

Supplementary Animation 3: Channel changes in an unnamed crater (compare main text Fig. 13). Note migration of curves by erosion of the outer, downhill part of the curve, and cutoff of one meander by formation of a new channel reach. Substrate is likely sandy, but gullies are largely cut into mantle material. The images have near-identical illumination (ESP_029032_1410: incidence angle 63.8°, phase angle 61.3°, subsolar azimuth 200.1°; ESP_046702_1410: incidence angle 61.2°, phase angle 58.6°, subsolar azimuth 201.8°).

Supplementary Tables

Supplementary Table 1 summarizes information about known gully changes on Mars. As noted in the main text, some changes are likely missed because of poor image conditions or poor match in lighting and/or geometry; therefore, this is a lower bound on gully activity in existing data. Only definite changes are reported here; additional possible and probable changes have been observed but are considered unconfirmed for various reasons. Typically, this is because either the quality of the comparison data is poor (e.g., shadows over the gullies), the comparison images are a poor match (very different illumination or spacecraft geometry), or because the effects of the change are subtle. These factors can trade off against each other—subtle changes may be considered confirmed if there is an extremely good match in lighting and viewing angles. It is likely that these candidate changes will eventually be tested, and some confirmed, by acquisition of additional data. In some cases where multiple changes occurred, only the most prominent are enumerated, as it is not practical to give all the details of assorted minor changes.

Most of the changes recorded here were first observed in this project or predecessor work (Dundas et al., 2010; 2012; 2015; Diniega et al., 2010). To our knowledge, the first definite observation of gully changes on Mars was in a Mars Orbiter Camera captioned image release by Malin and Edgett (2005; http://www.msss.com/mars_images/moc/2005/09/20/dunegullies/), showing a new dune gully in Matara crater. Some additional detections were reported in refereed publications by Malin et al. (2006). A few candidate changes were suggested for HiRISE imaging by the Mars Reconnaissance Orbiter Context Camera team after being observed in their data; we thank them for calling them to our attention. Sara Martinez-Alonso and Virginia Gulick noted individual sites. Raack et al. (2015) discussed the activity in gullies at one south polar pit site in more detail than possible here.

Supplementary Tables 1 and 2 are provided as separate CSV files. Supplementary Table 1 summarizes the following information for non-dune gullies (note that this includes gullies found in sandy material on non-dune steep slopes):

Field	Comment/Explanation
Site name	Geographic location and identifier number. Numbers index monitoring sites and therefore are non-sequential in this listing of active sites.
Latitude	Planetocentric
Longitude	East
Gully type	ACA indicates gullies with the classic alcove-channel-apron morphology. “Linear” gullies are generally sand-substrate gullies with small alcoves and long channels with little or no terminal deposit. “Channels” indicates gullies with minimal alcoves and aprons, but morphologically distinct from linear gullies.
Substrate	Non-sand, sand, light/rippled, or mixed. “Sand” refers to dark sand. “Light/rippled” refers to light-toned materials with ripples, suggesting aeolian modification, but lacking the dark blue color of active sand dunes on Mars (cf. Bridges et al., 2013). “Mixed” is used for cases where there is some component of dark sand within a gully that is mostly in non-sand material.

Orientation	Apparent downhill direction of the main slope. If flows of multiple orientations are summarized, the orientations are separated by semicolons.
Number of flows	Number of flows described by a given line. In some cases, individual events at a site have separate lines. In other cases, multiple similar events are reported together.
MY – before	Mars year of the last image before the change.*
L_S – before	L_S of the last image before the change.*
MY – after	Mars year of the last image before the change.*
L_S – after	L_S of the last image before the change.*
Bright?	Y if deposit is notably brighter than adjacent material in HiRISE red CCD, N otherwise.
Dark?	Y if deposit is notably darker than adjacent material in HiRISE red CCD, N otherwise.
Color?	States color if deposit is distinct in HiRISE color relative to adjacent material, N otherwise. U if there is no HiRISE color coverage. Colors are relative and based on color products with the near-IR/Red/Blue-green (IRB) filters assigned to red/green/blue channels, not true color.
Shadow-only?	Used for flows that appear distinct in a shadowed winter image, but are not visible when well-illuminated. Requires an "after" image with comparable shadows that does not show the flow in question.
Channel changes?	Y if there are visible changes in morphology along the channel for any of the flows, including brightness changes, deposition, and/or topographic changes of uncertain character. Includes cases of definite channel incision (next field).†
Channel incision?	Y if there is channel widening, deepening, extension, or formation of new channel segments, N otherwise.†
Thick deposit?	Y if there is a (near-)terminal deposit with visible thickness and topographic effects, N otherwise.†
Notes	Description of the changes, as needed. Coordinates of the form IMAGE_ID: X;Y give approximate locations of features of interest in HiRISE images. (These are from the red-filter RDR data product unless otherwise noted. They are typically chosen for good visibility of one of the more obvious parts of the change and are not necessarily the images that provide time constraints.) X and Y are pixel coordinates with the origin at upper left, with X increasing to the right and Y increasing downwards, as output by the HiView image viewer (http://www.uahirise.org/hiview/).

*Image intervals are conservative. In some cases there are intervening images, but we were not confident that it was possible to determine whether or not the change had occurred in the image, typically because of poor lighting or seasonal frost cover.

†Fields relating to topographic changes are U (uncertain) if there is no HiRISE image before the event or an observation is marginal. They are L (Likely) if the images suggest changes but the resolution/lighting match/scale of the changes is such that they are not considered definite. Flows with no evidence for topographic change are marked N, but

some of these may have changes that are not detectable in existing data. (For instance, topography is difficult to see in high-Sun images.)

Supplementary Table 2 provides locations and brief descriptions of known active dune gullies. Reiss et al. (2010) reported activity in the Russell crater linear gullies, and Pasquon et al. (2016) documented activity at several linear gully sites. Due to the large number of changes found in many dune gullies, the individual events are not listed separately. Changes in minor alcove-apron features without defined channels occur on many dunes but are not included here.

References

Bridges, N. T., Geissler, P., Silvestro, S., Banks, M., 2013. Bedform migration on Mars: Current results and future plans. *Aeolian Research*, 9, 133-151, doi:10.1016/j.aeolia.2013.02.004. .

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, doi: 10.1130/G31287.1.

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, doi: 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, doi:10.1016/j.icarus.2012.04.005.

Dundas, C.M., Diniega, S., McEwen, A.S., 2015. Long-term monitoring of Martian gully formation and evolution with MRO/HiRISE. *Icarus*, 251, 244-263, doi:10.1016/j.icarus.2014.05.013. .

Hecht, M. H., 2002. Metastability of liquid water on Mars. *Icarus*, 156, 373-386, doi:10.1006/icar.2001.6794.

Ingersoll, A. P., 1970. Mars: Occurrence of liquid water. *Science*, 168, 972-973.

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. Conf. XXXVIII, abstract #2423.

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, doi: 10.1126/science.1135156.

Pasquon, K., Gargani, J., Massé, M., Conway, S. J., 2016. Present-day formation and seasonal evolution of linear dune gullies on Mars. *Icarus*, 274, 195-210, doi:10.1016/j.icarus.2016.03.024.

Piqueux, S., Kleinböhl, A., Hayne, P. O., Heavens, N. G., Kass, D. M., McCleese, D. J., Schofield, J. T., Shirley, J. H., 2016. Discovery of a widespread low-latitude diurnal CO_2 frost cycle on Mars. *J. Geophys. Res. Planets*, 121, doi:10.1002/2016JE005034.

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, doi:10.1016/j.icarus.2014.03.040.

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, doi: 10.1029/2009GL042192.

Vincendon, M., Forget, F., Mustard, J., 2010a. Water ice at low to midlatitudes on Mars. J. *Geophys. Res.* 115, E10001, doi: 10.1029/2010JE003584.