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Seasonal activity and morphological changes in martian gullies

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ABSTRACT

Recent studies of martian dune and non-dune gullies have suggested a seasonal control on present-day gully activity. The timing of current gully activity, especially activity involving the formation or modification of channels (which commonly have been taken as evidence of fluvial processes), has important implications regarding likely gully formation processes and necessary environmental conditions. In this study, we describe the results of frequent meter-scale monitoring of several active gully sites by the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO). The aim is to better assess the scope and nature of current morphological changes and to provide improved constraints on timing of gully activity on both dune and non-dune slopes. Our observations indicate that (1) gully formation on Mars is ongoing today and (2) the most significant morphological changes are strongly associated with seasonal frost and defrosting activity. Observed changes include formation of all major components of typical gully landforms, although we have not observed alcove formation in coherent bedrock. These results reduce the need to invoke recent climate change or present-day groundwater seepage to explain the many martian gullies with pristine appearance.

1. Introduction

Archetypal martian gully landforms consist of alcoves, channels and depositional aprons (Malin and Edgett, 2000) and are found on a variety of slopes, such as crater walls, central peaks, and graben edges. Similar features are also seen on sand dunes. Since they were first reported, they have commonly been taken as evidence of liquid water in the geologically recent past. Observations of recent activity shed new light on the processes shaping martian gullies.

Martian gully landforms are often much larger than landforms called gullies on Earth, more comparable in size to terrestrial ravines or gorges (Neuendorf et al., 2005); in terrestrial usage these terms refer only to the erosional channel rather than the composite landform including alcoves and fans, if present. Nevertheless, through common usage in the Mars literature the term gullies has come to mean the composite landform. In this paper we will follow the Mars usage.

Non-dune gullies in the southern hemisphere are strongly concentrated in the mid-latitudes, with an additional concentration in the polar pits near 70°S (Balme et al., 2006; Heldmann and Mellon, 2004; Malin and Edgett, 2000). They are concentrated on pole-facing slopes at lower latitudes, while the distribution at higher latitudes is more complex (Balme et al., 2006; Heldmann and Mellon, 2004). The northern hemisphere gullies are likewise concentrated at mid-latitudes, but do not appear to preferentially face the pole, even at low latitudes (Bridges and Lackner, 2006; Heldmann et al., 2007). Heldmann et al. (2007) also noted that northern-hemisphere gullies tend to appear degraded, while Bridges and Lackner (2006) reported that those at high latitudes appear to be better preserved. Dickson and Head (2009) provide a thorough summary of the literature on gully distribution and orientation, which is much more detailed than the brief summary presented here.

Gullies on sand dunes have generally been omitted in gully survey studies and, until recently, only dune gullies in Russell crater had been described in detail (Mangold and Costard, 2003; Reiss and Jaumann, 2003). Those dune gullies have an unusual form consisting mostly of a long channel or trough, occasionally with terminal pits, but with minimal alcoves and depositional aprons. However, many dune gullies resemble the classic gullies found on crater walls and other steep slopes. Reiss et al. (2007) categorized different types of dune gully morphologies and Diniega et al. (2010) provided the first survey of dune gullies that resembled non-dune gullies in morphology (i.e., of alcove–channel–apron [ACA] or alcove–apron [AA] morphology) and activity within those features, focusing on the southern hemisphere. Reiss et al. (2010) reported on activity within Russell crater dune gullies (following Vedie et al. (2008), we will refer to such channel-dominated

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features as linear gullies as they consist of a generally linear channel or trough, although some examples are highly sinuous) and Hansen et al. (2011) described active dune gullies (generally of AA form) within the north polar erg.

The mechanism first proposed for martian gully formation was the release of groundwater (Gaidos, 2001; Malin and Edgett, 2000; Mellon and Phillips, 2001), perhaps abetted by geothermal activity (Hartmann, 2001). Subsequently, a host of other formation processes have been suggested. Two of these are driven by changing climate and temperature conditions at high obliquity: Costard et al. (2002) argued for melting of shallow ground ice, while Christensen (2003) suggested snowmelt; similar hypotheses were put forth for dune gullies by Bourke (2005). Another category is that of processes driven by CO_2 frost. Hoffman (2002) suggested that avalanches of seasonal CO_2 might be triggered by basal sublimation and cause erosion of the substrate. Avalanching or CO_2-supported debris flows were also discussed by several others (Balme et al., 2006; Cedillo-Flores et al., 2011; Di Achille et al., 2008; Ishii and Sasaki, 2004), along with frosted granular flow (Hugenholtz, 2008), in which frost coatings abet mass movement. Other proposed alternatives include dry mass wasting of fine-grained materials (Shinbrot et al., 2004; Treiman, 2003) or release of liquid CO_2 (Musselwhite et al., 2001). Some recent work supports an origin driven by melting of snow or latitude-dependent mantling deposits at higher obliquity (e.g., Bridges and Lackner, 2006; Dickson et al., 2007; Dickson and Head, 2009; Lanza et al., 2010; Levy et al., 2010; Schon et al., 2009; Schon and Head, 2011; Williams et al., 2009).

Shortly after the initial discovery, ongoing gully activity of some form was suggested. Defrosting spots were observed to be associated with gully channels at some sites (Bridges et al., 2001), and Hoffman (2002) reported darkened streaks within the channels of frost-covered high-latitude gullies. Subsequently, before-and-after images demonstrated the formation of two new deposits associated with mid-latitude gullies, indicating that martian gullies are currently active at some level (Malin et al., 2006). These new deposits were interpreted as evidence for groundwater release (Malin et al., 2006). However, more recent topographic measurements and modeling indicated that the deposits were also consistent with dry granular flows (Kolb et al., 2010b; McEwen et al., 2007a; Pelletier et al., 2008). In parallel with this work, a possible new dune gully (http://photojournal.jpl.nasa.gov/catalog/PIA04290), defrosting spots associated with Russell crater dune gullies (Hansen et al., 2007) and small alcove flows within non-dune gullies that were associated with seasonal frost (Mangold et al., 2008) suggested that consideration of CO_2-driven processes should be renewed.

More recently, tighter timing constraints were used to suggest that activity is seasonally modulated for both non-dune gullies (Dundas et al., 2010; Harrison et al., 2009) and dune gullies (Diniega et al., 2010; Reiss et al., 2010). Seasonal constraints for activity in non-dune gullies were not strong but generally excluded summer activity; Diniega et al. (2010) found that dune gullies tend to be active in fall or winter, while Reiss et al. (2010) reported that linear gullies on dunes in Russell crater were active in early spring. Interpretation of this seasonal dependence varies; some authors proposed liquid water (Harrison et al., 2009; Reiss et al., 2010), while others suggested a process driven by seasonal frost, likely CO_2 (Diniega et al., 2010; Dundas et al., 2010). Most recently, Hansen et al. (2011) reported the formation of large numbers of new dune gullies in the north polar erg within one martian winter and argued that they were driven by CO_2 sublimation from the seasonal polar cap based on correlations observed between new gullies and areas of sublimation activity. The north polar erg gullies formed through the movement of hundreds of cubic meters of sand within a single winter. They generally lacked the channel found in southern mid-latitude gullies, possibly because of the smaller sizes of the dunes.

To understand the nature of current gully activity and the role that present-day processes play in gully formation and evolution, more information is needed on current activity, especially regarding the timing and nature of changes. We have begun to address this need by using the High Resolution Imaging Science Experiment (HiRISE) to conduct frequent monitoring of several active gully sites. The purpose of this paper is to describe the results of this monitoring, provide improved constraints on timing of gully activity on both dune and non-dune slopes, and demonstrate the nature and extent of morphological changes that occur in the present climate. Section 2 describes the observations used in both intensive seasonal monitoring and in a broader survey. Section 3 then gives the results of this campaign to date. Activity and morphological changes observed in dune and non-dune gullies are described, with focus on gully sites of intensive monitoring. Finally, Section 4 discusses the results and broader implications of the observed activity.

Throughout this paper, martian seasons are referred to via L_s, the areocentric longitude of Mars in its orbit. L_s 0° designates the vernal equinox (start of southern autumn), L_s 90° the start of southern winter, etc. Specific years are designated via the Mars calendar of Clancy et al. (2001), in which Mars year (MY) 30 began at L_s 0° in October 2009. The HiRISE Primary Science Phase began at L_s 132° of MY 28.

2. HiRISE gully monitoring campaign

2.1. Seasonal monitoring

To obtain detailed constraints on the timing of gully activity, a variety of gully sites were selected for frequent monitoring, including during the winter when CO_2 frost is present. Imaging mid-latitude gullies in martian winter poses observational challenges. The low Sun reduces the available signal, and gullies on steep pole-facing slopes are in shadow for much of the winter. The HiRISE camera (McEwen et al., 2007b) is well-suited to conducting such imaging as it has a high signal-to-noise ratio (SNR) that permits some detail to be seen in shadows, and the routine off-nadir pointing capabilities of the Mars Reconnaissance Orbiter (MRO) (Zurek and Smrekar, 2007) allow selected sites to be precisely targeted for repeat imaging. The pixel scale may be as small as 25–30 cm, but in low light conditions observations are typically binned during acquisition at two or four times this scale to improve SNR. Typical HiRISE images are 5–6 km wide and may be tens of kilometers long, with a 1.0–1.2-km-wide central swath acquired through three color filters. The color swath is valuable in distinguishing between frost, dust, sand and rocks and can also highlight recent deposits that have distinct colors.

We selected a number of gully sites for repeated observations over the course of a martian winter (Fig. 1). Most locations were chosen on the basis of observed recent changes prior to the southern winter of MY 30 (Diniega et al., 2010; Dundas et al., 2010; Harrison et al., 2009; Reiss et al., 2010), in addition to one that was selected due to an observation of defrosted gully channels consistent with some seasonal activity. These sites include crater wall and dune gullies with ACA/AA morphology as well as linear dune gullies. We also describe activity seen in a previously acquired image series taken at high cadence for investigation of seasonal defrosting. Table 1 summarizes the sites discussed in Sections 3.1 and 3.2.

2.2. Long time-baseline HiRISE change detection

To supplement these monitoring series, we have surveyed gully sites where overlapping HiRISE observations span a long time baseline. Such sites offer the prospect of before-and-after HiRISE

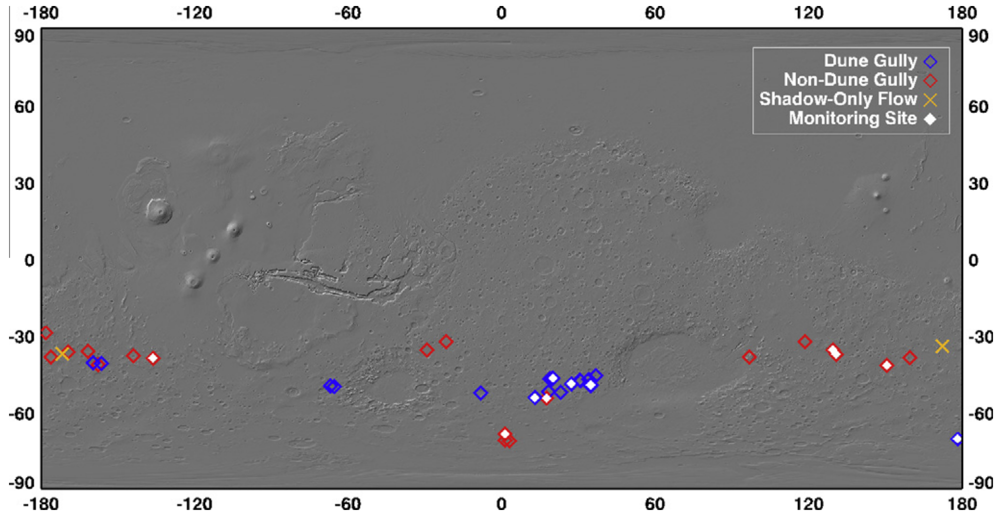

Fig. 1. Map showing the locations of known active gullies (this work; Diniega et al., 2010; Dundas et al., 2010; Harrison et al., 2009; Malin et al., 2006; Reiss et al., 2010). Blue diamonds indicate dune gullies, red diamonds indicate non-dune gullies and red ×s indicate gullies with 'shadow-only' changes. White diamonds indicate the sites of intensive monitoring discussed in Sections 3.1 and 3.2. Background is MOLA topography.

Table 1
Summary of monitoring sites.

Site	Latitude (°)	Longitude (E) (°)	Setting	Gully morphologies[a]
Gasa crater	−35.7	129.4	Crater wall	ACA
Pursat crater	−37.4	130.7	Crater wall	ACA
Unnamed crater	−38.9	223.7	Crater wall	ACA
Roseau crater	−41.7	150.6	Crater wall	ACA, poorly developed
Kaiser crater	−46.7	20.1	Dunes	ACA, AA
Unnamed crater	−49.0	27.2	Dunes	AA, linear
Matara crater, east edge	−49.5	34.7	Dunes	ACA
Matara crater, interior	−49.5	34.9	Dunes	ACA
Russell crater	−54.3	12.9	Dunes	Linear
Unnamed crater	−54.6	17.5	Crater wall	ACA
Polar pits	−68.5	1.3	Scarp	ACA
High latitude dunes	−70.4	178.2	Dunes	ACA

[a] For dune gullies where only a subset of gullies was examined, denotes morphology of studied gullies, not all gullies present.

coverage of changes, which provides much better ability to resolve changes in topography (as opposed to superficial albedo changes). A few examples of such changes were reported by Dundas et al. (2010), including movement of boulders and possible channel incision. Diniega et al. (2010), Reiss et al. (2010), and Hansen et al. (2011) reported more substantial morphologic changes in dune gullies, with definite channel incision and movement of tens to hundreds of cubic meters of sand. Overlapping sites were found by searching for images where the center coordinates of one image fell within the extremes of another. Cases where images overlap over only a fraction of their area may be omitted by this method, but those observations usually give little useful repeat coverage for change detection. In addition to deliberate imaging for change detection, overlapping images bracketing a significant time-span are often acquired when the second half of a stereo pair cannot be taken soon after the first and is instead left incomplete until the illumination conditions are again similar. We set a minimum time span of 4000 MRO orbits (just less than half of a Mars year) between the first and latest HiRISE images of a site, and used data available through MRO orbit 25,000. In this study we focus on the southern hemisphere and consider only images at latitudes poleward of 25°S, as gullies are rare equatorward of this latitude. The resulting data set includes over 150 non-dune-gully sites and 20 dune-gully sites, many with more than two images.

A manual comparison of large areas of hundreds of HiRISE image pairs at full resolution is impractical. Consequently, we searched for changes visible at reduced resolution and then compared these in detail with previous coverage. In most cases visible changes at lower resolution consist of light- or dark-toned deposits or color changes, but in some cases (generally on dune gullies) morphological changes can be seen. (Note that the terms "light/bright" and "dark" gully deposits are used in a relative sense and only indicate contrast with the immediate surroundings rather than any absolute albedo values. In general the southern mid-latitude gullies are concentrated in low-albedo regions, so even "light/bright" deposits could be darker than average Mars.) This approach is similar to that of Dundas et al. (2010) but includes additional imaging from roughly one Mars year, much of it specifically designed to look for changes in gullies. In dune gullies, albedo changes are less pronounced, but morphological changes tend to be larger; since the number of sites was more limited, we did compare consecutive images of dune gullies, although at reduced resolution. It is very likely that small or subtle changes are missed by this approach, and even significant changes may remain undiscovered if they are not accompanied by albedo changes.

2.3. Data biases

Some potential biases are present in this data set. This study considers only gullies in the southern hemisphere. Southern-hemisphere gullies may currently be more active than those in the northern mid-latitudes (Diniega et al., 2010; Dundas et al., 2010).

Such an asymmetry could be driven by the eccentricity of Mars' orbit, which results in more extreme seasonal variations in the southern hemisphere, but that will be assessed in a future study. The sites selected for intensive monitoring were mostly chosen on the basis of previously observed changes in order to maximize the chance of observing additional activity; they may therefore be among the most active gullies on Mars. This also applies, less strongly, to the broader survey of long-baseline observations. Many repeat observation sites were chosen on the basis of known changes, signatures of recent activity such as distinct deposits, or fresh appearance. For example, many new or preexisting bright gully deposits were first detected from MRO Context Camera (CTX) (Malin et al., 2007) images, in which wide coverage permits more systematic searches. (However, the resolution and SNR limits of CTX result in missing small-scale changes and may underrepresent relatively dark deposits. New deposits with the same broadband visible albedo as their surroundings but distinct in color images are especially likely to be missed by this approach, and such deposits are known to exist.) Thus, HiRISE gully targeting in general likely over-represents gullies known to be morphologically fresh based on CTX and other data sets. As a result of these biases, the level of observed activity could be higher than typical of gullies globally. However, the broader survey does include gullies that do not appear particularly fresh and the gullies examined here are within the range of typical gully morphology and size. Further work, beyond the scope of this investigation, will be needed to better understand how observed, present-day activity compares to all gully activity over space and time.

3. Observations

3.1. Overview

The aim of this study is to describe the extent and types of changes (or lack thereof) in the gully morphology that occur at each site and to construct a timed sequence of the general seasonal gully evolution processes. Wherever possible, we aim to provide quantitative descriptions of gully activity (such as channel length or volume of eroded material); such estimates could be used to constrain and calibrate physical and numerical models of gully formation processes.

As it has been proposed that seasonal frost is driving the observed activity, we also examine changes in seasonal frost, such as its areal extent and the appearance of seasonal albedo features, and look for spatial and temporal correlations between frost and gully activity. We attempt to categorize and describe frost activity in a manner that can be compared with previous studies (e.g., Gardin et al., 2010; Hansen et al., 2011; Kereszturi et al., 2010, 2011a,b) and generally use descriptive, non-genetic terminology.

Dune gullies are described first, ordered by latitude, as their image coverage is of higher temporal resolution so clearer estimates of timing and activity have generally been made. Non-dune gullies are then described. In the case of dune gullies, activity can be so extensive and widespread that we have focused on detailed descriptions of activity at selected gullies rather than cataloging every change in the dune field.

Recurring Slope Lineae (RSL), proposed as possible summertime brine flows (McEwen et al., 2011), often occur in or near small channels on steep slopes (gullies in the terrestrial sense) and sometimes in larger gully landforms, including (rarely) active sites. However, in aggregate, RSL do not appear to have any consistent relation to gully landforms. They are most commonly found in the southern mid-latitudes on non-pole-facing slopes, while gully landforms there are concentrated on pole-facing slopes, and individual lineae have no resolvable effect on topography in observations to date (McEwen et al., 2011). Any possible contribution of RSL to gully landform evolution remains to be determined, but they comprise a style of surface activity distinctly different from observed gully changes and are not considered in this study.

3.2. Dune gullies

3.2.1. Kaiser crater (46.7°S, 20.1°E)

This intracrater dune field contains an extensive barchan and transverse field with slipfaces towards the west. Gullies are found on the lee slopes of several dunes within this field (Diniega et al., 2010), but in this study we focus only on the gullies found on the eastern-most dune: a huge barchan (among the largest in the Solar System at roughly 7 km wide and 300 m tall) that contains three groups of gully systems on the lee slope which differ in orientation/location on the dune's slipface and morphology (Fig. 2). Activity within the southern and central gully systems (primarily the deposition of dark material onto and extending the existing debris aprons) has been observed during each of the last four Mars years (MY 26–29; Diniega et al. (2010)). Both of these gully systems had significant morphological changes during the winter of MY 30. In particular, the southern group (group b in Fig. 2A), which consists of a few gullies of a range of sizes and with very wide aprons, has undergone extensive episodic apron deposition, channel (re)cutting, and alcove formation and retreat.

Activity within this gully system was initially observed in autumn: during the periods L_s 324–60°, 60–62°, 62–87° (Fig. 2B) the dune surface became increasingly frosted and thin, long dark lineae appeared which extended from the alcove bases onto the debris apron. The lineae generally went over existing topography (such as ripples) without obscuring it, although a few areas contained blocky material with bright haloes and did opaquely cover the underlying dune surface. These features continued to appear through at least L_s 127°, along with larger dark fans that covered topography. Three large new channels (5–10 m width, 90–150 m long) formed between L_s 119–127° indicate the transport of at least several thousand cubic meters of material into large and deep (0.5–1 m) debris aprons (Fig. 2C). Smaller-scale alcove collapse and channel downcutting occurred within the largest gully between L_s 146–163°.

Within the central gully system, a large number of relatively equal-sized gullies with more clearly defined channels (group a in Fig. 2A), erosion operated at a smaller scale and occurred slightly later in the season. Between L_s 62–87°, 104–119°, and 119–127°, slumping material appeared with increasing frequency in the bottoms of alcoves and channels and spread out into fan deposits at the end of or spilling over the sides of channels. The dune completely defrosted by L_s 178° and further monitoring through L_s 284° has not yielded any additional morphological changes.

3.2.2. Unnamed crater (49°S, 27.2°E)

Dune gullies in a crater near Proctor crater also exhibited winter activity in MY 30. Frost was widespread on these dunes by L_s 88°. Indications of defrosting activity such as dark spots and flows over the frost appeared by L_s 133°, but significant morphologic changes were not observed until the interval L_s 152–179°. The most significant changes noted were expansion of an alcove and extension of a linear gully and expansion of the terminal pit, but extensive defrosting activity (spots and flows) were observed on the frosted dunes.

The site of alcove expansion showed a possible defrosting spot by L_s 133°, and had several more distinct spots by L_s 146°. Alcove expansion occurred between L_s 152–179° and was accompanied by emplacement of material covering an extensive area below the alcove, without a well-defined channel. Between L_s 179–195°, the defrosted alcove was unchanged, but the newly deposited

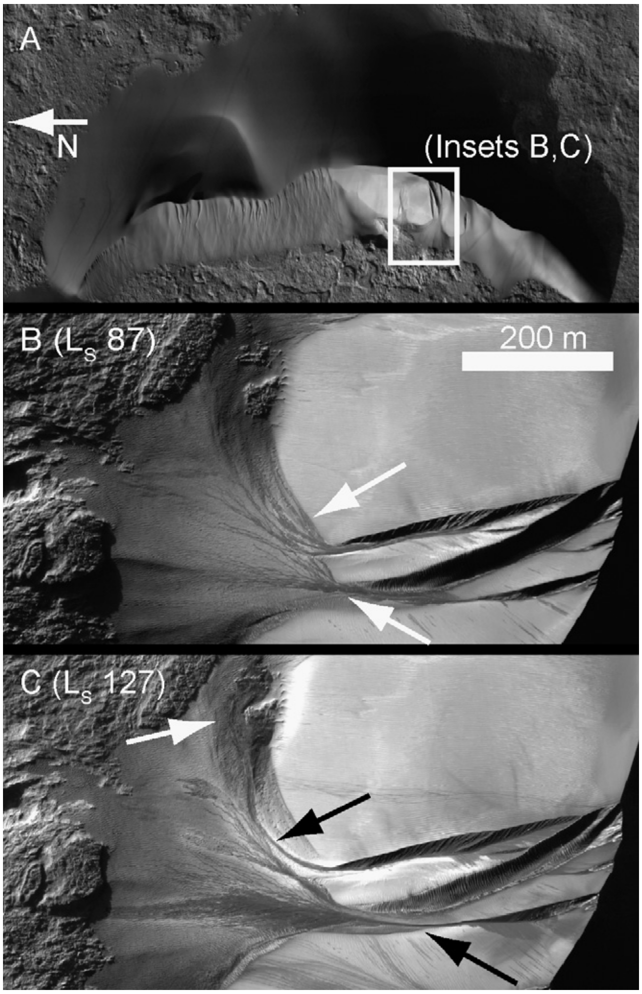

Fig. 2. HiRISE images showing different types of activity on the Kaiser crater barchan dune: black arrows indicate new channels and white arrows indicate other changes. (A) Overview image; north is to the left and illumination is from the bottom. (HiRISE image ESP_016973_1330). Inset location is shown for (B) and (C). (B) Thin, dark lineae extend from the alcoves across the apron (ESP_017685_1330). (C) Two new channels have formed and a debris apron deposit is deep enough to cover rocky terrain with relief of 0.5–1 m (ESP_018819_1330). On the apron, thicker dark lineae, some ending in fan shaped deposits and containing blocky materials, are visible. After the image shown in (C) was acquired, more thin, dark flows appeared and one more channel was cut along the middle gully between L_s 146–163. No changes were observed after L_s 163. (Throughout the paper, image identifiers with prefix ESP or PSP are HiRISE images. North is up and illumination from the left unless otherwise noted. Images have been stretched to optimally illustrate surface features. The HiRISE images used in this paper are available from the Planetary Data System or at http://hirise.lpl.arizona.edu.)

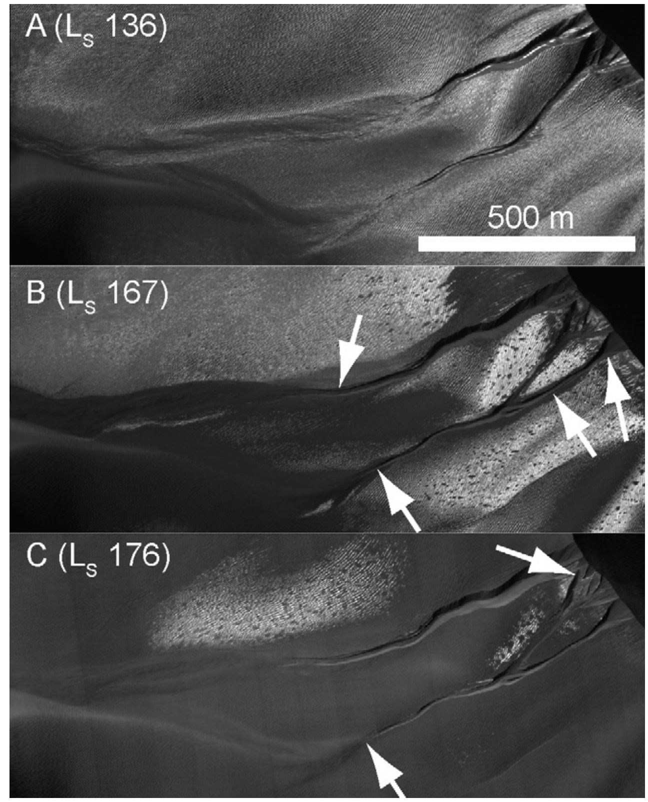

Fig. 3. A new alcove and channel were added to this gully system in Matara crater during MY 30. In addition, substantial changes occurred within the pre-existing gullies, with headward erosion of alcoves, widening and lengthening (and then infilling) of channels, and extension of the debris aprons. From the top, the HiRISE images are ESP_019069_1300, ESP_019636_1300, and ESP_020058_1300.

apron material developed small bright spots and underwent several changes. Apron changes continued between L_s 195–17° (no intervening images). At the end of this interval the spots were no longer present, suggesting that they were frost or ice mixed with the apron deposits that sublimated, causing changes to the morphology. Minor changes occurred at the terminus of a linear gully between L_s 179–195°; during this period, the upslope area also defrosted.

3.2.3. Matara crater (49.5°S, 34.9°E)

This crater contains a 16-km-diameter densely-packed mound of transverse dunes with slipfaces to the east and crest-to-crest wavelength in excess of 1 km. The eastern edge of the dune field also contains many superimposed barchan dunes (typically several hundred meters wide) climbing towards the northwest over the larger transverse dunes. Gullies are located primarily on the eastern and southern edges of this field. Diniega et al. (2010) discussed two large gully systems within this field, each of which has been active at least twice over the past six Mars years. Continued monitoring at both of these sites over the past year showed that both underwent significant modification during winter of MY 30, including the formation of new alcoves and channels.

The large gully system located in the interior of the field, which had undergone alcove/channel widening and apron extension during the winter of MY 29, did not yield any observable changes until late in the winter of MY 30: between L_s 136–167° a new alcove and channel (10 m wide, 180 m long) appeared, existing channels lengthened and widened through downcutting into the aprons, and all aprons were extended (Fig. 3B). Alcoves continued eroding via headward retreat between L_s 167–176° and the channels began to be infilled (Fig. 3C). Additionally, along the dune slope to the north of this gully system was a smaller gully system which twice exhibited headward retreat of the alcoves and formation of a new channel and fan deposit, between L_s 300–167° and 167–176°. New terminal pits (3–4 m in diameter) also formed along the ends of small channels, just past the extent of the debris fans, between L_s 158–167°. The surface had defrosted by L_s 192° and no further changes were seen as of L_s 299°.

Similar new pits, some at the end of thin (1–2 m width) channels, also formed on the debris apron of the very large gully found on the eastern edge of the Matara crater dune field (Fig. 4E). Extension of this apron (as the dark apron deposits covered bright bedforms at the edge of the field and gully apron) has been observed twice before: between MY 25–28 and 28–29. During the winter of MY 30, only the upper portions of the apron changed in extent

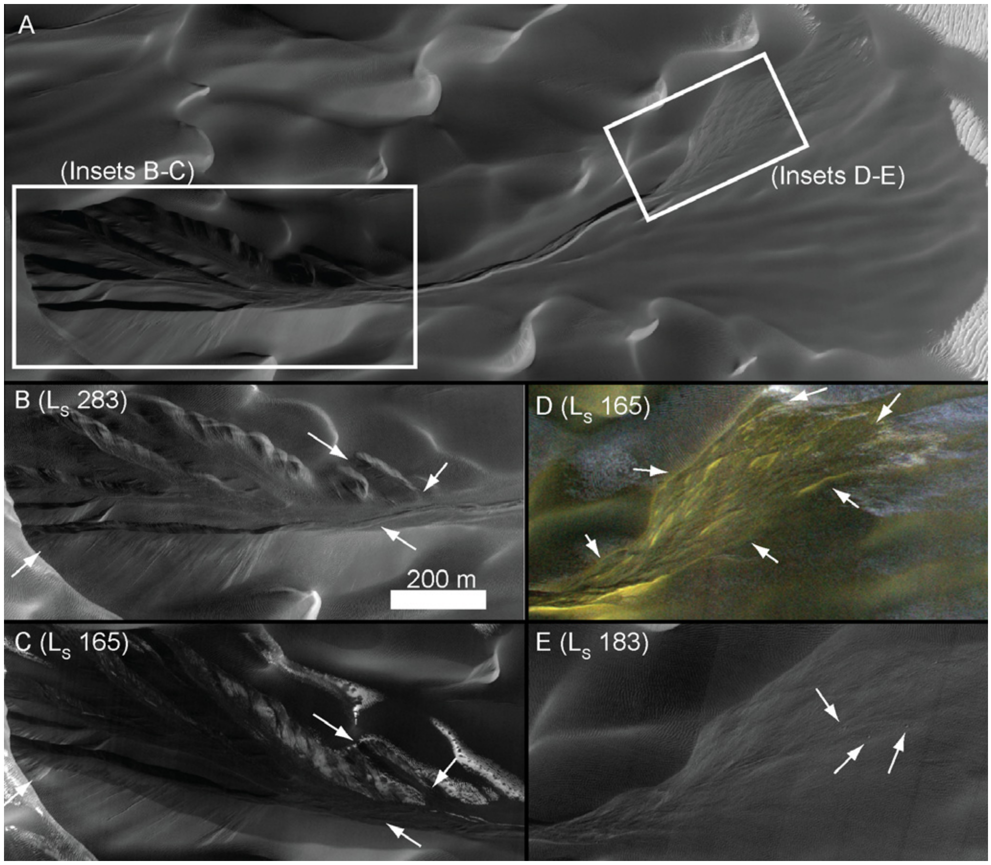

Fig. 4. A large dune gully in Matara crater that has consistently shown signs of morphological change during winter. (A) Overview image (PSP_006648_1300). This gully had previously undergone major extension of its debris apron. In the winter of MY 30, changes were observed in its alcove and main channel (B: ESP_013478_1300, from MY 29, C: ESP_019781_1300) and a new deposit was added to the upper portion of its apron (D: ESP_019781_1300; arrows indicate the edges of the region with changes). (E) Small pits subsequently formed on the upper apron (ESP_020203_1300). Some pits are at the terminal end of thin channels (Fig. 7C). All insets are at the same scale.

and surface appearance (Fig. 4D). The distal edge of this apron is also undergoing rapid aeolian modification, as shown through the formation of fresh 1 m-wavelength, well-organized ripples (Bridges et al., 2012).

The alcove of this gully system also changed over the past winter, with incremental headward retreat in several locations (ranging from a few meters up to 25 m; L_s 56–199°; Fig. 4B and C) starting as early as L_s 56°. Eroded material moved downslope, infilling the existing channel. However, it was not all simple deposition – a few thin (1 m width) channels were incised into the larger, now-mostly-infilled main channel. The oldest portions of the alcove (areas covered by 3 m-wavelength ripples) appear to be inactive with respect to gully evolution, but consist of at least a surficial layer of mobile sediments – ripple migration occurred during MY 29–30 at the top of the main gully alcove. In MY 30, the dune had defrosted by L_s 183° and no further changes were observed in this gully system through L_s 288°.

3.2.4. Russell crater (54.3°S, 12.9°E)

This 200 km diameter crater contains a dune field with a curved, 500 m high and 40 km wide megadune along its eastern boundary. The gullies located on this megadune are linear gullies (Section 1) and thus were omitted in the previous survey study of ACA/AA dune gullies (Diniega et al., 2010). However, gullies of similar morphology have been seen on crater walls and other slopes and previously identified gully activity (Gardin et al., 2010; Jouannic et al., 2010; Reiss et al., 2010) may be consistent (in type and timing) with the activity observed within dune and non-dune gullies of classic gully morphology. Thus, we include it in this study.

Frost is visible in channels and alcoves during autumn and the megadune exhibited pronounced seasonal frost markings throughout winter. Dark albedo spots and fans (Hansen et al., 2010a,b) are visible in images taken L_s 116–183°, becoming progressively larger and more numerous. No gully activity was observed until late winter when the dune was actively defrosting. Thin dark flows were observed in and around the upper alcoves and channels, beginning as early as L_s 151°. Between L_s 183–209°, several small (1–2 m wide) channels lengthened up to a few tens of meters. This activity is consistent with observations from the previous two winter seasons, when small channels lengthened between L_s 198–218° and 192–221°, respectively (Reiss et al., 2010). Dark outlines appeared around many of the upper-portions of the channels, extending from the dune crest and gully alcoves. Where these dark outlines extended to the bottom of a channel, dark fans and digitate deposits disrupt the pre-existing rippled dune surface. Meter-scale blocks were observed near the toes of channels at L_s 209° (Fig. 5) associated with dark haloes around the host channels, but were not definitively associated with morphological changes in the channels. These blocks disappeared by the time of the next HiRISE image of the gullies, indicating that they were predominantly composed of CO_2 ice; water frost would not accumulate in such volumes, and if present would sublimate more slowly. The dune had completely defrosted by L_s 244° and no further changes were detected through L_s 286°.

3.2.5. Unnamed crater (70.4°S, 178.2°E)

This polar dune field was frosted in the first image of the winter of MY 30, taken L_s 173°, and was completely defrosted by L_s 264°.

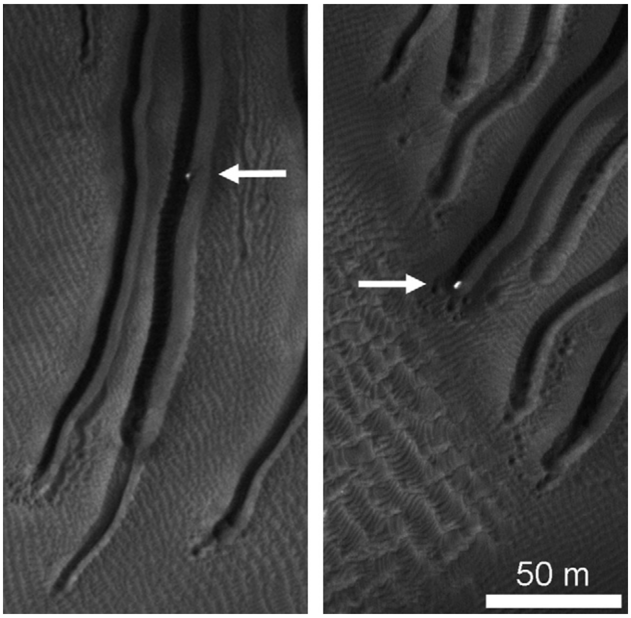

Fig. 5. Ice blocks near channel termini in Russell crater linear gullies (ESP_020784_1255, L_s 209°). The blocks had disappeared by the time these gullies were next imaged, indicating a composition of CO_2 ice. Note dark haloes around the channels with blocks, suggesting activity within the channel.

Dune-gully activity within this field appears similar to activity seen within the north polar erg (Hansen et al., 2011) and Russell crater (Gardin et al., 2010), consisting of dark lineae incrementally extending from dark spots (generally along or near the dune crest and sometimes within pre-existing gully alcoves and channels) between L_s 173–199°, 199–205°, and 205–250°. The largest dark lineae (up to 80 m long) generally originate within large dark spots (Fig. 6; some with concentric rings of alternating albedo, such as those described by Hansen et al. (2010a,b) and Kereszturi et al. (2011b)) and end in dark fan/digitate deposits. These deposits fade over time to more closely (but not exactly) match the appearance of the dune slope.

The distal edges of these deposits and connected gully channels sometimes contain collections of dark blocks and isolated bright blocks of ice (Fig. 6). Four of these blocks lie at the end of new thin (1–2 m wide) channels (Fig. 7), which were observed to form between images taken at L_s 205° and 250°. These four blocks were each roughly 1.25–1.5 m across (it was not possible to measure height). Two of the four bright blocks were gone due to sublimation by L_s 305°. The other two had disappeared by L_s 359°. The new channels were apparently very shallow, because they were no longer visible by the end of summer, likely due to aeolian modification.

3.3. Non-dune gullies

3.3.1. Gasa crater (35.7°S, 129.4°E)

This extremely fresh, ~7 km diameter crater has large gullies cut into the pole-facing sector of the rim. Dundas et al. (2010) reported two separate new deposits associated with these crater-wall gullies, including topographic changes such as movement of boulders and erosion or burial of a small ridge within a channel. Additional changes have been observed during the recent period of frequent monitoring. Several new deposits were observed to form on gully aprons. Two dark deposits appeared during the past martian fall or winter: one between L_s 65–109°, and one between L_s 109–152°. (These new dark deposits were first observed while in shadow, supporting the suggestion of Dundas et al. (2010) that

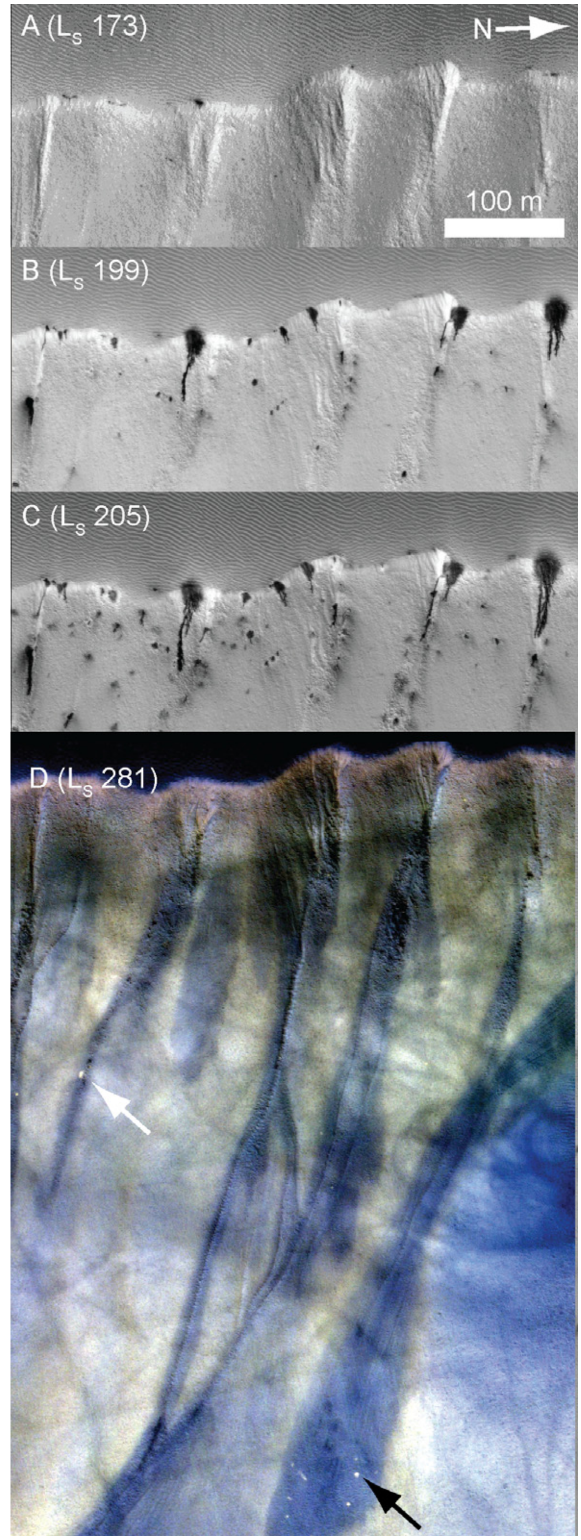

Fig. 6. (A–C) Appearance of dark spots and the associated extension of dark lineae within gully alcoves in dune gullies found within an unnamed crater at 70°S, 178°E (ESP_019987_1095, ESP_020554_1095 and ESP_020699_1095). (D) Is an enhanced-color image of the defrosted surface showing the formation of dark fan-shaped aprons (ESP_022255_1095); these aprons often contain blocks, some of which are bright. Over time, these blocks fade and disappear, suggesting that they are primarily composed of ice. An unstretched image is available in the Supplementary Online Material. All panels are at the same scale.

a previous dark deposit in Gasa crater did in fact form between L_s 123–183°, although a wider range was given there because of

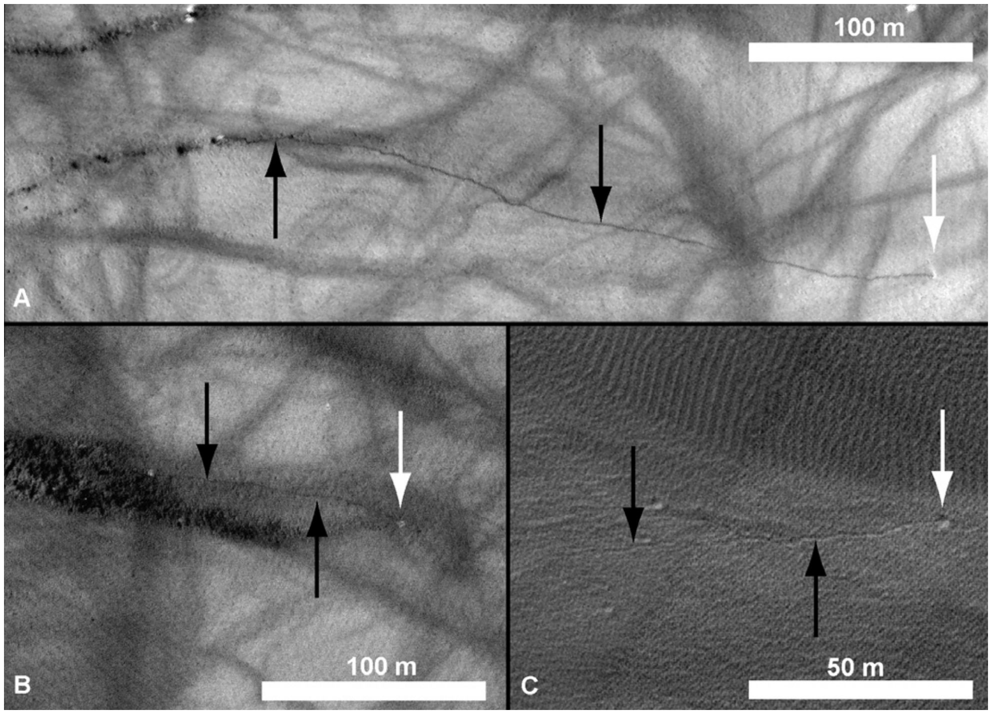

Fig. 7. Some blocks are found at the terminal end of new, thin (1–2 m wide) channels. (A and B) Show two examples within the dune field found at 70°S, 178°E (the dark sinuous tracks are from dust devils). (C) Shows a similar channel on the apron of the large dune gully in Matara crater. This channel has a terminal pit instead of a block. Within all images, the dune surface is defrosted.

uncertainties due to shadowing.) A bright deposit appeared between L_s 152–169° and a deposit with little contrast except in color appeared between L_s 65–152°. (Some intervals span multiple observations because lighting conditions prevent intervening images from being used as timing constraints with any confidence.) Very small mass movements in alcoves were observed in other seasons over the preceding year, but confirmed topographic changes on aprons were confined to late fall or winter.

The most substantial of these changes occurred between L_s 109–152° within the alcove and apron of a large pole-facing gully. Changes include channel widening of 0.5–1 m in places, movement of meter-scale boulders and deposition of decameter-scale mounds of material (Fig. 8). Despite appearing very distinct when in shadow, this deposit shows little contrast with its surroundings in the HiRISE red[1] filter; however, it is very clear in color, particularly the blue–green filter. Both deposition and erosion occurred along much of the length of the 'deposit' as defined by its appearance in color. (There is not a well-defined transition from erosion to deposition that could be analyzed in the manner of Kolb et al. (2010b); local slopes along its path range from 16° to 22°, while the larger-scale slope is nearly constant.) In some cases it appears that material has been removed from a preexisting channel. Near the toe, large deposited mounds are concentrated in the interior of the deposit, but small lobes are observed corresponding to the edges of fresh material in color. Deposits with visible relief cover over a thousand square meters on the apron alone, probably indicating that hundreds of cubic meters of material were transported. The alcove shows only small differences and also exhibited a minor change sometime between L_s 212–312°/MY 29, in which a small amount of material slumped into the upper channel.

The other dark deposit, formed between L_s 65–109°, also shows little contrast in the HiRISE red filter, and has relatively little contrast in the HiRISE color swath. Resolvable topographic changes associated with this deposit are minor at best. The most recent bright deposit likewise shows no visible relief. Minor changes were observed upslope from this deposit prior to formation: a small dark lobe appeared on the channel wall between L_s 212°/MY 29 and L_s 50°/MY 30, a large boulder shifted between L_s 50–152°, and a digitate dark flow was visible in the channel in the image at L_s 152° but not subsequently. Minor topographic changes occurred in the channel associated with the color-distinct deposit. Due to shadow and lack of contrast in red-channel images, the time of formation of this deposit is difficult to constrain.

In the MY 30 monitoring images, patches of frost can be seen on some pole-facing slopes at L_s 109° and 152°. These images occur near the beginning and end of the frost season for slopes at this latitude but did not capture the peak frost abundance, which is expected to occur sometime between these times (Schorghofer and Edgett, 2006; Vincendon et al., 2010a,b). However, an image from MY 29 (PSP_009901_1440) shows more abundant frost in the gully alcoves at L_s 123° (Fig. 8), including some streaks and spots suggesting minor defrosting activity.

3.3.2. Unnamed crater (38.9°S, 223.7°E)

This crater was among the first gully sites imaged by HiRISE (TRA_000878_1410, L_s 116°/MY 28). In that image the gullied slopes were covered in frost, although parts of the channels and alcoves were unfrosted. The site was chosen for monitoring in order to evaluate the frost cycle and determine whether the unfrosted channels and alcoves were related to any activity, not on the basis of any previously observed changes.

During the winter, extensive frost developed on the pole-facing slope and within most gully alcoves at this site by L_s 95°. A handful of dark spots appeared by L_s 115°, and these features became more common by L_s 123–136°. In the same interval, dark filamentary features developed along the thalwegs of several frosted alcoves (Fig. 9). In general over this time period the spots and filaments

[1] For interpretation of color in Figs. 4, 6, 10, and 13, the reader is referred to the web version of this article.

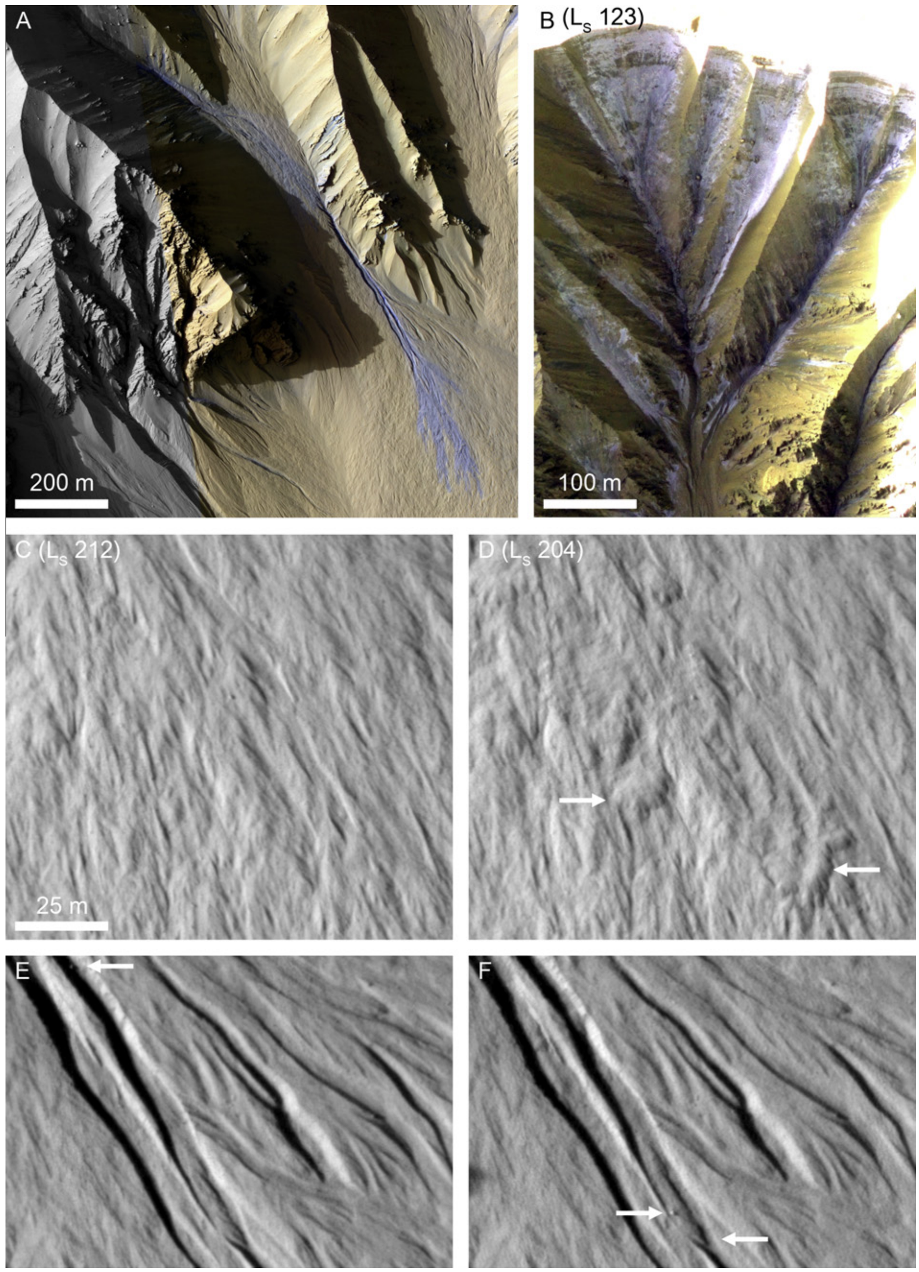

Fig. 8. (A) Overview of the most substantial new deposit in Gasa crater (ESP_020661_1440). (B) Seasonal frost in the alcove of another gully in Gasa crater, L_s 123° (PSP_009901_1440, MY 28). Bright, relatively blue lithic material is common in Gasa alcoves, but frost shown here is more extensive. Image has been stretched to show detail in shadow; original image available at www.uahirise.org. (C–F) Details of morphologic changes in the deposit shown in A. (D) Shows decameter-scale hummocks with visible relief near the middle of the deposit (arrows indicate examples). (F) Shows one of several channel segments that has widened (right arrow). Note also meter-scale boulder (left arrow) that may have originated near the upper left of (E) (arrow) or further upslope. (Orthorectified cutouts from ESP_012024_1440 (C and E; incidence angle 57.4°, phase angle 49.3°, L_s 212 of MY 29) and ESP_020661_1440 (D and F; incidence angle 57.9°, phase angle 47.6°, L_s 204 of MY 30).) An animation showing the changes is available in the Supplementary Online Material.

became more extensive, but examples are observed where the contrast between them and adjacent frost diminished. Between L_s 136° and the next image at L_s 158°, the frost almost completely vanished. Also during this interval, a small new dark deposit was emplaced on the upper apron of one of the gullies (Fig. 9), with probable small topographic changes including channel incision.

3.3.3. Polar pit gullies (68.5°S, 1.3°E)

A series of monitoring images was acquired over a polar pit gully site in MY 29 as part of an investigation of seasonal frost, and several additional monitoring images were acquired over the site in MY 30. The MY 30 coverage is more limited, but shows activity of a nature and scope similar to that in MY 29.

The detailed monitoring series in MY 29 showed a frosted surface with extensive evidence for defrosting activity associated with gullies. Figs. 9 and 10 show examples. The major form of this activity is a series of dark spots within gully channels, often but not always sourced at boulders, which had initiated by L_s 159°. Over a period of weeks, narrow dark flows develop from the spots and extend down the channel thalwegs. Measurements with a HiRISE Digital Elevation Model indicate that these flows advanced on slopes of 10–15°, indicating some degree of fluidization. The average velocity is variable both between spots and over time, reaching values of up to meters per day. In many cases flows cross into other dark spots lower in channels, precluding accurate velocity measurements for the flow front. It cannot be determined from HiRISE

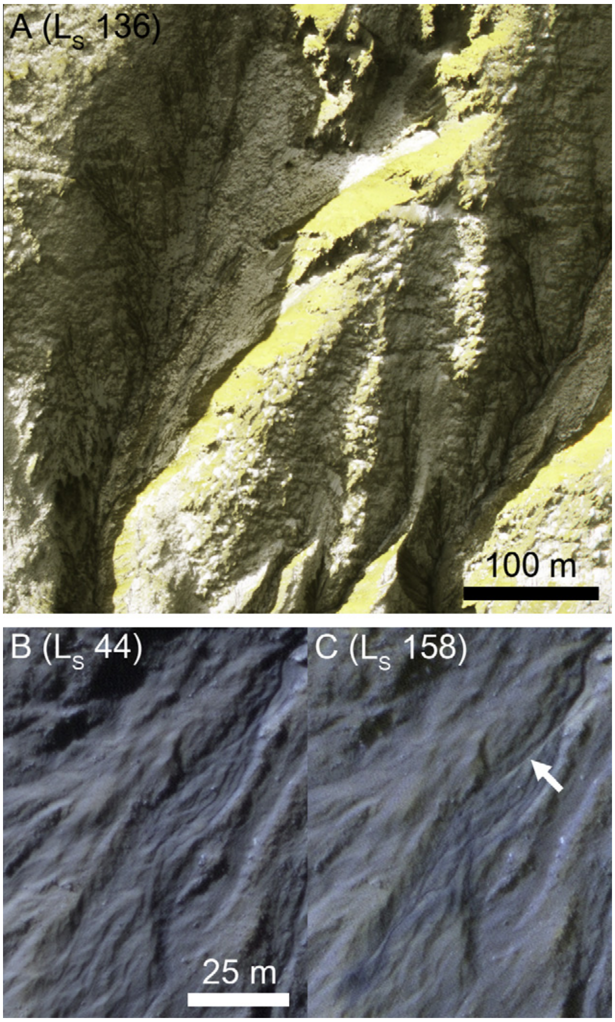

Fig. 9. (A) Defrosting spots in a gully alcove, as well as filamentary features along the thalwegs (ESP_019062_1410). The image has been given a hard stretch to show details in shadow; an unstretched image is available in the Supplementary Online Material. (B and C) Changes on the apron below the left alcove from (A). A new dark deposit is visible in the lower left of (C), and possible channel incision has occurred (arrow). (Cutouts from ESP_016438_1405 (incidence angle 70.9°, phase angle 67.3°) and ESP_019629_1410 (incidence angle 70.7°, phase angle 71.6°).) An animation showing the change is available in the Supplementary Online Material.

observations whether flows advance continuously or episodically, but if the latter, episodic events were frequent enough to drive advances between each image. Later in the season, parts of some of the spots appear to revert to surface frost, as the contrast between them and the surrounding surface is much reduced and the color reverts to match the surrounding frost (Fig. 10). Activity of this type most commonly occurs within gullies, but examples occur on the un-gullied portion of slopes; many gullies show similar activity, but a large fraction do not. The gullies showing defrosting activity and flows appear morphologically fresher than those that do not.

The most prominent activity in this series occurred in a gully in the southern part of the site, where a darkening front moved down the gully channel (Fig. 11). After reaching the channel mouth, the contrast between the darkening front and the frosted surface diminished, suggesting re-frosting. Subsequent to this reduction in contrast, a dark digitate feature was emplaced at the channel mouth sometime between L_s 209–226°. This digitate deposit was dark only in comparison with the frosted surface, because little contrast can be seen in later defrosted images. Deposition was substantial enough to have partially infilled the channel mouth in both MY 29 and MY 30. The infill was associated with the appearance of the digitate deposit in MY 29, while infill in MY 30 occurred between L_s 218–249°. A similar series of activity with associated deposition was observed in a gully in the southwestern part of the site.

3.3.4. Other monitoring sites

Several additional crater-wall sites were imaged repeatedly after the summer of MY 29. Roseau (41.7°S, 150.6°E) and Pursat (37.4°S, 130.7°E) craters both have previously known recent bright deposits, but did not exhibit obvious further activity to date. We looked for seasonal frost in these images to check whether it was present in the vicinity of the recent deposits. In both cases frost was observed within the craters, but not evident upslope of the deposits. However, neither site was imaged near the time of peak seasonal frost abundance.

A crater at 54.6°S, 17.5°E was monitored as previous activity was observed. Areally extensive frost developed in the alcove and also developed dark spots, but defrosted images showed no indication of new deposits between MY 28 and MY 30. However, the fresh deposit visible in MY 28 became much less distinct. The contrast between the deposit and surroundings has been much reduced, to the point that the previously sharp outline of the deposit is difficult to distinguish.

3.4. Long-baseline survey sites

This section describes changes observed at sites where long-baseline HiRISE repeat coverage exists, but not at a high frequency of coverage (Section 2.2). We have focused only on sites where repeat HiRISE coverage exists and only looked for changes occurring after the first HiRISE image of each site, in order to allow us to assess topographic changes. This approach almost certainly omits some events producing small or low-contrast features; hence, rather than providing a complete atlas of martian gully activity, this section gives additional examples of morphologic changes and indications of activity.

Several additional examples of crater-wall gully activity similar to those described previously (Dundas et al., 2010; Harrison et al., 2009; Malin et al., 2006) have been observed. These include both bright and dark deposits, sometimes with little or no discernable topographic change, as well as deposits that were distinct only in HiRISE color. A mass movement occurred in a gully in Palikir crater (41.6°S, 202.3°E), with evidence for both channel erosion and deposition (Fig. 12). Channel widening was especially large in this case: part of the channel appears to have widened by approximately 3 m. This change was not associated with an obvious bright or dark deposit as is the case for most known changes, but was discovered in the course of a separate change detection search using orthorectified images (Ojha et al., 2011). This underlines the likelihood that gully activity is more extensive than currently documented events. Repeat imaging of the sites of gully change reported by Malin et al. (2006) has not shown any further changes, indicating that activity is episodic.

A second type of activity was observed in Gorgonum Chaos (37.2°S, 188.3°E), where many apparently new dark deposits appeared sometime between L_s 18–150° of MY 29 and were observed while in shadow. These dark features were not visible when subsequently well-illuminated. Activity reported by Dundas et al. (2010) in Ariadnes Colles (34.4°S, 172.3°E) is of the same character. At both sites, many apparently dark deposits can be seen in shadow, but little trace can be seen when illuminated (Fig. 13). Unlike low-contrast deposits in Gasa crater and the polar pits (Figs. 7, 9 and 10), no distinct color or topographic changes can be seen afterwards. One possibility is that these are either new or preexisting

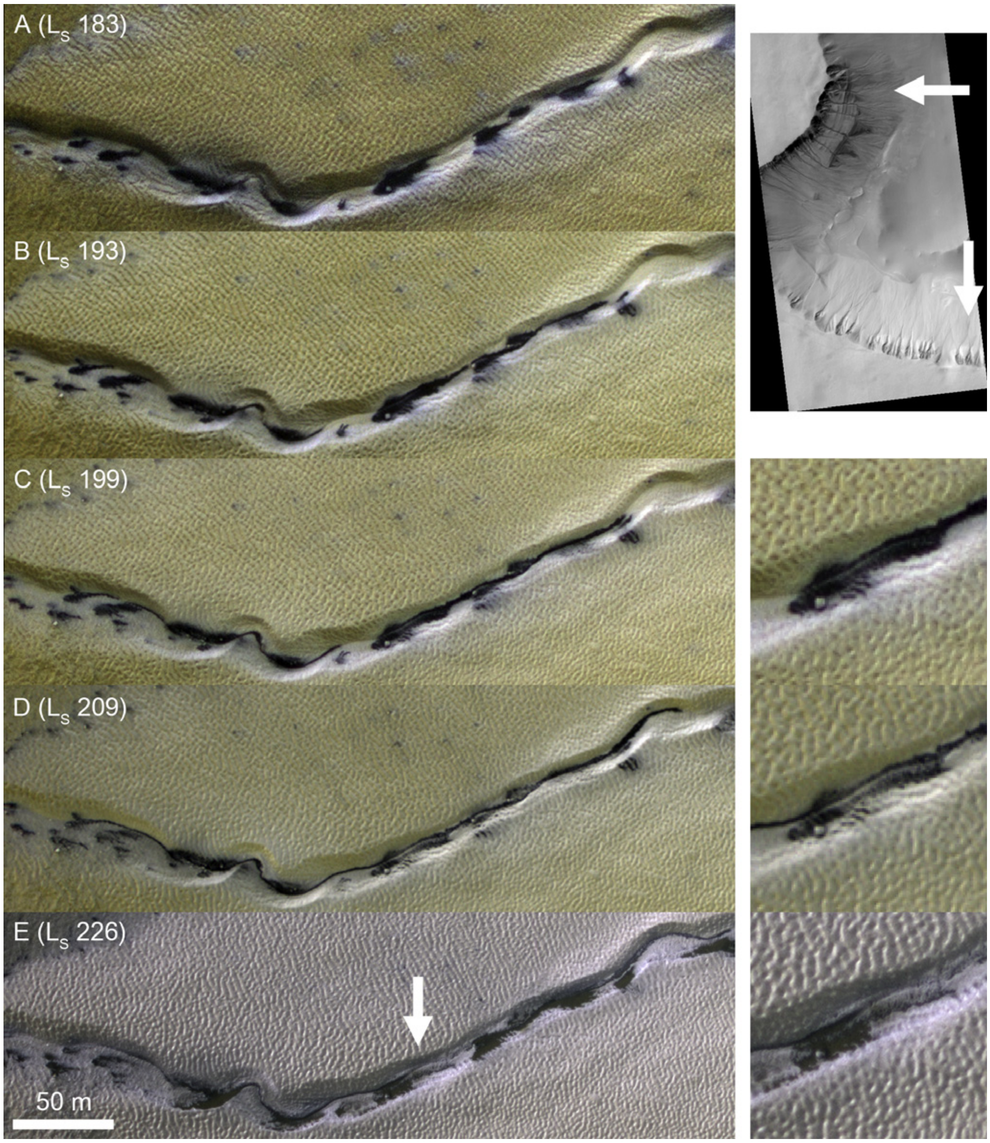

Fig. 10. Advance of dark defrosting flows along the channel thalweg in a polar pit gully. Light-toned surfaces are frosted in all panels. Note apparent refrosting late in the series; arrow in bottom panel indicates an example (enlarged at right) where a previously continuous dark lineation has been disconnected. Cutouts are individually stretched for maximum contrast and are mostly in shadow. (A–E: ESP_011396_1115, ESP_011607_1115, ESP_011752_1115, ESP_011963_1115, ESP_012319_1115.) Context image (top right) indicates the gully in this figure (top arrow) and that in Fig. 11 (bottom arrow).

flows that are dark by comparison with frosted surroundings, as in Fig. 10E (preexisting flows might develop different amounts of frost due to thermophysical differences). The gully aprons show no obvious indication of frost cover, but dusty, thin or translucent frost might be hard to distinguish in HiRISE imagery.

Linear gullies on sand-covered crater walls (dark, rippled surfaces) at several sites have morphologies identical to the linear gullies on the Russell crater dunes. (These are plotted as dune gullies in Fig. 1, but gullies with some fraction of sand on the channel or apron are not.) We have observed significant changes in several such gullies. Observed morphological changes include incision of substantial channels and formation of terminal pits (Fig. 14). The timing constraints are consistent with preferential occurrence in the frosted season.

Many changes have also been observed at other dune gully sites, along with extensive evidence for active defrosting processes. Dark lineae and flows on frosted dunes are extremely common, often not associated with distinct gullies or significant topographic changes. Topographic changes include headward erosion of alcoves, channel incision and infill, deposition on aprons, and formation of new linear gullies, including thin channels with larger terminal pits. The timing of these observations is consistent with the seasonal control noted at the sites of frequent monitoring. Small alcove-like notches along dune crestlines are frequently observed to change, but we have omitted those from this study since they lack other gully-like features.

The global distribution of known active gullies is shown in Fig. 1. Active non-dune gullies are concentrated between 30–40°S, broadly consistent with the overall concentration of gullies in this latitude band, while active dune gullies are found at higher latitude. The longitudinal distribution of active non-dune gullies has several gaps, but these may simply reflect low concentrations of gullies or observational biases. Known active dune gullies are strongly clustered, but this may simply reflect the availability (and image coverage) of large and steeply-sloped dunes (Diniega et al., 2010).

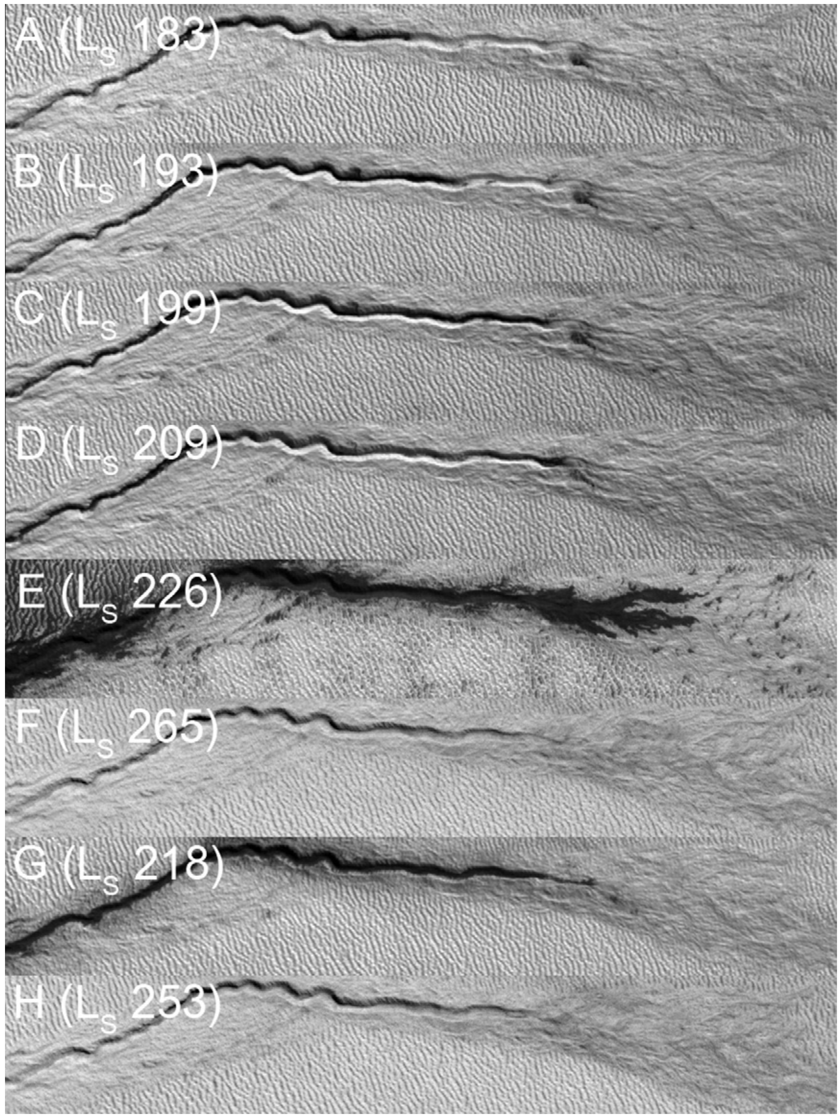

Fig. 11. Another style of activity in a gully channel: advance of a wave of darkening along a frosted channel (A–C), apparent refrosting or disappearance of dark material (D), emplacement of a large dark flow on a surface beginning to defrost (E), and defrosted surface (F). (G and H) The following Mars year: similar channel darkening (G) and defrosted surface (H). Note changes at channel toe when comparing (D–F) and (F–H); extreme albedo contrast makes comparing with E and G difficult. Cutouts are individually stretched for contrast. (Top to bottom: ESP_011396_1115, ESP_011607_1115, ESP_011752_1115, ESP_011963_1115, ESP_012319_1115, ESP_013097_1115, ESP_020956_1115, ESP_021668_1115.)

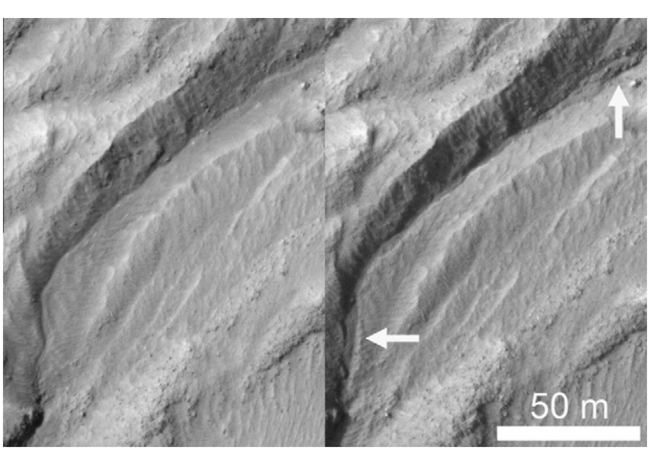

Fig. 12. Changes in Newton crater gully channel: deposition (upper right arrow) and channel widening (lower left) (left: PSP_005943_1380, right: ESP_011428_1380).

4. Discussion

4.1. Morphological changes

4.1.1. Large-scale morphology

In the case of dune gullies, the entire process of gully formation, including connected alcove–channel–apron formation, has been observed to occur under present conditions (Figs. 2 and 3). In some cases, the new alcoves, channels, and aprons involve the transport of hundreds to thousands of cubic meters of sand, yielding features that are comparable in scale and appearance to other dune gullies. Many other dune gullies have a pristine appearance, suggesting that they are similarly recent.

Substantial changes are also observed in non-dune gullies. Current activity is not limited to degrading preexisting gullies by mass wasting; observations of channel incision indicate that channels, which are often regarded as evidence of liquid-driven formation instead of dry mass wasting, can form in the present climate. As alcove collapse and apron deposition are also observed, all of the

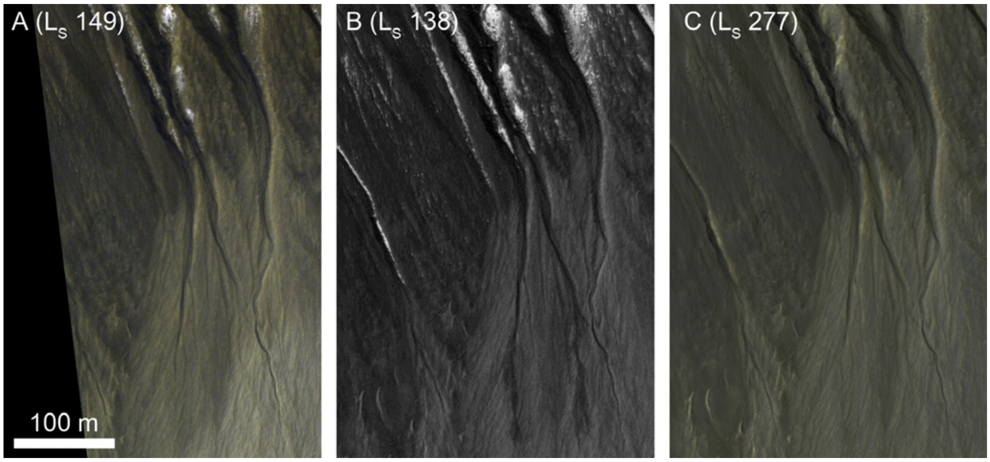

Fig. 13. Changes visible only in shadow. Dark features are visible in (B) (HiRISE RED channel, PSP_010295_1455), but minimal difference can be seen in before-and-after images with better illumination and color (A and C; PSP_001764_1455 and ESP_013341_1455). Some traces corresponding to the dark outline in (B) can also be faintly seen in (C) but may also be present in (A). Note that (A) is from MY 28 while (B) and (C) are from MY 29. Panel B has been stretched to show detail in shadow; original image available at www.uahirise.org.

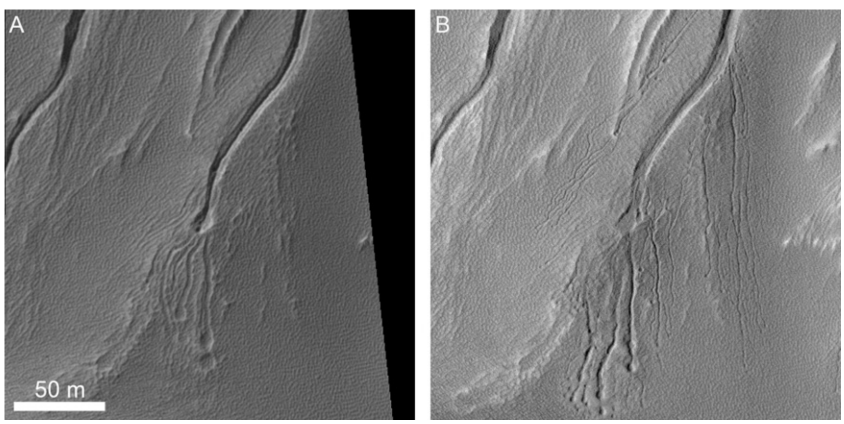

Fig. 14. Changes in linear gullies on a sandy slope in Avire crater. Numerous meter-scale new channels were incised, many with terminal pits. (A: PSP_001697_1390, B: ESP_012206_1390.)

large-scale gully features can be created by currently active processes, although we have not observed significant bedrock erosion in alcoves to date.

This does not rule out a significant role for other gully-forming processes in the past, such as snowmelt in a different climate at high obliquity, and it is possible that morphological details requiring such processes can be identified. However, the need to invoke such climate-change-driven effects is reduced by the observed changes occurring today, and consideration should be given to the possibility that current processes have played a major role in gully formation. Moreover, since observed new landforms resemble fluvial features but probably form without relevant amounts of liquid water (Section 4.5), terrestrial analogs should be applied cautiously.

4.1.2. Formation of channels with terminal pits

The channel-dominated gullies that we refer to as linear often have terminal pits. Pits have been proposed to form through sublimation of volatiles within debris flows (Di Achille et al., 2008; Vedie et al., 2008) or detached older flow fronts (Reiss et al., 2010). Reiss et al. (2010) reported channel incision in linear dune gullies under current conditions. We have confirmed this with observations of new channels at a range of sites, and also observed formation of new terminal pits, often with a diameter wider than the associated channel. The observation of new terminal pits integrated with new channels indicates that the pits are not remains of former channels. Within all dune fields, pits and the associated thin channels all formed after frost coverage began to recede and frost sublimation became prominent (Fig. 6; $\sim L_s$ 150–180° in the mid-latitudes and L_s 170–260° in the polar fields).

The discovery of new channels associated with blocks of CO_2 ice (Figs. 6 and 7) suggests that sliding blocks of ice could initiate formation of larger-scale channels and then produce enlarged terminal pits as they sublimated. This process is somewhat analogous to the formation of kettle holes in glacial outwash settings on Earth, but could be modified by vigorous CO_2 sublimation. We have also observed formation of linear gullies with terminal pits (e.g., Fig. 14), and blocks of ice at the toes of well-developed linear gullies in Russell crater (Fig. 5). However, new channels definitively associated with blocks disappeared within a Mars year, and blocks of ice have not been definitively observed to correspond to new pits. Hence, it is not yet clear how effective this process is in general. HiRISE images will be collected in future years to see if any additional blocks follow the same paths in the high-latitude gullies, which would imply that numerous years or events are required to establish a resolvable channel by this mechanism, and to test for definitive connections between blocks of ice and new channels or pits at other sites.

4.2. Rates of formation

The speed and frequency of dune-gully formation is highlighted by the widespread ripple migration recently documented on Mars (Bridges et al., 2012). This aeolian activity would rapidly modify and erase gullies if gully formation or activity were infrequent (Hansen et al., 2011). As an example, active ripples are observed on the Matara crater dunes: at the apron edges, new ripples with a spacing of 1 m have formed within one Mars year and mature ripples around the alcove have migrated with speeds of ~0.5 m/yr. (Elsewhere on Mars, speeds up to 9 m/yr have been observed (Bridges et al., 2012).) A typical ripple wavelength is 2.5 m; a standard height-to-wavelength relationship implies a height of ~0.1 m (Lancaster, 1995). If such ripples approach the channel at an angle θ and velocity u, then the net volume flux of sand into the channel per unit length is $0.05 * u * \cos\theta$. For an approach angle of 45°, a ripple speed of 0.5 m/yr, and a typical channel cross-section, the time to entirely fill the channel of the largest Matara dune gully is ~10,000 years. Timescales to erase smaller gullies such as that in Fig. 3 would be an order of magnitude less. This is a simplistic estimate as aeolian transport would also rework the channel and alcove walls, the flux of saltating sand is generally higher than that implied by ripple movement alone, and sand may also be blown out of the channel. However, since many gullies with pristine appearance are observed, the newly formed gully in Fig. 3 is probably not an aberration.

Rates of formation of non-dune gullies cannot be constrained in this manner, but the level of activity observed in Gasa crater indicates that considerable mass transport is occurring there. (Since Gasa is a very young crater and there has been relatively little time for its steep slopes to degrade, it may be particularly unstable.) Deposits of the largest observed mass movement had visible relief over around a thousand square meters of the apron, likely indicating movement of hundreds of cubic meters of material. A typical gully alcove in Gasa crater has a volume of ~10^6–10^7 m^3; if this mass movement transported 500 m^3 onto the apron, an entire alcove could have been eroded by 2000–20,000 such events. The estimated age of Gasa crater is ~1 Myr (Schon et al., 2009). Considerable uncertainty applies to age estimates based on counts of small craters (McEwen and Bierhaus, 2006), but if this age is accurate, the present alcoves could have been eroded with roughly one such event per alcove per 50–500 years. Since one such event has been observed over roughly 4 years among ~25 alcoves in Gasa crater, such a rate of activity is not unreasonable. The frequency of large events could be reduced if events like the multiple observed smaller mass movements cumulatively move comparable volumes. The eroded alcove volume above is likely somewhat underestimated since alcove divides in Gasa have merged, but the point is simply that present-day activity integrated over reasonable timescales can plausibly account for substantial mass transport in gullies. It is likely that rates have varied over time, and quite possible that much alcove erosion in Gasa crater was accomplished by rarer, larger slope failures (Okubo et al., 2011).

Gasa crater produced many secondary craters over surrounding terrains, including gullied slopes, providing an additional age constraint on gully activity. Schon et al. (2009) reported on a location where it appeared that parts of the gully fan were cratered by Gasa secondaries while other parts post-dated Gasa, and argued that this supported the view that climate change was needed to produce even the sharpest and youngest gullies. Later stereo images from HiRISE showed that all of the gully fans formed after the Gasa secondaries at this location (McEwen et al., 2010). HiRISE images now cover more than 10 other nearby gullied craters, and we have not found a single clear case where Gasa secondaries overlie sharp gullies. The secondaries may overlie older gully deposits, but if so they are rather indistinct. Gasa secondaries do generally post-date the mid-latitude mantling deposits. It has been suggested that melting in those deposits was the source of some gullies (Schon and Head, 2011), although in places sharp gullies developed after the mantle was substantially eroded (e.g., ESP_016982_1465). The many fresh gullies younger than Gasa crater imply that many modern-day gullies have formed or seen considerable activity over the past ~1 Ma, as originally proposed by Malin and Edgett (2000).

4.3. Timing and sequence of activity

4.3.1. Mid-latitude gullies

Although the exact timing of different types of activity varied within the mid-latitude dune gullies, the overall sequence of activity was consistent between the dune-gully systems and broadly consistent with changes observed in crater-wall gullies in Gasa crater and the unnamed crater at 38.9°S, 223.7°E (Fig. 15 and Table 2).

Changes in dune gullies begin to occur in mid-to-late autumn and through mid-winter, starting with the formation of dark lineae extending from alcoves down onto the apron. These appear to be the result of down-slope transported material and grow in number and size/thickness as frost coverage increases. As winter progresses, more deposits appear on the apron and with increased thickness, obscuring the underlying ripple topography and terminating in small fans. Larger slumps also occur during this time, yielding changes in the appearance of alcove and channel bottoms (including the formation or incision of small channels and the formation of large ripple-like features) and deposits of (often blocky) material on the dune and apron slopes. Finally, activity peaks near the end of winter with precipitous events altering all three gully-system components – just around the time that frost coverage begins to decrease and dark spots begin appearing on the dune surface, implying a connection with frost sublimation. Gully activity then drops off with frost coverage, with smaller amounts of alcove erosion occurring through the end of winter, and ceases entirely once all frost disappears.

Activity in non-dune gullies shows a pattern similar to that observed on dunes. In the unnamed crater at 38.9°S, spots, flows and filamentary features were observed to form. The one observed change on a gully apron there occurred during the same interval in which most of the frost disappeared. Coverage of Gasa crater during the frosted period is unfortunately poor, but activity there is broadly consistent with this pattern. The largest change occurred in the interval in which most seasonal frost came and went. Minor changes along channels and aprons occurred just before and after the major frosted period, still consistent with seasonal control; the connection with frost is less clear, but it is possible that it was dusty or translucent, or present in small amounts. During the summer, only a few cases of minor mass wasting in alcoves were seen.

Except for a few cases of alcove headward retreat within Matara crater, large morphological changes occurred only near peak frost abundance or towards the end of the frosted period: channel and alcove formation occurred between L_s 119–127° in Kaiser crater and L_s 135–160° in Matara crater, the largest event (including channel widening and the formation of a dark deposit) occurred between L_s 109–152° in Gasa crater, and possible channel incision occurred between L_s 136–158° within a crater-wall gully at 39°S. As this timing is roughly consistent between events within several dune and non-dune gully systems and the time of removal of the seasonal frost, this suggests a common process for this type of activity.

Additionally, within each gully system, the large-scale activity occurred only once during the winter season-suggesting that this is the result of a discrete and perhaps threshold-activated event. A threshold-type frost-driven process (such as one related to sublimation) is consistent with the variations in observed timing, as

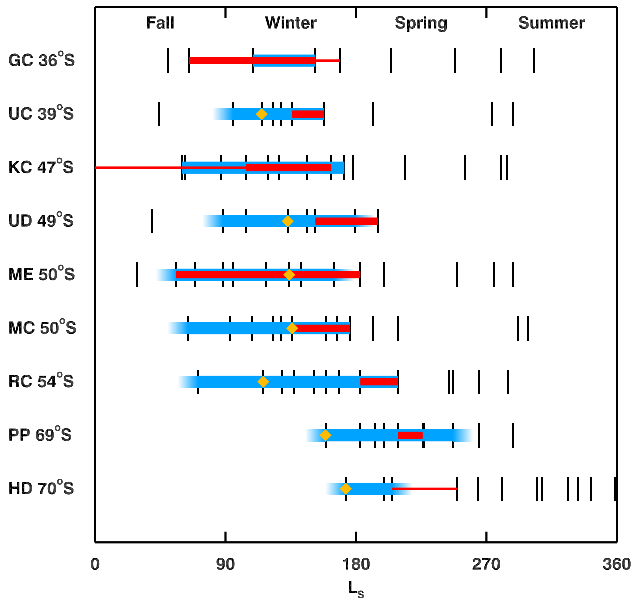

Fig. 15. Timeline of activity at detailed monitoring sites summarized in Table 2 and Section 3. The L_s range where images show frost in active gullies is shown in blue; as imaging did not capture the precise beginning and end of frost deposition, these are minimum ranges. (This is most pronounced at the two highest-latitude sites, where frost was undoubtedly present for many months before imaged. Frost on level surfaces at those latitudes likely forms near the start of the year.) Tapering bars indicate places where the first or last frosted images had more than small traces. Due to the occurrence of relatively bright lithic material, frost is particularly hard to distinguish in alcoves in Gasa crater, especially outside the HiRISE color swath; frost was present in some alcoves and on other slopes at the ends of the indicated interval and is expected to have been widespread between the endpoints (Fig. 9), but only the minimal interval is shown due to this uncertainty. Note that some sites have multiple active gullies that may defrost at slightly different times. Thick red bars indicate *maximum* time intervals for major gully activity, defined as observable morphologic changes on gully channels or aprons, and thin red bars indicate minor flows through channels or onto aprons without resolvable topographic effects. (Some intervals include more than one event.) Alcove slumping may be less seasonally controlled and is not plotted. Yellow diamonds indicate the start of observable defrosting activity such as spots or flows (not included as minor activity). Vertical bars indicate the times of HiRISE images. While coverage from multiple Mars years is available for several sites, the figure summarizes observations from only MY 30, except for the polar pit gullies where MY 29 had better HiRISE coverage. The minor activity interval at Kaiser crater extends back into the previous Mars year. (Abbreviations: GC, Gasa crater; UC, unnamed crater; KC, Kaiser crater dunes; UD, unnamed dunes; ME, Matara crater dunes east; MC, Matara crater dunes central; RC, Russell crater dunes; PP, polar pit; HD, high-latitude dunes.)

activity generally occurs later at higher latitudes. However, variations in timing would also depend on differences in local conditions, such as gully orientation and geometry and surface thermophysical properties.

4.3.2. High-latitude gullies

Activity in higher latitude gully systems is broadly consistent with this pattern, with better-defined defrosting flows. In the polar pit gullies, the initial defrosting flows along channels originate early in the defrosting period and gradually extend down the slope. These may or may not directly drive the most significant activity. Large deposits such as that in Fig. 11 were not observed in most channels with the smaller flows and, as seen in Fig. 11, the gully channel appears to refrost (or the contrast between the flow and the surrounding frosted surface diminishes) prior to emplacement of the large dark flow. However, it is likely not a coincidence that this large deposit occurs in the same gully as the preceding channel-darkening flow while the remaining gullies on this slope segment show neither style of activity. As at lower latitudes, the most significant morphological changes occur as the slopes are defrosting.

Similar activity was seen within the polar dune gullies (Figs. 6 and 7), with dark lineae extending from dark spots as the dunes defrosted. Once the dune surface was defrosted, bright blocks were visible within the channels and along the distal edges of the fan deposits. Some blocks appeared to have slid downhill, leaving behind a new channel. Over time these blocks disappear, consistent with being large blocks of ice. The new channels disappeared by the end of the summer, suggesting that the channels were shallow enough to be erased by the aeolian activity.

Definitive, persistent channel incision has not yet been observed in high-latitude gullies. Tracks left by ice blocks on dunes appear to be superficial and rapidly erased, while the major events in polar pit gullies largely filled in channel termini. However, while we have distinguished between defrosting flows and other types of activity, defrosting flows along channels mobilize channel material and so must entail some level of channel incision. They therefore do contribute to gully formation at some level.

4.3.3. Style of defrosting activity

Marked defrosting activity is observed in non-dune gullies. Most spectacularly, dark defrosting flows develop along gully channels in polar pit gullies, culminating in some cases in the emplacement of substantial deposits and resolvable topographic changes in the late stages of defrosting. It is possible that the

Table 2
Summary of monitoring observations.

Site	Latitude (°)	Defrosting spots	Defrosting flows	Channel/apron flows	Morphological changes
Gasa crater	−35.7	–[c]	–[c]	65–169°	65–152°
Pursat crater	−37.4	–[d]	–[d]	N[a]	N[a]
Unnamed crater	−38.9	115°	123–136°[b]	136–158°	136–158° (Probable)
Roseau crater	−41.7	–[d]	–[d]	N[a]	N[a]
Kaiser crater	−46.7	N	N	324–163°	104–163°
Unnamed crater	−49.0	133°	N	152–195°	152–195°
Matara crater, east edge	−49.5	134°	N	56–183°	56–183°
Matara crater, interior	−49.5	93°	N	136–176°	136–176°
Russell crater	−54.3	116°	151–183°	183–209°	183–209°
Unnamed crater	−54.6	143°	N	N[a]	N[a]
Polar pits	−68.5	159°[d]	159–226°	209–226°	209–226°
High latitude dunes	−70.4	173°[d]	173–205°	205–250°	N

A number given under 'defrosting spots' represents the L_s of the first (perhaps only) image taken that contained defrosting spots. Numbers for defrosting flows indicate the L_s range in which flows descending from defrosting spots were observed. A number range given under the other categories represents the L_s range for images bracketing observed changes. 'channel/apron flows' denotes the possible L_s range of all flows reaching gully aprons, while 'morphological changes' gives the range for those flows producing resolvable topographic changes on the channel or apron.

[a] Gullies known to be active prior to frequent monitoring.
[b] Filamentary features in gully alcoves.
[c] Single winter image prior to frequent monitoring showed possible defrosting flows.
[d] Monitoring series missed bulk of frosted season.

smaller filamentary features observed in some alcoves (Fig. 9) are of the same nature. Dark defrosting spots without associated flow features are also observed in many gullies.

Defrosting flows are also prominent in and near many dune gullies, particularly those at higher latitude (in Russell crater and the unnamed crater at 70.4°S, 178.2°E). Gardin et al. (2010) described defrosting processes within Russell crater dune field that yielded defrosting flows extending from dark spots between L_s 173–198°; our observations extend this range. These features are of similar dimensions (1–2 m in width, tens to a few hundred meters in length) and appearance (going over ripples, but not obscuring them) as the dark lineae in the dune gullies found in both the northern (Hansen et al., 2010a,b) and southern polar regions. We observed somewhat similar features on the large Kaiser crater dune, but these do not originate at a dark spot (Fig. 2) and we did not observe them to incrementally lengthen through the winter season, but instead appear, sometimes over a very short period (e.g., L_s 60–62°), throughout the autumn and early winter. Given these differences, these features may not have formed through the same processes as the dark lineae observed in Russell crater and more polar regions. For the present study we note them as an unusual form of gully activity and leave a detailed study of their formation to future work.

4.4. Dune versus non-dune gullies

Like previous workers, we have distinguished between dune and non-dune gullies in the course of this study. However, this distinction may not be necessary. Both are found at similar latitudes. The morphology of the ACA dune gullies can be very similar to that of non-dune gullies found on other steep slopes (Fig. 16), and ACA dune gullies grade into less well-developed (usually smaller) AA dune gullies. The style and timing of activity observed in gullies in both substrates are comparable.

The loose substrate of a sand dune is significantly different from rocky slopes like crater walls, and this undoubtedly affects erosion rates. The largest observed morphological changes are mostly in dune gullies, which is consistent with the same processes having larger effects on the unconsolidated substrate. Non-dune gullies may be limited by the rate of breakdown of wall rock into loose debris in the alcove, or simply developed in mantling material (Schon and Head, 2011). Current processes are capable of transporting boulders within gullies (Dundas et al., 2010), so only a modest amount of rock breakdown is required, although most material on aprons is finer-grained. The similar final morphologies argue that the controlling processes are also similar, so the difference may simply be in the rate of formation.

Linear dune gullies like those found in Russell crater do appear qualitatively different, and it is reasonable to think that this indicates a difference in process. However, features resembling these gullies (narrow channels with terminal pits) have formed within an ACA dune gully (Fig. 4E). It is possible that linear gullies reflect the dominance of a process that is merely a contributor to ACA gullies. If the hypothesis in Section 4.1.2 is supported by future observations, the difference may be the relative importance of ice block movement versus other processes. It is also possible that the substrate influences the morphology, but this cannot account for observed ACA dune gullies. Regardless, both types of gully exhibit similar seasonal timing of activity. Therefore, current processes are likely to be related.

4.5. Implications for gully processes

Our observations of the types and timing of gully activity support the hypothesis that frost-related processes somehow initiate or enhance gully formation on both dune and non-dune slopes. We have observed large-scale changes, including channel incision involving hundreds of cubic meters of sand, occurring under conditions where it is difficult to generate a significant amount of liquid water, and with a seasonal control that is difficult to explain by dry mass wasting alone. The largest observed morphological changes generally occur during the late stages of seasonal frost cover, during or just after the period when defrosting spots and flows appear. Substantial defrosting activity is observed within gullies, including significant flows along channels and within alcoves, and CO_2 frost blocks are observed near the toes of linear gully channels with dark haloes suggesting recent activity. HiRISE observations show that some seasonal frost occurs even at the lowest-latitude active gully known (at 29°S, Fig. 17).

Seasonal frost on Mars is dominated by CO_2. H_2O has a higher frost point than CO_2 and so should condense earlier, over wider areas, and at lower latitudes, but the available mass of H_2O is far less, especially in the southern hemisphere. At high latitudes, CO_2 frost blankets the entire surface and forms the seasonal polar cap, which may be over a meter thick (e.g., Aharonson et al., 2004). In the mid-latitudes, CO_2 frost forms on cold, pole-facing slopes (Pilorget et al., 2011; Schorghofer and Edgett, 2006; Vincendon et al., 2010a) with thickness on the order of centimeters. Using observations by CRISM (the Compact Reconnaissance Imaging Spectrometer for Mars; Murchie et al., 2007), Vincendon et al. (2010a) reported CO_2 frost on steep pole-facing slopes at latitudes as low as ~34°S. (The composition of the frost in Fig. 17 cannot be determined from HiRISE data, and small frost patches in deep shadow would be difficult to identify using standard processing of CRISM data.) Peak CO_2 frost abundance may occur in early spring (after L_s 180°) at high latitudes, but occurs progressively earlier at lower latitudes (e.g., Kelly et al., 2006). Water frost reaches lower latitudes but is generally expected to be only tens of microns (much less than 1 mm) thick (Vincendon et al., 2010b).

We note that HiRISE may not be able to observe all frost or ice, which can be hard to distinguish if it contains dust or is dust-coated or translucent. Both dusty and translucent ices have been reported based on infrared spectral observations of the martian southern seasonal cap (e.g., Langevin et al., 2007). Thin H_2O frost should precede CO_2 deposition but is likely to disappear rapidly after CO_2 frost, and may be hard to see in visible-wavelength images (Schorghofer and Edgett, 2006). In general, the observed frosted periods are a reasonable match to expectations for CO_2 ice, but they may be somewhat underestimated.

Dark defrosting spots are generally interpreted as dust and sand exposure or mobilization due to localized CO_2 sublimation (e.g., Hansen et al., 2010a,b; Kieffer, 2000, 2007; Kieffer et al., 2006; Piqueux et al., 2003), while flow features appear similar to other defrosting activity observed on Mars, which has variously been attributed to sand destabilized by CO_2 sublimation (Gardin et al., 2010; Hansen et al., 2011) or to brine flow (Kereszturi et al., 2010, 2011a). The observed temporal correlation between these features and the larger-scale gully activity is consistent with results of Hansen et al. (2011) from the north polar erg showing active sublimation related to gully sites.

There is a tendency for activity in higher-latitude gullies to occur later in the season, consistent with expectations for seasonal frost activity. Pilorget et al. (2011) modeled the time of first gas ejection by CO_2 frost. For 20° pole-facing slopes this estimated time ranged from near L_s 130° at the latitude of Gasa crater to L_s 200° near the highest-latitude gullies. In detail, the timing will vary with slope, orientation, thermophysical properties and other variables, but in general terms this timing is consistent with that seen in Fig. 15.

Many CO_2 frost-related processes for gully activity have been suggested (Balme et al., 2006; Cedillo-Flores et al., 2011; Hansen et al., 2007, 2011; Hoffman, 2002; Hugenholtz, 2008; Ishii and

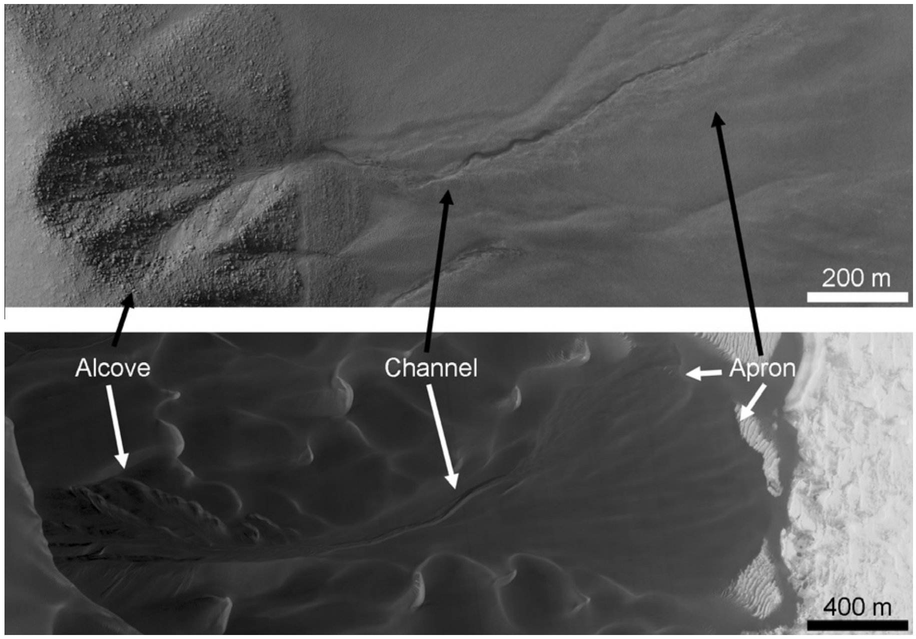

Fig. 16. Comparison of alcove–channel–apron morphologies in a classic gully setting (rocky slopes in polar pits, ESP_013097_1115) and sand dunes (Matara crater, ESP_022115_1300). Light is from the left and north is up in both images.

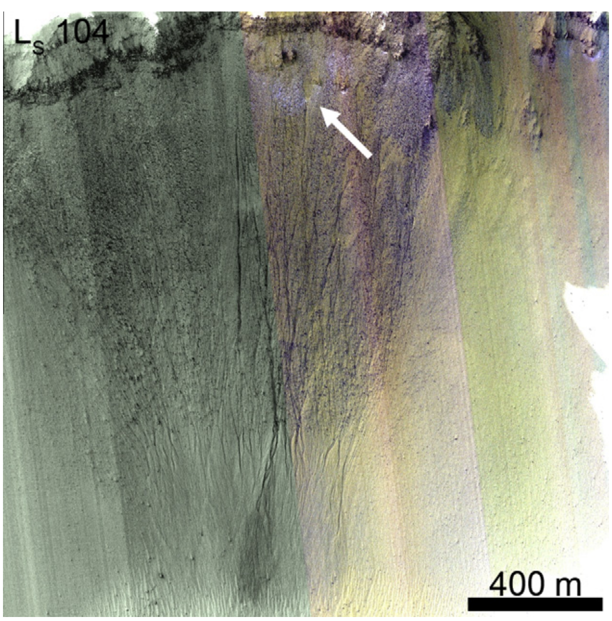

Fig. 17. Seasonal frost (arrow) at the lowest-latitude known active gully (29.1°S, 181.8°E). (Merged grayscale and color image from HiRISE image ESP_018180_1505 with extreme stretch to show features in shadow.)

Sasaki, 2004). We note evidence consistent with several of these processes. Avalanching or the movement of blocks downslope is consistent with the observation of blocks of ice with associated tracks, and with the ephemeral bright spots observed in several fresh apron deposits in dune gullies (consistent with ice mixed into the slumped sand and subsequently sublimating, although an alternate possibility is that sand buried frost). Slowly creeping flows such as those in the polar pit gullies resemble activity that has been attributed to sublimation (Hansen et al., 2011) and might be explained by the model of Cedillo-Flores et al. (2011), in which CO_2 sublimating under sediment fluidizes it and triggers flow. In other cases there is no definitive evidence for a particular process other than the association of the event with frost or the defrosting period. It is interesting to note that even relatively early minor flow activity such as that in Gasa crater or the Kaiser crater dunes nevertheless occurs quite close to the period of seasonal frost; one possible explanation is that small amounts of CO_2 or H_2O frost can mediate some activity, perhaps via frosted granular flow (Hugenholtz, 2008). It is also possible that we are somewhat underestimating the period of seasonal frost occurrence, as discussed above.

Not all observed defrosting activity is associated with gullies, although it is often concentrated within them (e.g., Fig. 10; Bridges et al., 2001; Hoffman, 2002). A number of factors could account for this incongruity. It could be that some activity has only minor effects that are obscured by aeolian or periglacial processes and incapable of forming gullies. A related possibility could be that gullies form where frost-related activity takes advantage of local weaknesses, or where defrosting activity is perennially repeated. Gully development could also be self-reinforcing if original topographic effects concentrate frost activity. These possibilities are not mutually exclusive, but serve to point out that defrosting activity outside gullies does not rule out a major role for frost in gully development.

The small dark flows observed in association with extant seasonal frost are unlikely to be flows of brines or melted water frost. The observed refrosting of some dark flows, particularly in the polar pit gullies, well after the beginning of general defrosting suggests that the flows are advancing over frost and subsequently either sink in or are removed by aeolian processes. Flow of water or brine would require thin flows to slowly advance over CO_2 frost at a temperature (~145 K) far below the eutectic of any likely brine (Möhlmann and Thomsen, 2011) over timescales more than sufficient to allow temperatures to equilibrate with the ice and the similarly cold atmosphere. Mixtures of salts might allow liquid at very low temperatures, but high salt concentrations would imply very small liquid volumes.

The availability of relevant amounts of liquid in gullies in the present climate is doubtful. Seasonal water frost observed by Viking Lander 2 was initially tens of microns thick, but in late winter it was redistributed into cold traps where it formed a layer a few hundred microns thick (Svitek and Murray, 1990). Water frost on pole-facing slopes in the southern hemisphere is inferred to be similarly thin (Vincendon et al., 2010b), but gully alcoves could be particularly effective cold traps (Dickson and Head, 2009; Hecht and Bridges, 2003). Hecht and Bridges (2003) proposed that cold-trapped frost in alcoves could melt when suddenly heated upon removal of seasonal CO_2, which is broadly consistent with the observed timing of some events. (Sudden heating is required to avoid sublimating the frost before it can become warm enough to melt.) They suggested that melting such frost could have been responsible for gully formation in the past, but also that in the current climate it is unlikely to be effective due to low frost abundance. Modeling by Kossacki and Markiewicz (2004) supports this assessment, since they found that only about 0.2 kg/m^2 (a depth of approximately 0.2 mm) of melt water is produced for some reasonable cases. However, even if alcove cold traps were far more efficient than expected and trapped millimeters of H_2O frost, and even if all of the frost were able to melt, it would be unlikely to trigger mass movements of the scale observed. This is most straightforwardly shown for the new alcove in Fig. 3, since the source could not include much outside area; the alcove depth is variable, but for an average depth of even 1 m, complete melting of millimeters of frost would produce <1% liquid water in the source volume. Well-developed alcoves could produce more substantial volumes of frost under these extreme assumptions, but it would still be necessary for all of the meltwater to flow through the subsurface without refreezing and collect within the alcove (even though melting temperatures extend only to very shallow depths) rather than simply dampening the upper sand or regolith.

Deliquescent salts could potentially generate brine solutions on Mars (Möhlmann and Thomsen, 2011), which might drive gully activity. However, the quantity of liquid generated by this process is not likely to be large—like seasonal water frost, it is limited by the amount of water available from the atmosphere.

Groundwater discharge is unlikely to drive the observed gully activity, for two reasons. First, aquifer discharge high on sand dunes is extremely unlikely, and given the similarities between dune and non-dune gully activity it is likely that they have the same nature. Second, although models of aquifer discharge predict varying forms of seasonal dependence (Goldspiel and Squyres, 2011), they do not predict a strong peak in discharge confined to the winter.

Dry mass wasting (with no volatile involvement) is likely to be the cause of some of the observed gully changes as it is consistent with the morphologies of some recent bright deposits (Kolb et al., 2010a; Pelletier et al., 2008) and some activity occurs on slopes where little or no seasonal frost is expected. For example, minor spring or summer alcove slumps observed in Gasa crater probably involve no volatiles, and a minor flow reaching a gully apron there may have preceded significant frost accumulation. It is also possible that some dry activity occurs after volatile-driven processes destabilize a slope; this may be the case for the headward erosion observed in Matara crater. However, the marked seasonality of observed flows through channels and onto aprons is very difficult to explain via dry mass wasting. Release of adsorbed water might reduce soil cohesion, but adsorption should be minimized near midsummer, not late winter or early spring. Thermally triggered rockfalls cannot occur on sand dunes, and thermal expansion will have a trivial effect on the overall slope even if the upper reaches warm significantly more than the base. Wind stress is unlikely to trigger large mass wasting events, and the times and locations of high wind stresses (Toigo and Richardson, 2003) show little correlation with gully activity.

Some activity remains enigmatic under any model. In particular, activity at sites with multiple dark flows visible only in shadow may be qualitatively different than other gully activity. The gullies themselves do not appear unusual, and the timing is consistent with activity during the frosted period; however, the number and seeming transience of the dark flows distinguish them from other gully changes. It is possible that the apparent dark flows are preexisting and are distinguished from their surroundings by subtle differences in seasonal frost cover. Current data are not sufficient to draw strong conclusions about this form of activity.

These (and other) hypotheses about gully formation and activity in the present climate can be tested via quantitative modeling, laboratory experiments and, where appropriate, terrestrial analog studies. This paper has aimed to provide an overview of the nature of gully activity and some quantitative estimates that can be used to validate and calibrate future studies. There is a clear need for modeling studies constrained by detailed observational series such as those described here. Once a model has been checked against existing measurements and observations, it can then be used to generate testable predictions. In particular, we would recommend studies into exactly how latitude, gully orientation, and gully geometry affect activity rates and magnitude. Potential tests include predictions on the location of active gullies as well as their geometry, and more detailed comparison of the distribution of gullies with seasonal frost in past and present climate conditions.

5. Conclusions

Gully formation on Mars is ongoing today. Formation of all of the main components of typical gully landforms (alcoves, channels and aprons) has been observed, indicating that current processes can account for each of the major features of gullies rather than simply modifying preexisting landforms. Complete dune gullies are observed to form in the present climate. Although other processes in past climates are entirely possible, they may not be required to explain most gully landforms. Many dune gullies have morphologies and patterns of behavior that are broadly similar to non-dune gullies, supporting a related origin. Despite their distinct morphology, linear dune gullies may be formed by closely related processes; they are forming and evolving today, possibly in conjunction with the movement of blocks of CO_2 ice. New deposits observed in crater wall gullies may be bright, dark or neutral relative to their surroundings; activity does not inherently produce bright deposits. In both dune and non-dune gullies most significant changes are associated with seasonal frost and defrosting activity. Likely driving processes are those controlled by the presence or removal of CO_2 frost deposits, but the relative importance of these and other processes remain to be determined.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.icarus.2012.04.005.

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