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Present-day gully activity in Sisyphi Cavi, Mars – Flow-like features and block movements

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Abstract

The continuously increasing number of multi-temporal high-resolution images from the surface of Mars offers the possibility for detailed studies of present-day surface activity. In this study we investigated all gullies in the Sisyphi Cavi region (355° E, 71° S) of the south polar region of Mars. This region is influenced by the seasonal deposition of a decimeters-thick translucent slab ice in late autumn/winter and its subsequent sublimation in spring. We mapped all gullies ($n = 17,760$) and measured their orientations. We also identified gullies with contemporary activity ($n = 35$) using multi-temporal HiRISE images for martian years (MY) 28 to 34. We observed two different kinds of activity: (1) dark flow-like features, and (2) movement of blocks. For both, sediment was transported from the source region (alcove and/or flanks of channels) down the gully. Using image data from HRSC, CTX, and HiRISE, we monitored the general defrosting of the study region. We also analyzed the maximum daytime surface temperatures of the complete study region based on TES data from MYs 24 to 26. To identify the origin and triggering mechanism of the observed activity, we used: (1) detailed topographic investigations (e.g., slope angles) of two extensively gullied slopes based on two HiRISE-DTMs, (2) identification of small scale displacements with Digital Image Correlation (DIC), and (3) orientation measurements of active gullies and comparison to non-active gullies.

We found that for the active gullies studied, activity happens at the end of spring between $L_s \sim 225^\circ$ and $\sim 250^\circ$. This is consistent with the timing of final stages of defrosting in the region. At this time, some surfaces are already defrosted while others still host the seasonal slab ice cover. For the surfaces with slab ice, dark defrosting spots (and flows, if the surface is inclined) are observed on dark dunes as well as on gully aprons and in gully channels. These spots form when, triggered by basal sublimation generated overpressure, sediment entrained in CO_2 -gas is transported through

cracks within the ice and redeposited onto the frosted surface. We compared and linked both morphologic features (dark dune spots and dark flow-like features) and concluded that these features have comparable or even the same triggering mechanisms. Based on this extensive study, the most plausible mechanism for ongoing gully activity can be divided into two steps: 1) accumulation of material within gully channels via small dry flows on top of the slab ice (comparable to dark dune spots/flows), 2) when a critical mass is reached, the sediment flows down the still frosted gully on top of the sublimating ice or as a mixture of dry material and ice in a catastrophic flow. The triggering factor for the movement of blocks remains unclear, as their timing could not be constrained with the available data. We identified headwall erosion in one gully in the study region, whereas a discrete source could not be identified for the other sites, suggesting multiple failure mechanisms could be active in such gullies. Finally, through volume balance calculations we show that active gullies in Sisyphe Cavi could have been formed within decades to several tens of thousands of MY, but gully-morphology indicates a much-longer period for formation of the entire gully-landform.

Introduction

Gullies on Mars are features comprised of an alcove, channel, and debris apron and can range up to several kilometers in length (Malin and Edgett, 2000; Figure 1). They are found on steep slopes in the mid to high latitudes of Mars and have a wide range of morphologies (e.g., Dickson et al., 2007; Dickson and Head, 2009; Conway et al., 2011, 2015; Harrison et al., 2015). They were initially thought to originate from erosion and deposition of sediments by flowing liquid water, in a similar fashion to gullies on Earth (Malin and Edgett, 2000).

69 An alternate hypothesis, proposed shortly after the discovery of gullies, is that CO₂ could play a
70 role in triggering sediment motion that forms gullies (Musselwhite et al., 2001; Hoffman, 2002).
71 CO₂ ice is deposited on the martian surface every winter, forming a continuous layer down to ~50°
72 in both hemispheres and a discontinuous layer down to ~30° latitude (Piqueux et al., 2003;
73 Schorghofer and Edgett, 2006; Vincendon et al., 2010a, 2010b; Pilorget et al., 2011) mirroring the
74 latitudinal distribution of gullies. The CO₂ hypothesis was initially proposed based on the presence
75 of gullies located near the south pole of Mars where annual CO₂ frost deposits would be at their
76 thickest (Hoffman, 2002; Ishii and Sasaki, 2004; Cedillo-Flores et al., 2011) and where surface
77 temperatures are too low to support the presence of liquid water. The mechanism proposed by
78 Hoffman et al. (2002) was that liquid CO₂ outbursts were responsible for gullies here, but the
79 stability of liquid CO₂ on Mars means its presence is even more unlikely than liquid water (Stewart
80 and Nimmo, 2002). Ishii and Sasaki (2004) and Ishii et al. (2006) proposed that gullies could be
81 formed by CO₂ ice avalanches and Hugenholtz (2008) slightly modified this idea by suggesting
82 CO₂ ice coated grains could avalanche by vaporization of the CO₂ frost. Cedillo-Flores et al. (2011)
83 proposed a mechanism by which dust or sand superposed onto a CO₂ ice surface would be
84 mobilized by sublimation of the underlying CO₂ ice. Pilorget and Forget (2016) suggested that
85 martian gullies could result from basal CO₂ sublimation of an ice layer and subsequent movement
86 of material underneath the CO₂ ice layer.

87 Ongoing observations of gully activity at the present-day have continued to raise questions, not
88 only regarding the formation mechanisms of gullies, but also the triggering mechanisms of the
89 activity (Malin et al., 2006; McEwen et al., 2007a; Diniega et al., 2010; Dundas et al., 2010, Reiss
90 et al., 2010, Dundas et al., 2012; Jouannic et al., 2012; Dundas et al., 2015; Raack et al., 2015;
91 Pasquon et al., 2016; Dundas et al., 2019; Pasquon et al., 2019a, 2019b). Recent laboratory

experiments under martian atmospheric conditions have shown that unstable water on the martian surface could have an influence on the formation of recent and present-day mass wasting features (Raack et al., 2017; Herny et al., 2019), but the climatic conditions (e.g., low surface temperatures) at times when gully activity occurs on Mars makes water-triggered activity very unlikely. As a consequence, the focus of research has moved from H₂O- to CO₂-related mechanisms when investigating contemporary gully activity, but all three possible triggering factors (H₂O, CO₂ and dry or possible combinations) should continue to be considered for active gullies on Mars.

This study focuses on polar pit gullies, which were the focus of the initial studies referring to CO₂ frost as the mechanism behind martian gullies. Our objective is to exploit all available imaging data to identify and catalogue the types, timing, and frequency of present-day activity in these gullies with the aim to provide insights into the processes driving this activity. We also investigate whether the present-day processes could account for the presence and morphology of all the gullies in the south-polar pits or whether other mechanisms need to be invoked. Furthermore, the polar location of the gullies investigated in this study combined with the polar orbits of the main imaging orbiters means that there is a higher frequency of observations compared to gullies at lower latitudes, providing a unique opportunity to study the activity of gullies in detail.

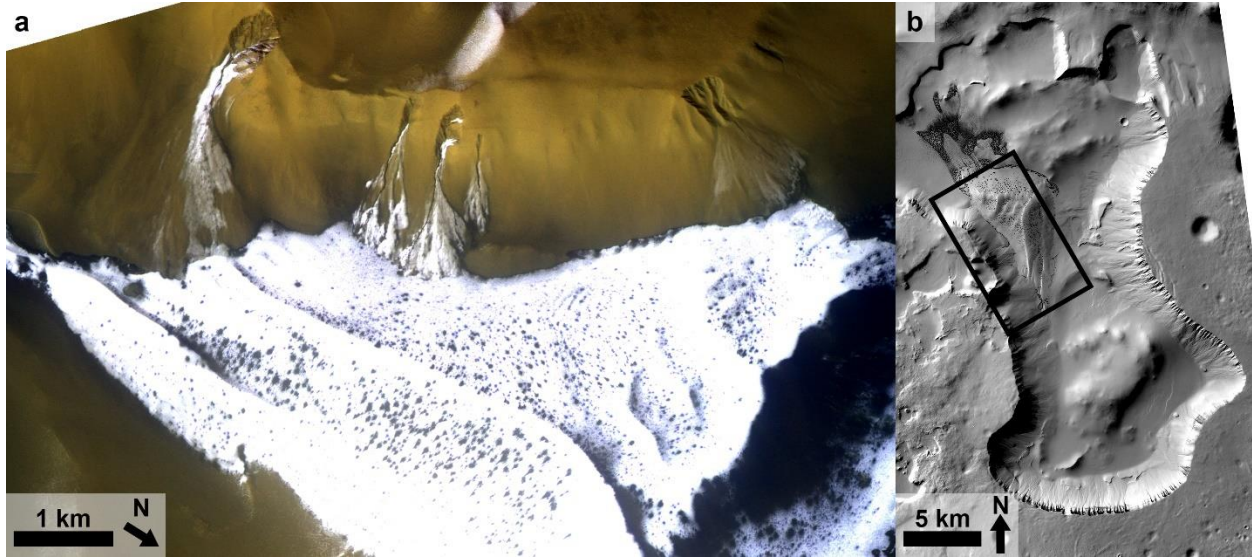


Figure 1: (a) Color and Stereo Surface Imaging System (CaSSIS) image (Thomas et al., 2017) of a gullied slope within the study region. The gullies are the same as those presented in Figure 14. Bright surfaces correspond to the annually deposited CO₂ surface frost cover. This image was acquired at the end of spring when the general defrosting of the study region was already well-advanced. CO₂ surface frosts are only visible on the large dark dune, which is completely covered with a bright ice cover, and on gully aprons / alcoves. Dark spots on the dune show slight flow-like streaks where the slope is highest (on the lower part of the dune). Image (MY34_003464_256_1) was acquired in MY 34 at Ls 242°, flow direction is from top to bottom. (b) Context image of the complete gullied region (Region 5, see Figure 2). Image was acquired in MY 30 at Ls 201° (CTX-image G06_020600_1115) where surface frost covers the complete region and first dark spots on the dune and defrosting of gully alcoves at the north-facing (equator-facing) slope are visible. The black frame represents the location of the CaSSIS image.

1. Study region

The study region comprises the complete Sisyphi Cavi region, an area with numerous polar pits (depressions) up to ~1 km deep (Tanaka and Scott, 1987). Sisyphi Cavi is named after “Sisyphus”, the ancient king of Ephyra. In Greek mythology, Sisyphus was punished in the underworld after his death. He had to roll a large boulder up a steep hill, but each time just before reaching the top of the hill, the boulder would roll down again and he would have to start again. This frustrating punishment including rolling boulders turns out to be surprisingly relevant to this work and shows the name was well-chosen (see Section 3.1.2).

The formation of these irregular steep-sided polar pits in general and specifically in this region is not well understood. The pits are incised into relatively smooth upland surfaces of Amazonian age (Tanaka and Scott, 1987) and some layering is visible at their slopes. There are two large regions with polar pitted terrain (Angusti Cavi at ~290° E and ~77° S; Sisyphi Cavi at ~355° E and ~71° S) near the south pole, which were first noticed on Mariner 9 images and described by Murray et al. (1972) and Sharp (1973) as eolian erosion (denudation) of sedimentary rocks of eolian or volcanic origin. Later, Howard (1981) raised the hypothesis that basal melting of ground ice formed these pits, which was supported by Thomas et al. (1992) who reported that the region consists of volatile-rich polar cap deposits, and by Head (2000) and Ghatan and Head (2002). The basal melting is believed to have been brought about by increased geothermal heat flux in the vicinity of subglacial volcanoes located in the eastern part of Sisyphi Cavi (Ghatan and Head, 2002).

No matter of their origin, the pits of the Sisyphi Cavi form steep slopes in the polar regions. Gullies form preferentially on steep slopes (Conway et al., 2019) so this is one of two polar concentrations of gullies in the southern hemisphere, the other being Angusti Cavi. We defined our study region

from -66° to -76° S and from 340° to 10° E in which nearly all the pits in Sisyphe Cavi were covered (Figure 2). Raack et al. (2015) were the first to study the activity of gullies in Sisyphe Cavi in detail. One of their gullies showed signs of activity every Mars year (MY) during their observation phase between MYs 29 and 31 and was analyzed in detail. Raack et al. (2015) found that sediments were transported down the gully and deposited over and next to the apron. Gully activity appeared during mid-spring when surface temperatures began to rise and the seasonal surface ice sublimated. Based on spectral observations and numerical modeling, the surface ice was identified as CO₂ translucent slab ice with minor contaminations of H₂O ice. The most plausible mechanism for the observed activity were dry flows mobilized over the sublimating CO₂ ice surface (e.g., Cedillo-Flores et al., 2011). The material for the dry flows was most likely to originate from the slopes of the gully channel, triggered by sublimation. Our here presented work includes the active gully analyzed by Raack et al. (2015) and adds new insights based on newly available high-resolution datasets.

Studies of gully activity by Dundas et al. (2012, 2015, 2019) also included the Sisyphe Cavi gullies. Dundas et al. (2012, 2015, 2019) noted activity in them but made no detailed specific morphologic observations. In a study of the topographic long profiles of gullies on Mars, Conway et al. (2015) found that gullies in the polar pits had shallower slopes than those elsewhere and that they had generally a more pronounced curvature. Gullies in Sisyphe Cavi can be named to be “classic gullies” with a distinct alcove, channel, and apron system.

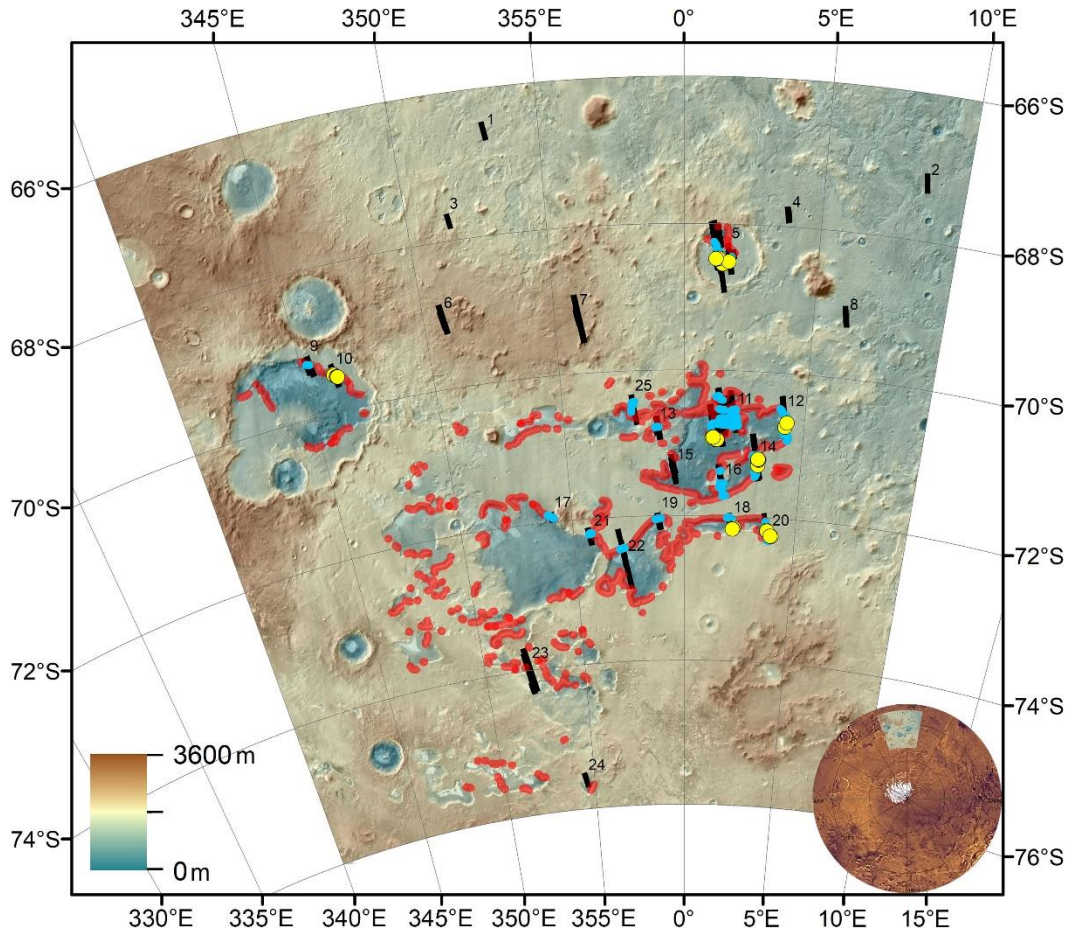


Figure 2: THEMIS-IR data superposed by a MOLA digital terrain model (DTM) of the study region, which comprises the complete Sisyphe Cavi region. Multi-temporal HiRISE image footprints are represented by black rectangles, numbered from north (1) to south (24), except (25) because these multi-temporal datasets were acquired after the begin of our study. These footprints (25) can be found in the middle of the study region. These numbers represent the 25 individual multi-temporal covered study regions which were investigated. Gully activity was found in seven of them (5, 10, 11, 12, 14, 18, 20, see yellow dots). Red dots represent mapped gullies based on CTX imagery ($n = 17,760$), blue dots represent mapped gullies on multi-temporal HiRISE imagery ($n = 2,067$), yellow dots represent contemporary active gullies ($n = 35$) identified on multi-temporal HiRISE images.

2. Data and methods

2.1. Datasets

We used different visual and thermal datasets for our study of active gullies and the defrosting within the study region. For a general overview, context, and topographic information, we used Thermal Emission Imaging System daytime infrared (THEMIS-IR) (Christensen et al., 2004) data combined with a Mars Orbiter Laser Altimeter digital terrain model (MOLA DTM) (Zuber et al., 1992). MOLA polar gridded data (460 m/pix) were used for slope orientation measurements. Furthermore, 28 High Resolution Stereo Camera (HRSC) images (at approximately 12.5 m/pixel, Jaumann et al., 2007) were also used for a general overview of the study region and for frost identification during spring, as a validation of observations with the Context Camera (CTX). CTX images (Malin et al., 2007) were used for mapping and orientation measurements of all gullies and gullied slopes, as well as for identification of defrosting in the entire study region. We used 382 CTX images with a resolution of ~5 m/pixel. Furthermore, we used a CTX mosaic provided by Dickson et al. (2018) as a basis for the mapping of all gullies in the study region. For detailed and multi-temporal investigations, we analyzed 212 multi-temporal (with a coverage of at least two images of same area) High Resolution Imaging Science Experiment (HiRISE) images with a resolution between 0.25 and 1 m/pixel (McEwen et al., 2007b). Two Colour and Stereo Surface Imaging System (CaSSIS) images (Thomas et al., 2017) were used for a color overview of frost-covered gullied slopes.

Visual datasets were identified using the MUTED webtool (Heyer et al., 2018), which provides a direct download link to the PDS Geoscience Node (<http://pds-geosciences.wustl.edu/dataserv/mars.html>). CTX and HiRISE images were downloaded as a pre-processed product for direct integration into an ESRI ArcGIS project. Possible necessary

adjustments of the exact location and perfect co-registration of multi-temporal datasets were done manually in ArcGIS. We identified 25 different regions with multi-temporal coverage (see Figure 1). In seven of these regions, we identified contemporary gully activity (active mass wasting features within gullies). Furthermore, we undertook detailed analyses of the timing of defrosting within these seven regions and measured the orientations of active mass wasting features on HiRISE images.

For thermal investigations, we used data from the Thermal Emission Spectrometer (TES) with a resolution of about 3 km/pixel (Christensen et al., 2001). We used all available daytime surface temperatures, which were collected between ~13:00 and ~15:00 local mean solar time (where maximum surface temperatures occur on Mars), except some data from MY 25. During this year, data were collected during a global martian dust storm that occurred from about end of June to approximately September in 2001 (https://www.jpl.nasa.gov/releases/2001/duststorm_010709.html and <https://mars.nasa.gov/resources/7886/dust-storms-of-2001/>). During this time, the instrument was not able to collect reliable data and surface temperatures were not usable for our study. Consequently, we did not take the data from MY 25 at $L_S 185^\circ$ to $L_S 260^\circ$ (~26th June to ~27th October 2001) into account. In general, TES data were acquired in earlier martian years (MY 24 to 26) than the identified contemporary activity (MY 28 to 34). However, we assume that large variations of surface temperatures within the observation time of our investigations and in the study region did not occur and that annually temperatures did not show any large variations. TES data were processed and downloaded directly from the TES webpage at the Arizona State University (ASU) (http://tes.asu.edu/data_tool/).

2.2. Methods

2.2.1. Mapping of gullies and slopes

We have mapped all gullies within the study region based on CTX images in order to place our detailed observations in context and assess the representativeness of the HiRISE sampling. In total, 17,760 single gullies were identified and marked. Individual gullies were identified by clearly visible alcoves associated with depositional fans, which are the most prominent features of a gully. Channels are more difficult to identify because sometimes their widths are below the resolution of the CTX data used. Hence, some of the identified sites may be relict gullies, lacking channels. We also identified and marked all gullies that were present within the multi-temporal HiRISE imagery (n = 2,067).

2.2.2. Multi-temporal analysis

For the identification of areas with both gully activity and high spatial and temporal repeat coverage of high-resolution images, we used the Multi-Temporal Database of Planetary Image Data (MUTED; Heyer et al., 2018). The web-based tool enables users to identify orbital images covering the same surface area on Mars based on user-defined spatial and temporal constraints. In particular, the database was used to find multi-temporal images with a spatial resolution better than 15 m/pix (for CTX images) within the area of interest.

After the import of multi-temporal HiRISE imagery into an ArcGIS project, we manually georeferenced particular images to get the best visual overlap to identify changes between the images. In a first step, we focused in the comparison of images with similar timings within a year (comparable solar longitudes) and similar solar incidence angles. This was done so as to have comparable shadows on the surface, which makes it easier to identify changes associated with

activity and reduces mistakes, e.g., misidentification of shadows at different angles as mass wasting activity. In a second step, we tried to narrow down the timing of activity to a minimum by analyzing images within a year. If these images are available, (sometimes only a few images within several different years are available), we identified the image “before” and “after” the activity happened, which gives us the maximum timing within a year. For this study, we used the layer-based ArcGIS structure to click manually through all available HiRISE images (Figs. 3-7).

2.2.3. Slope measurements and topography

Slope measurements of six active gullies based on HiRISE-Digital Terrain Models (HiRISE-DTMs) were conducted (in red, Figure 8). We used one publicly released HiRISE-DTM (HiRISE stereo pair ESP_013097_1115 and ESP_013585_1115) in region 5 (Figure 8b) which was downloaded from the UA-HiRISE webpage (<https://www.uahirise.org/dtm/>) and we processed another HiRISE stereo pair, ESP_023290_1090 and ESP_048608_1090, in region 11 (Figure 8a) with the standard routines in the USGS Integrated Software for Imagers and Spectrometers (ISIS3) and SOCET SET (Kirk et al., 2008). Both DTMs were used to visualize the slope angles of the six active gullies (Figure 8: A, B, F, G, L, N) in comparison with non-active adjacent gullies (Figure 8: C, D, E, H, I, J, K, M, O, P). Profile measurements followed the path from the beginning of their alcoves, through their channels, and across their aprons to the termini of the slopes (Figure 8). Vertical exaggeration is about 2.7 in the displayed figures. For a better statistical analysis of all gullies, we calculated the average slope angle of each individual gully separated in segments of 100 m (Figure 8 and Supplementary Table 02). With this method, we were able to identify broad trends in the slopes of the gully profiles.

2.2.4. Orientations

We have undertaken four different measurements of orientations, binned into 10° azimuth intervals: (1) the number of pixels of all gullied slopes identified on CTX imagery ($n = 8,303$) based on an aspect map derived from a 21-pixel moving window applied to the MOLA polar gridded data at 460 m/pix, (2) all individual gullies ($n = 17,760$) found on CTX imagery, (3) the number of pixels of all gullied slopes identified on HiRISE imagery ($n = 1,430$) also based on the same aspect map used for gullied slopes identified on CTX imagery, and (4) all active gullies ($n = 35$) based on multi-temporal HiRISE imagery (Figure 9). Individual gully orientation measurements were derived from the mapped gully alcoves (as points) and sampling the value directly underneath the point representing the alcoves of the underlying MOLA aspect map. Orientations of active gullies were derived from the long profiles of the gullies they were hosted in and, if possible, from the direct visible path of active dark flow-like feature. The analysis of the gullied and non-gullied slopes was carried out on all pixels with slopes $> 6^\circ$ because this value was the lowest value that reliably captured all the gullied and non-gullied slopes without including parts of the plateaux or pit-floors. Please note that the resolution of the MOLA aspect map smoothed out the gully-alcoves so that it represents the general orientation of the hillslope. The number of pixels of all gullied slopes (1) and (3) were divided by the orientation of all pixels of all slopes (gullied and non-gullied CTX-identified slopes: 43,632 pixels in total; gullied and non-gullied HiRISE-identified slopes: 1,648 pixels in total) to account for the influence and biases of the general pre-existing topography, resulting in normalized data. Densities for all gullies (2) and active gullies (4) were calculated by (2) dividing the number of all gullies by the total area with gullies based on CTX imagery (in pixels) for each orientation, and (4) dividing the number

of all active gullies by the total area with gullies based on multi-temporal HiRISE imagery (in pixels) for each orientation, respectively.

2.2.5. Slow small-scale displacement detection

To investigate the possibility of small-scale movements like creep as precursors to gully activity, which can only be observed over multi-annual time scales, we applied a method called digital image correlation (DIC). We produced four HiRISE-DTMs of region 11 to investigate the flow event that occurred between MY32 and 33 (Figure 4) as well as to study general gully activity in the region. We used five HiRISE-images: PSP_005621_1090, ESP_023290_1090, ESP_030859_1090, ESP_039747_1090 and ESP_048608_1090 to cover the time between MY 28 and 33. DTM production was conducted using the Ames Stereo Pipeline (ASP, Beyer et al., 2018). Governed by the available HiRISE images, all produced DTMs are either pre-event or co-event DTMs, i.e., no post-event DTM could be produced. The change in surface appearance and texture due to the recent flow feature that occurred between MY 32 and 33 is minimal and did not influence the quality of the image matching during stereo correlation. All images were bundle adjusted and matching was performed with a Bayes EM-weighted affine adaptive window correlator to ensure the highest possible DTM quality. Due to the good correlation quality, the point cloud files could be meshed to DTMs with very high spatial resolutions ranging from 0.5 to 3 m/pixel. Despite the low noise content, all DTMs feature distinct striped inter-CCD seam artifacts that are common for HiRISE-based DTMs. Tab. 2 in the Appendix reports additional relevant details about the produced and used DTMs.

Orthorectification was performed using the Ames Stereo Pipeline, where DTMs from timeframes MY 28 to 30 and MY 28 to 33 have been used to orthorectify HiRISE images PSP_005621_1090,

ESP_023290_1090, and ESP_048608_1090 (Figure 10). This was necessary because digital image correlation (DIC) needs highly accurate orthorectification to extract small-scale horizontal surface displacements.

DIC is an image processing technique that allows for the quantification of coherent, in-CVP (camera viewing plane) surface displacements in multi-temporal imagery (Ayoub et al., 2009; Heid and Kääb, 2012; Bickel et al., 2018). The technique is limited by its ability to co-register pixel neighborhoods within a specified search window, i.e., incoherent or too large surface displacements between two image acquisitions will cause a loss of signal. This usually limits the applicability of DIC to monitoring of continuous and slow displacements, e.g., of glaciers (Heid and Kääb, 2012), volcanic edifices (Casu et al., 2011), and slow moving landslides (Bickel et al., 2018). This limitation is particularly restrictive for space- and airborne sensors, as revisit rates are usually lower and the displacement of objects between two acquisitions might be larger, and potentially, too large. On Mars, DIC has successfully been applied to monitor dune migration and sand fluxes using HiRISE imagery, e.g., in Nili Patera (Bridges et al., 2012) although it was unsuccessful for coseismic displacement of faults in Cerberus Fossae on Mars (Grindrod et al., 2018).

The three above mentioned orthorectified HiRISE images have been selected for the DIC analysis for two reasons: 1) Their maximum temporal baseline, as a larger difference in time will allow for the detection of smaller displacements (PSP_005621_1090 of MY 28 and ESP_048608_1090 of MY 33); and 2) As they could potentially indicate pre-event displacement in the gully of interest (PSP_005621_1090 of MY 28 and ESP_023290_1090 of MY 30). Prior to DIC ingestion, a dynamic contrast enhancement has been applied (Wallis filter) and all orthorectified images were co-registered with sub-pixel accuracy, as past studies have found that these steps generally increase

the correlation quality and coverage of the displacement field, if present (Bickel et al., 2018). Subsequently, a frequency domain-based DIC code that is applying a Fast-Fourier-Transform (Bickel et al., 2018) has been used to analyze the potential displacement between both image pairs, using varying template and search window sizes. No post-processing of the results has been performed to maintain the full interpretability of the results.

2.2.6. Thermal investigations and seasonal frost coverage

For thermal investigations, we collected all TES surface temperature datasets from MY 24 to 26 (except some measurements in MY 25 due to the influence of a global dust storm, see above) and binned them into five groups of 2° of latitude from 66° to 76° . We then calculated the mean of all individual measurements at the same time with their associated standard deviation (black lines of red dots in Figure 11). For our thermal studies, we investigated all available surface temperature datasets of all years together (except some data from MY 25 due to a global dust storm). No further division into different MYs was done because annually variations of MY 24 and 26 are small and negligible.

Furthermore, we also detected and investigated the seasonal frost coverage based on CTX and HRSC imagery. We identified seasonal frost coverage by its bright appearance compared to unfrosted regions (well-defined during the sublimation phases in spring by dark defrosting spots) and the assumption, that the study region is covered by surface frost during the winter, which was shown by Raack et al. (2015) in the same study region and substantiated by the general low surface temperatures during winter (Piqueux et al., 2003). For investigations of the timings of surface frost, we looked into all available CTX and HRSC images of the study region. We generalized the frost cover and marked an image as “frosted” even when only a small part of the image shows bright

ice cover. This results in detailed information on the timing of surface frost in the complete study region based on two different datasets without detailed analyses of local differences of frost coverage such as orientations and altitude.

3. Results

We have identified 25 regions with multi-temporal HiRISE coverage (see black rectangles in Figure 2), 13 regions include coverage of gullies. In total, 2,067 individual gullies were identified on multi-temporal HiRISE images. In seven regions we identified contemporary active mass wasting features within gullies. Overall, we found only 35 (~1.7 %) individual gullies that showed activity within MY 28 to 34 (yellow dots in Figure 2 and Supplementary Table 01). One large gully showed two independent activities at two different places in the wide alcove, therefore we classified these activities as gully independent activities 32 and 33 (see Supplementary Table 01). The activity can be divided into flow-like features ($n = 22$), as well as block movements within gullies ($n = 16$), where three of them are combined features which makes 35 active gullies in total. For seasonal investigations, multi-temporal coverage of some images within one martian year are necessary. Due to the greater frequency of HiRISE-coverage of some regions within the study area, we were able to narrow-down the activity of 10 gullies during one martian year.

3.1. Present-day mass wasting activity on multi-temporal HiRISE imagery

Present-day activity was defined by clearly visible erosion and/or deposition of material down a gully. Although some gullies could also show seasonally generated albedo differences and dark flow-like features, no sediment transport was detectable in these gullies so we classify these gullies

as “non-active”. We distinguished between flow-like features (dark toned flow-like forms with visible transport of material) and block movements (movement of blocks down the gully slope).

3.1.1. Flow-like features

The most widespread present-day activity of gullies are flow-like features. We found 22 gullies with active flow-like features or new deposits and erosion forms most likely caused by flow-like activity. Three of them are associated with identifiable block movements. Ten of these 22 active gullies show flow-like activity within only one MY and six of these ten gullies show repeated activity. In detail, three gullies show activity in two separate MYs, two gullies within three different MYs, and one gully shows activity within five MYs (see Supplementary Table 01). Movements within repeatedly active gullies originated in the same places and covered the same depositional areas of the gully.

Flow-like features have identifiable transport of sediment, which is probably dust and/or sand (Raack et al., 2015). The presence of pervasive surface sand/dust is supported by the presence of pervasive surface ripples and the seasonal appearance of dark spots on gully aprons, and next to or within gully channels. These dark spots are likely formed by transport of sand and dust from under the translucent slab ice (e.g., Piqueux et al., 2003; Kieffer et al., 2006; Thomas et al. 2011) as larger particles cannot be mobilized (see further discussion of these features in Section 4.1).

Based on our seasonal observations, we found that the flow-like features occurred episodically, i.e., changes appeared between two images and were not gradual. This was observed as an accumulation of gully channel material in the "before" image, whereas the "after" image displayed distinct flow features over the apron (Figure 3). Sometimes, the deposited material was observed without observable accumulation of material in the channel beforehand. The flow-like features

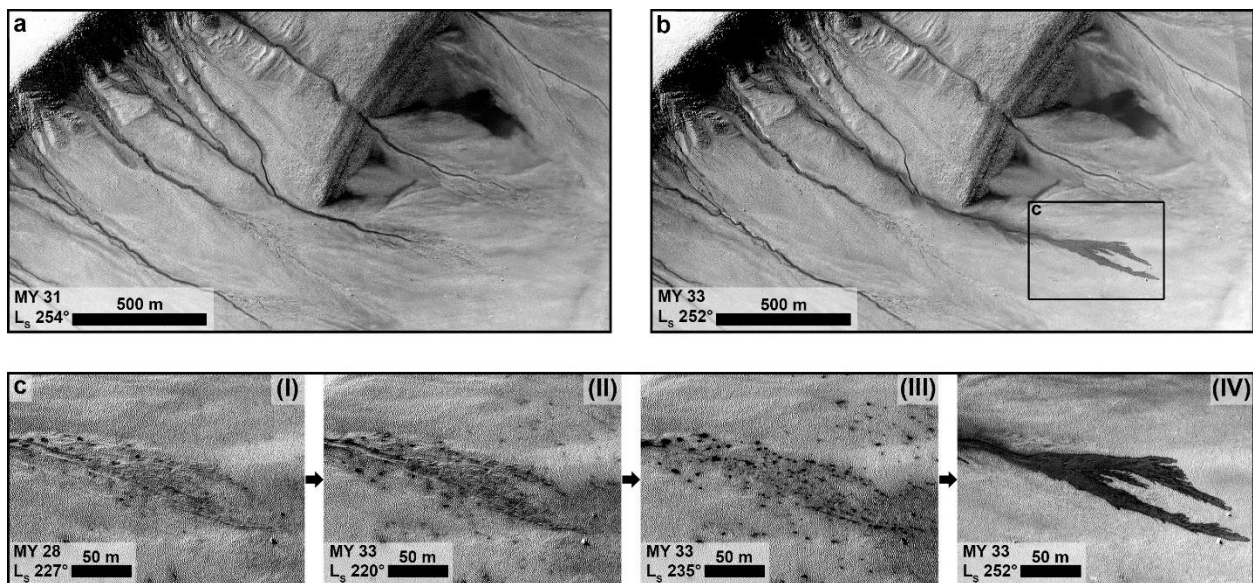
appear dark compared to their surroundings. Over time, the transported material brightens and fades until mid-summer, which could be due to gradual deposition of dust, comparable to the fading of, e.g., dust devil tracks (Reiss et al., 2016) and slope streaks (Schorghofer et al., 2007). However, fading of a flow-like feature in Sisyphi Cavi was also observed by Raack et al. (2015) and their investigation of the corrected Lambert albedo images showed that the flow-like feature did not brighten, but that the surroundings darkened over time due to seasonal frost sublimation. In summer, the surroundings and the flow-like features have a very similar albedo which can only be observed in the corrected albedo images. This indicates that the brightening is not caused by dust deposition but is a result of frost sublimation. The brightening did not appear to alter the changes in surface relief associated with the dark flow-like features, therefore this study will focus on the formation of these mass movements and not their fading.

In some cases, seasonal observations were not possible and no dark flow-like features were identifiable, but a change of the surface relief caused by sediment transport was still visible. In Figure 4 an example flow-like feature is shown, with the formation of relatively small new transportation channels (Figure 4b), block movement (Figure 4b), erosion of ripples or superposition of ripples with transported material (Figure 4c), and a general change of the relief of the surface. Thickness and consequently volume calculations cannot be made because it was not possible to measure the height of the newly formed deposits, either on digital terrain models (DTMs) or with shadow measurements (for some volume estimations, see Raack et al., 2015). This indicates that the deposits have a thickness of some decimeters or less.

One gully (#3) in the study region had clearly identifiable headwall erosion and loss of material, which was transported down the gully. This was the only gully where the source region of transported material was clearly visible and measurable (Figure 5). Raack et al. (2015) analyzed

the same gully but no source region for the identified activity was found as it only became apparent in more recently acquired images. At some localities, the gully-alcove headwall erosion of up to several meters (max. ~5 m) occurred between MY 29 and MY 33. This headwall erosion is the first and only evidence of a clearly identifiable source region for transported material in the study region.

The only noticeable features located upslope of observed sediment transport are small (up to ~15 m), dark flow-like features on the steep flanks of the gully channels (Figure 6). These features were found in some active gullies, as well as in non-active gullies. We infer that sediment erosion and transportation are taking place at these locations, because there dark layers paralleling the crest of the gully channel flanks (Figure 6 d-e), from which the small dark flow-like features emanate. A second indicator for sediment transport, even if it is not topographically visible, is the accumulation of dark material within gully channels (Figure 6). These accumulations are formed by confluence of the small, dark flow-like features. This was also proposed, but not directly observed by Raack et al. (2015), due to the lack of datasets with sufficiently high resolution.



443 **Figure 3:** Before and after images of a south-east facing slope of a polar pit (Region 5, see Figure
444 1) within MYs 31 and 33 at comparable L_s of 254° **(a)** and 252° **(b)**. The downslope direction is
445 from top left to bottom right. The active part of the gully in the middle of the images (gully #1,
446 same as gully N in Figure 8b) is apparent because of the appearance of a dark flow-like feature in
447 MY 33, which superposes the existing apron and has deposited new material. **(c)** I-IV Detailed
448 views of the evolution of the appearance of the active part of the apron in MY 28 (L_s 227°) and
449 MY 33 at L_s 220° , 235° , and 252° . Between the first (*I*, MY 28) and the second image (*II*, MY 33
450 at L_s 220°), there is no identifiable change of the surface, except for in the pattern of the annually
451 active dark defrosting spots. Between the second (*II*) and the third (*III*) image, these dark defrosting
452 spots expand, but no flow is visible. 26 sols later in the fourth (*IV*) image, a dark flow is visible
453 and the dark defrosting spots are no longer visible, which indicates advanced sublimation of the
454 slab ice and probably the complete defrosting of the surface. HiRISE-images **(a)**
455 ESP_030503_1115, **(b)** ESP_048107_1115, **(c)** (*I*) PSP_003511_1115, (*II*) ESP_047039_1115,
456 (*III*) ESP_047751_1115, (*IV*) ESP_048107_1115. North is up in all images.

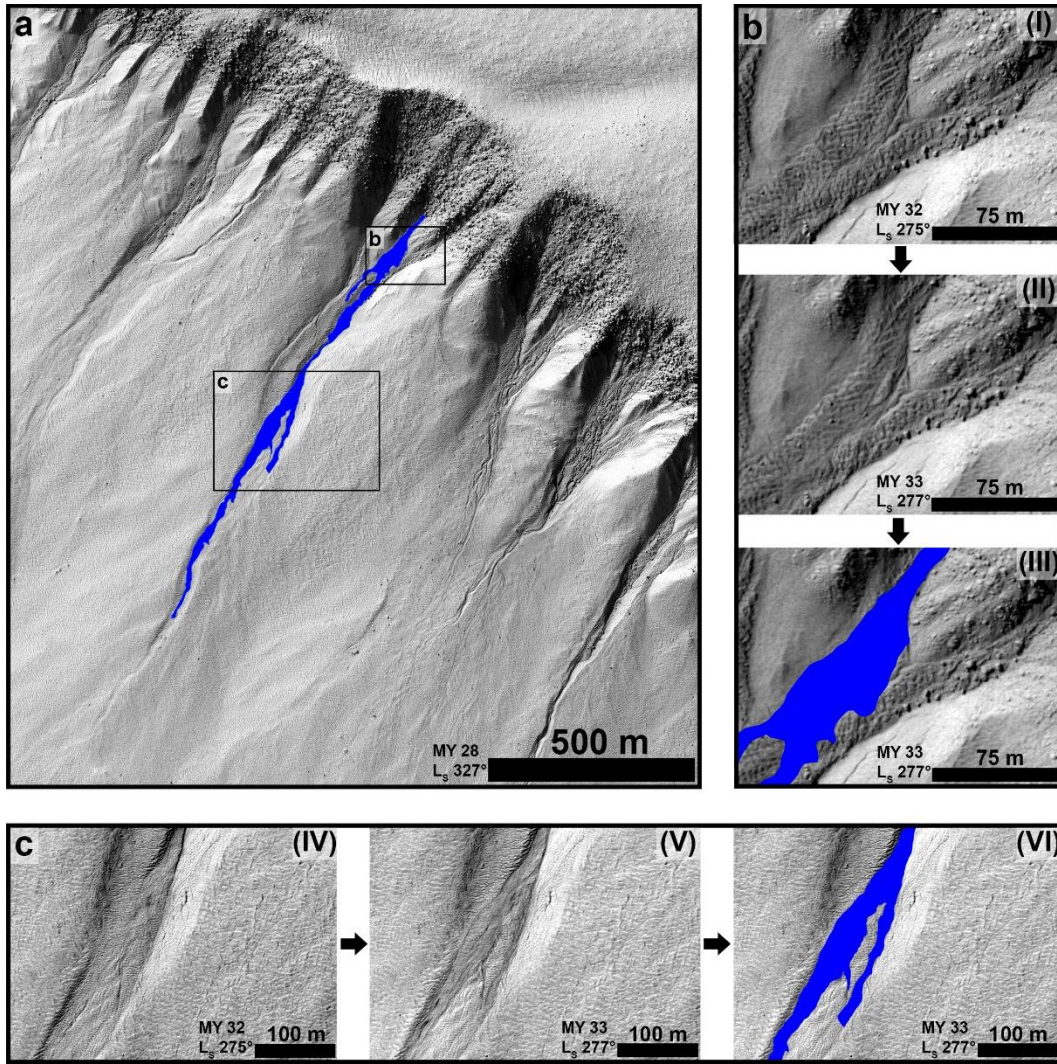


Figure 4: (a) Present-day active gully #11 (MY 28, L_s 327°) on a south-west facing slope in Region 11 (see Figure 1 and gully A of Figure 8a). The area within the gully affected by the activity (erosion and deposition of material) is mapped in blue. With more than 1 km in length, this active mass wasting form was the largest identified in this study. (b) (I-III) Close-ups of a part of the gully alcove before (I), in MY 32 at L_s 275°, and after (II), in MY 33 at L_s 277°, almost exactly one martian year apart. The third image (III) shows the affected region (mostly by erosion) mapped in blue. (c) (IV-VI) Close-ups of a part of the gully's transportation channel before (IV), in MY 32 at L_s 275°, and after (V), in MY 33 at L_s 277°, comparable to (b) in terms of timing. Similarly, the third image (VI) shows (mapped in blue) the region affected by activity, by erosion, as well as

deposition. HiRISE-images (a) PSP_005621_1090, (b) (I) ESP_039747_1090, (II and III) ESP_048608_1090 (c) (IV) ESP_039747_1090, (V and VI) ESP_048608_1090. North is up in all images.

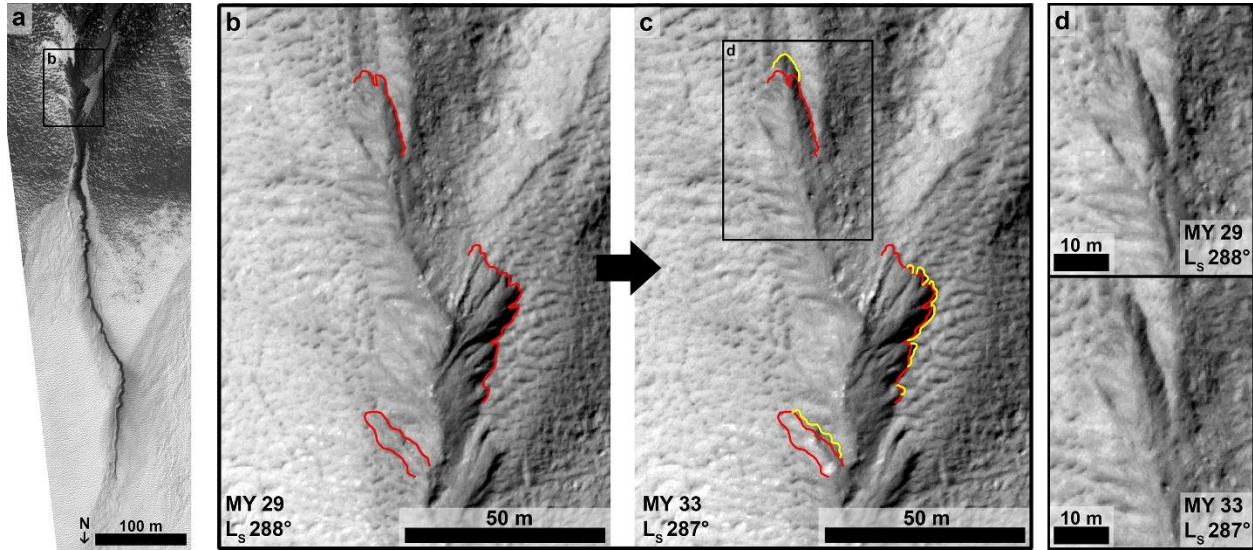


Figure 5: Headwall erosion of active gully #3 presented in Raack et al. (2015) (also seen in Figure 8b – gully G). (a) Overview of the active gully. The gully shows activity every year in the form of a large, dark flow within the gully channel and new material superposition on top of the gully apron (Raack et al., 2015). (b) Detail of the gully alcove in MY 29 at the beginning of summer (Ls 288°). The large gully alcove was filled with material (rippled surface, presumably ice-rich mantle, e.g., Mustard et al., 2001; Raack et al., 2012), which is eroded, leading to a smaller gully alcove. Red lines represent clearly identifiable outlines of the headwall of the alcove. (c) In MY 33 at the beginning of summer (Ls 287°) headwall erosion of a few meters could be identified (yellow lines represent the new headwall of the alcove). Especially the uppermost region of the gully alcove shows the highest erosion rate within the four martian years. (d) Detail of the top of the gully alcove in MY 29 and 33. Erosion of a few meters of material is clearly visible. HiRISE-images (a) ESP_029725_1115, (b) ESP_013585_1115, and (c) ESP_048819_1115. North is down in all images as indicated.

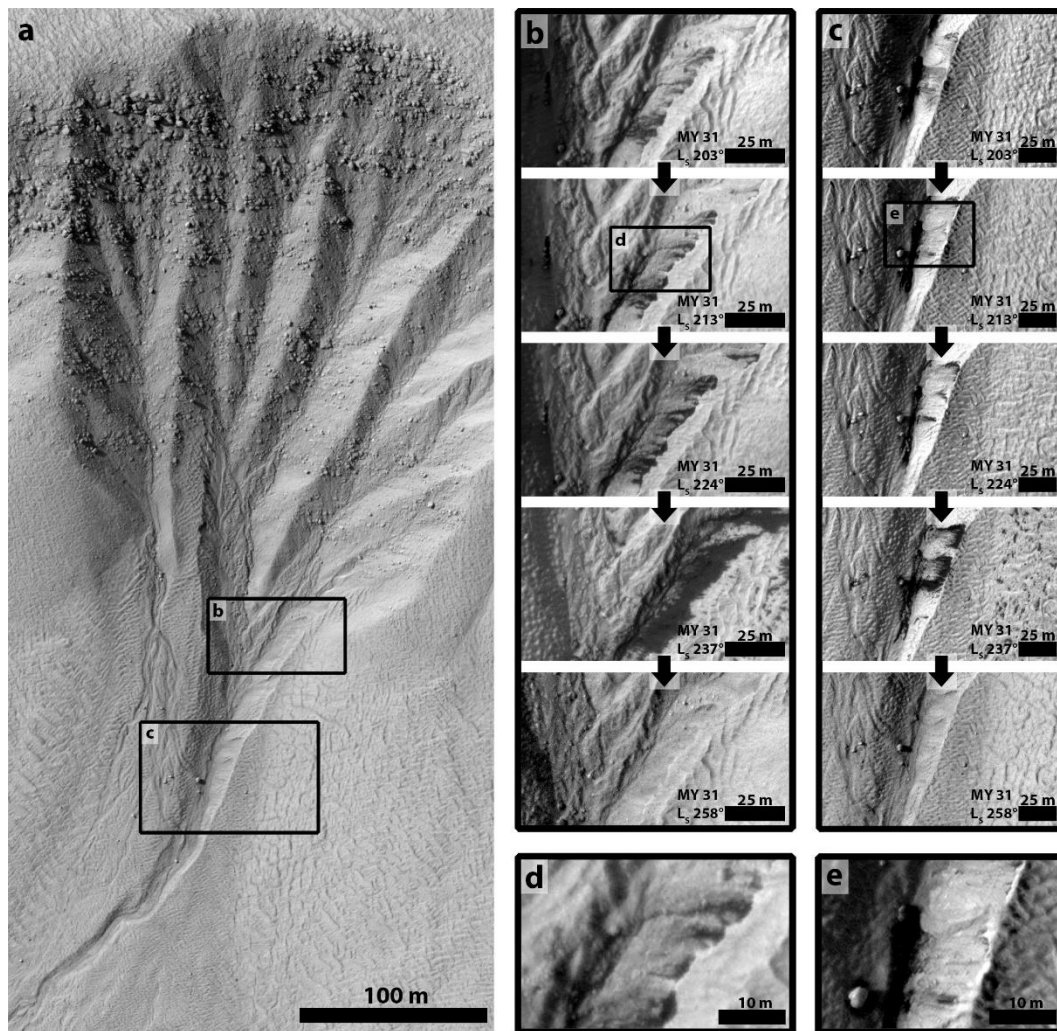


Figure 6: (a) Example of a gully alcove with identifiable small, dark flow-like features emanating from a layer on gully channel flanks. Here, the small, dark flow-like features are too small to show any transported sediment. The small, flow-like features accumulate within the gully channel, but there is no associated large flow-like feature with transported material. (b) + (c) Two detailed image time series of the gully channel from beginning of spring (Ls 203°) until the end of spring (Ls 258°) where defrosting is at its maximum. Dark material flows down the gully channel flank into the interior of the channel. Here, dark material accumulates and flows down the gully channel, which is detectable in (c). (d) + (e) Details of the layer on the gully channel flanks from where the dark material emanates. The layer is only several meters wide and identification with HiRISE

images is difficult. **(a)** Overview: HiRISE-image ESP_040486_1105 (L_s 309°). **(b)** + **(c)**
Sequence: HiRISE-images ESP_029475_1105, ESP_029686_1105, ESP_029897_1105,
ESP_030174_1105, and ESP_030609_1105. North is up in all images.

3.1.2. Activity of block movements

Block movements are clearly identified transported blocks of about 1-2 m in diameter between
images which could have slid, tumbled or rolled down slope under gravity or have been transported
in a flow. In the study region, block movements only occur within gully alcoves where slopes are
relatively steep and have undergone more recent modification compared to non-gullied slopes.
Furthermore, gully alcoves uncover an underlying rocky surface, which is otherwise superposed
by a mantling deposit in this region (Figure 7). This rocky surface is often the source for blocks,
which then move down the slope.

We observed 16 different gullies (three of them also associated with identified dark flow-like
features) with identifiable block movements within the study region. Only one block movement
could be seasonally investigated (Figure 12), while all other block movements occur in regions
with only limited temporal HiRISE-coverage. The number of 16 block movements is a minimum
number because block movements are hard to identify and some block movements (particularly
short displacements) are likely to have been missed during our investigations. Three of the
identified gullies show a combined activity of flow-like features and block movements. Here,
blocks moved several meters in the same direction as the flow-like features and/or were superposed
by transported material. In the last case it is hard to distinguish between moved blocks or just
superposed blocks by loose fine material. Tracks associated with the block movements were not

found. Only in one case (Figure 7), the path of the block down the slope is roughly traceable by the displacement of some other blocks.

The distance moved by the blocks varied between ~1 m to 230 m at maximum (Figure 7b). Most blocks moved only 1-2 meters ($n = 9$), which typically corresponds to a block rolling from one face to another. The other remaining block movements ($n = 6$) moved between 5 and 40 meters.

In one case, a block seemed to disappear completely, which means it was not found in the ‘after’-image and therefore the travel distance could not be measured.

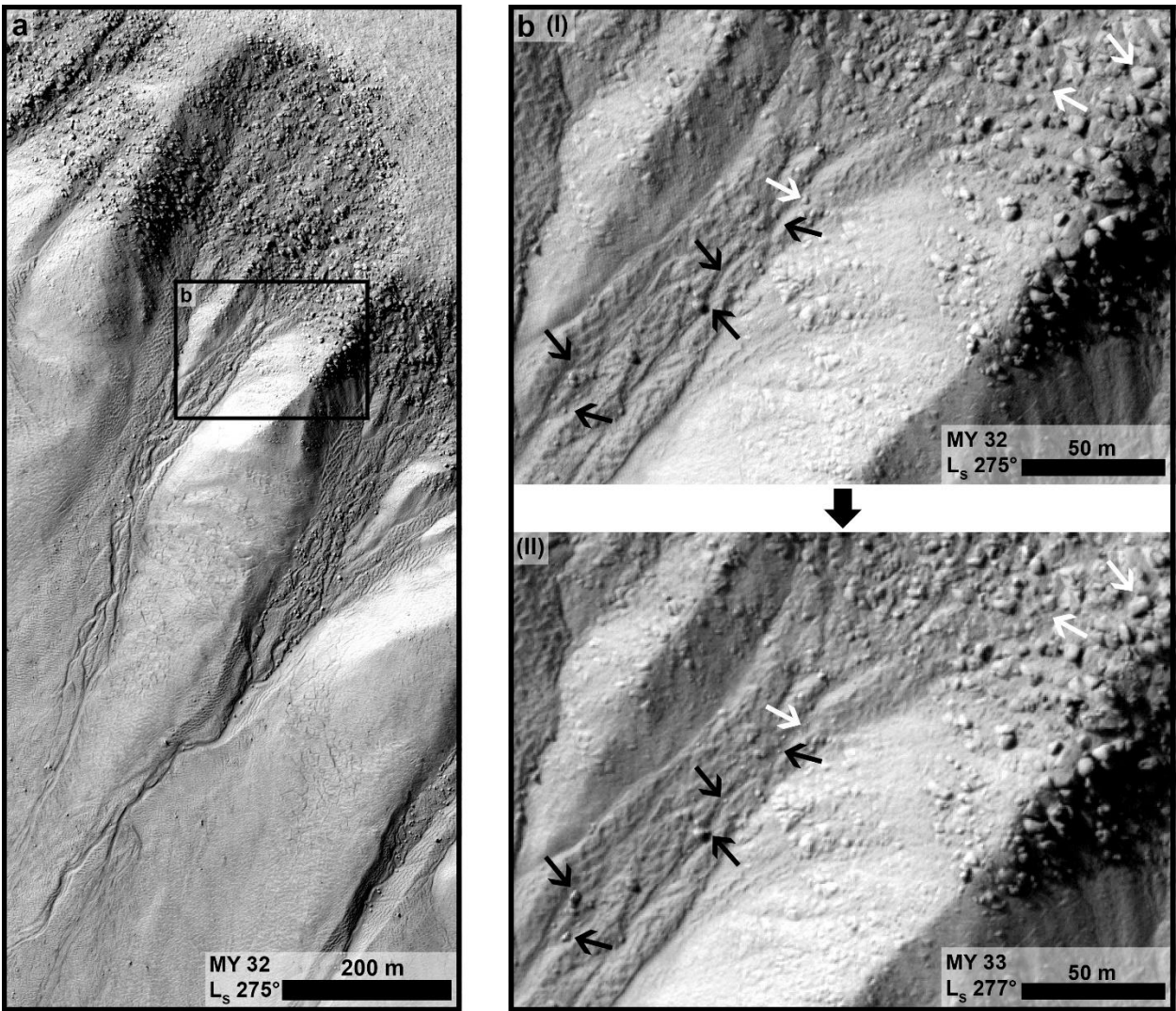


Figure 7: (a) Gully #12 with present-day activity in form of block movement within the alcove in Region 11 (see Figure 2) on a south-south-west facing slope. Overview image **(a)** and detail **(b)** (*I*) were taken in MY 32 at L_s 275°. **(b)** Detail is presented as before (*I*) and after (*II*) images whereupon the after (*II*) image was taken nearly exactly one martian year later (MY 33 at L_s 277°) than the before image. White arrows point to eroded/disappeared blocks, while the black arrows point to newly deposited blocks. The transported blocks are generally only a few pixels in diameter (~1 m); only the largest block (lower left) has a diameter of about 4-5 m. HiRISE-images **(a)** and **(b)** (*I*) ESP_039747_1090, **(b)** (*II*) ESP_048608_1090. North is up in all images.

3.2. Topography, orientation, and digital image correlation

To identify possible mechanisms responsible for the identified present-day activity of gullies in Sisyphi Cavi, we investigated the topography of the active gullies based on HiRISE DTMs, the orientation of all slopes and gullies in the study region, and possible small-scale surface changes / activities based on digital image correlation of HiRISE images.

3.2.1. Topography

We measured the topographic long profiles of selected gullies on slopes of region 11 (Figure 8a) and region 5 (Figure 8b) by tracing the path of the gullies from the top of the alcove to the end of the depositional fan. Gullies marked by red profiles in Figure 8 show present-day activity and the position of the activity is bracketed by black bars with arrows.

In region 11, the shape of all the gullies (6 measured gullies, 3 with present-day activity) is very comparable (Figure 8a (1)), and no systematic differences in the general shape of the long profile between active and non-active gullies could be identified. All gullies have a rectilinear profile with

547 a steeper upper part and shallower lower part, which starts around 400 m downslope,
548 corresponding to the change from exposed rocks to fans. Present-day activity originates at the
549 steeper upper part of the gullies and material is subsequently transported down the gully channel
550 to where slopes are shallower (around 10° - 15°).

551 Furthermore, the average slope angles calculated every 100 meters of gully length (Figure 8a (2))
552 are broadly similar. The average slope angles in the alcove area reach maxima of between 30° and
553 45° and diminish to around 20° towards the base of the alcoves. The alcoves show a higher
554 variation in slopes compared to the rest of the profiles. The remaining downslope parts of the
555 profiles have relatively constant slopes of around 10° , which drop to 5° in the last few hundred
556 meters. Two of the three active gullies (A and B) have steeper average slope angles in the first 200
557 to 300 m, while other non-active gullies only show shallower slope angles. Gully slopes A and B
558 could be not measured in their entirety (the end of the profile is missing) because the DTM does
559 not cover the complete slope.

560 The profiles of the gullies in region 5 are very comparable to those in region 11. However, they
561 appear a somewhat smoother and have shorter, steeper upper parts (around 200-250 m) than the
562 gullies in region 11 (Figure 8b (3)). Comparable to region 11, gully activity originates on the
563 steeper slopes at the beginning of the gully profile and continues down to shallower sloping
564 regions. Furthermore, the gullies in region 5 are also very comparable to each other, except gully
565 L, which appears smoother at the beginning than the others and has a steeper slope angle at the
566 end (similar to gullies H and M). The smooth beginning is because the top of the profile is not
567 included in the DTM. The increase of average slope angles at the end is caused by the occurrence
568 of a ridge at the base of the slope (Figure 8b (4)). All other profiles show comparable patterns as
569 well as comparable average slope angles. Slope angles decrease from up to $\sim 50^{\circ}$ (alcove of gully

570 N) down to $\sim 0^\circ$ (apron of gully L). Consequently, no differences of active and non-active gullies
571 in region 5 was found.

572 The average slope angles of all measured gullies of both regions are provided in Supplementary
573 Table 02. The average slope angles for the entire lengths of all measured gullies varied between
574 16° and 10° (gullies A and B are not taken into account because the profiles do not extend to the
575 terminus of the hillslope and therefore have anomalously higher average slope angles). The
576 average slope angles of for the entire lengths of the active gullies ranges between 15° and 10° ,
577 which provides additional confirmation that no difference in topography between active and non-
578 active gullies is measurable.

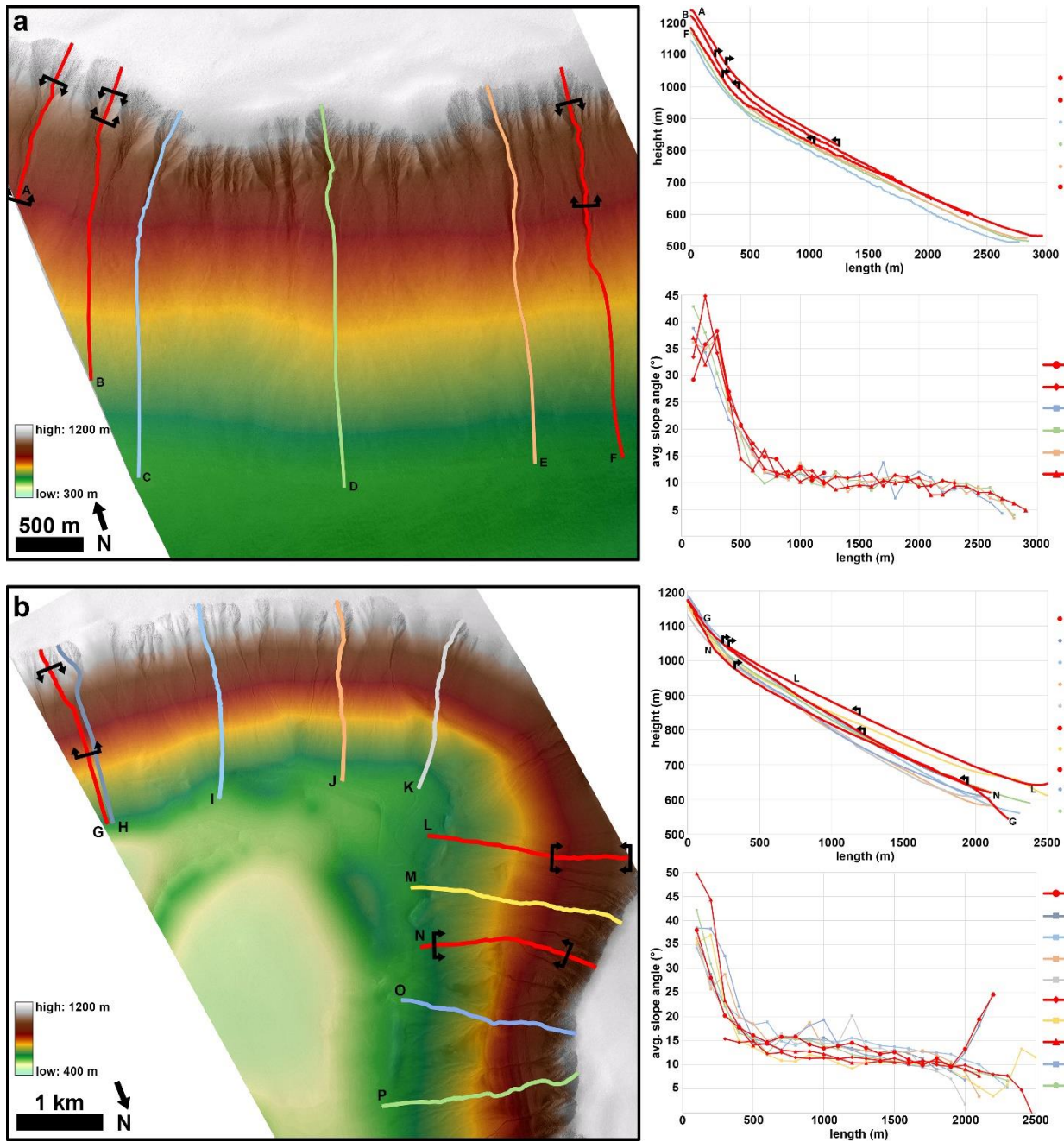


Figure 8: (a) Colorized DTM from HiRISE stereo pair ESP_023290_1090 and ESP_048608_1090 in region 11 (see Figure 2) with semi-transparent orthophoto. On the right side are the associated topographic profiles as a function of height vs. distance from top of the alcove (above) and as a function of average slope angles as calculated over 100 m segments (see also table 1) vs. distance (below). The profiles start at the crest of the alcove and end at the visually

identified terminus of the hillslope. Note that the termini of measured gullies (aprons) often stop before the end of the slope. Active gullies (A, B, and F) are marked in red; between the areas of the black bars with arrows, contemporary activity was identified. **(b)** Colorized DTM of HiRISE stereo pairs ESP_013097_1115 and ESP_013585_1115 in region 5 (see Figure 2) with semi-transparent orthophoto. See also Raack et al. (2015) for more information of this specific area. On the right side same profiles as in (a). Active gullies (G, L, N) are also marked in red. Profiles G and H have increasing slopes at the end of the profile due to the presence of a small local depression. However, this has no influence on the gullies because the depression is located beyond the end of the gully deposits.

3.2.2. Orientation

To identify a possible triggering mechanism of gully activity and to find differences between active and non-active gullies, the orientations of gullies, gully densities, and gullied slopes based on CTX and HiRISE imagery of the complete study region were investigated. Four different measurements were performed:

- (1) Orientation of pixels identified on MOLA gridded data (460 m/pix) of gullied slopes (slope angle $> 6^\circ$) found on CTX imagery. In total, 8,303 pixels cover all gullied slopes and show a clear north-south trend (Figure 9a). After normalization against all slopes $> 6^\circ$ in the complete study region (35,329 pixels), the north-south trend is still visible (Figure 9b), but not so distinct compared to non-normalized data. Both the normalized and non-normalized orientation plots show a slightly preferred south-facing (or pole-facing) trend for all gullied slopes.

(2) Orientation of all gullies in the study region based on CTX imagery. In total, 17,760 individual gullies were identified and measured. The data show a strong north-south trend with slightly more south-facing gullies than north-facing gullies (Figure 9c). The density of gullies is remarkably uniform with orientation (Figure 9d). The highest peak of gully density is found between 50° and 60° (northeast) and a slightly lower density of gullies is found on south- to west-facing slopes.

(3) Orientation of pixels identified on MOLA gridded data (460 m/pix) of gullied slopes (slope angle > 6°) found on multitemporal HiRISE imagery. In total, 1,430 pixels cover all gullied slopes (Figure 9e), while only 218 pixels cover non-gullied slopes. This is an effect of the intensive monitoring of gullied slopes with the HiRISE camera in this region. After normalization against all slopes > 6° of multitemporal HiRISE-covered slopes (1,648 pixels), a very uniform distribution is visible (Figure 9f).

(4) Orientation of all active gullies based on multi-temporal HiRISE imagery. In total, 35 individual gullies show present-day activity and were measured. The data show a southwest and a northwest facing trend (Figure 9g). The color-coding represents dark flow-like features (in red) and block movements (black). Only two gullies are east facing. The density clearly shows a higher density of active gullies facing northwest (Figure 9h). Same color-coding as in Figure 9g), which shows the highest density of flow-like features orientated towards north-west. Comparison with Figure 9e reveals that the lack of active east-facing gullies could be due to imaging bias, but that the lack of north-facing active gullies is most likely real.

In summary, gullies tend to be oriented north-south in the study region with a slight bias towards south-facing slopes and the highest density towards the north. In contrast, active gullies tend to be

oriented towards the northwest and to a lesser extent the southwest, with a lack of north-south facing active gullies.

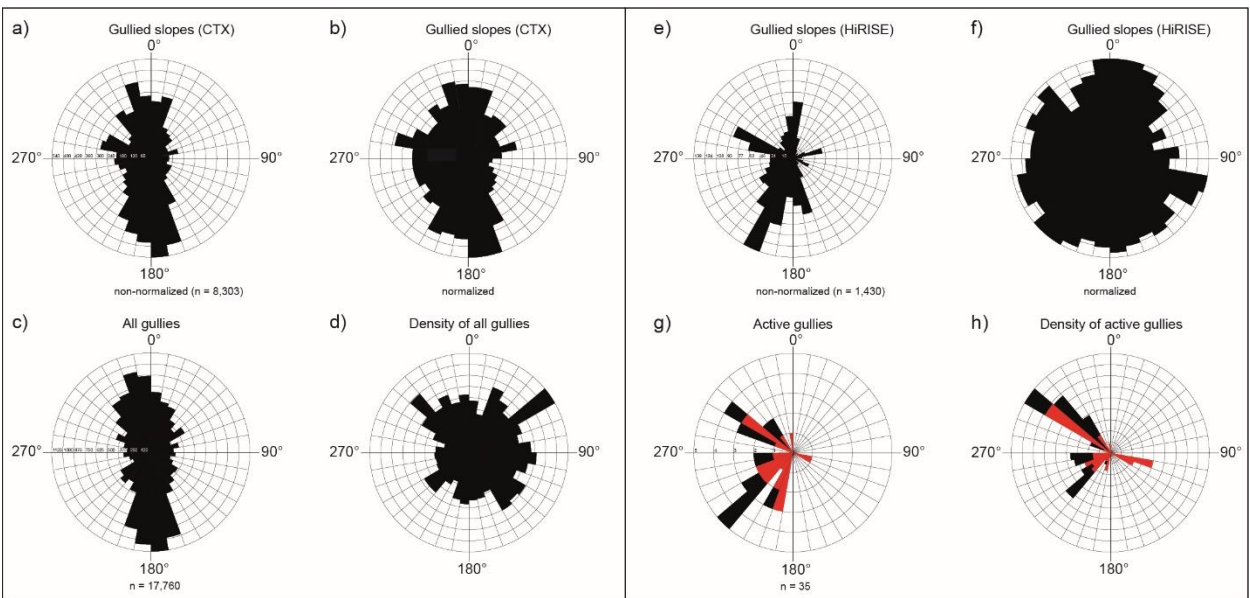


Figure 9: (a) Orientations of all sloping pixels with gullies based on MOLA data ($n = 8,303$) and (b) the same data normalized against all sloping pixels. (c) Orientations of all mapped individual gullies ($n = 17,760$) based on CTX imagery and (d) densities of all mapped gullies measured in units of gullies per MOLA pixel (the data in c divided by a). (e) Orientations of all pixels with gullied slopes included in multi-temporal HiRISE imagery ($n = 1,430$) and (f) normalized by the total number of sloping pixels covered by multi-temporal HiRISE images. (g) Orientations of all investigated present-day active gullies ($n = 35$) identified in multi-temporal HiRISE imagery (red = dark flow-like features and black = block movements), and (h) densities of all active gullies measured in numbers of gullies per pixel (the data in g divided by f), same color-coding as in (g).

3.2.3. Digital image correlation

The correlation of both HiRISE pairs at location 11 that cover the event between MY32 and 33 (see also Figure 4) does not show any displacements in the periods from MY 28 to 30 (pre-event)

and to 33 (co-event), respectively (Figure 10). This could indicate that 1) there is no pre-event displacement of the hillslopes hosting the investigated martian flow-like features, and 2) that there is no slope creep occurring at all or that such creep is smaller than 25 cm within the five observed martian years, i.e., less than ~5 cm per MY on average.

Parts of the displacement fields (Figure 10) show systematic and erroneous displacement values that are the result of either 1) moving shadows that are caused by slightly different illumination conditions for the used images or 2) inter-CCD seam artifacts. These types of artifacts cannot be avoided, which is why the respective areas have been masked to maintain clarity (Figure 10). The low root mean square error (RMSE) values, which are a measure for the quality of the image correlation, across these affected regions of the images indicate that the rectangular patches in the displacement fields are in fact caused by errors in the DTM used for the HiRISE image orthorectification and are not actual (rapid) displacement.

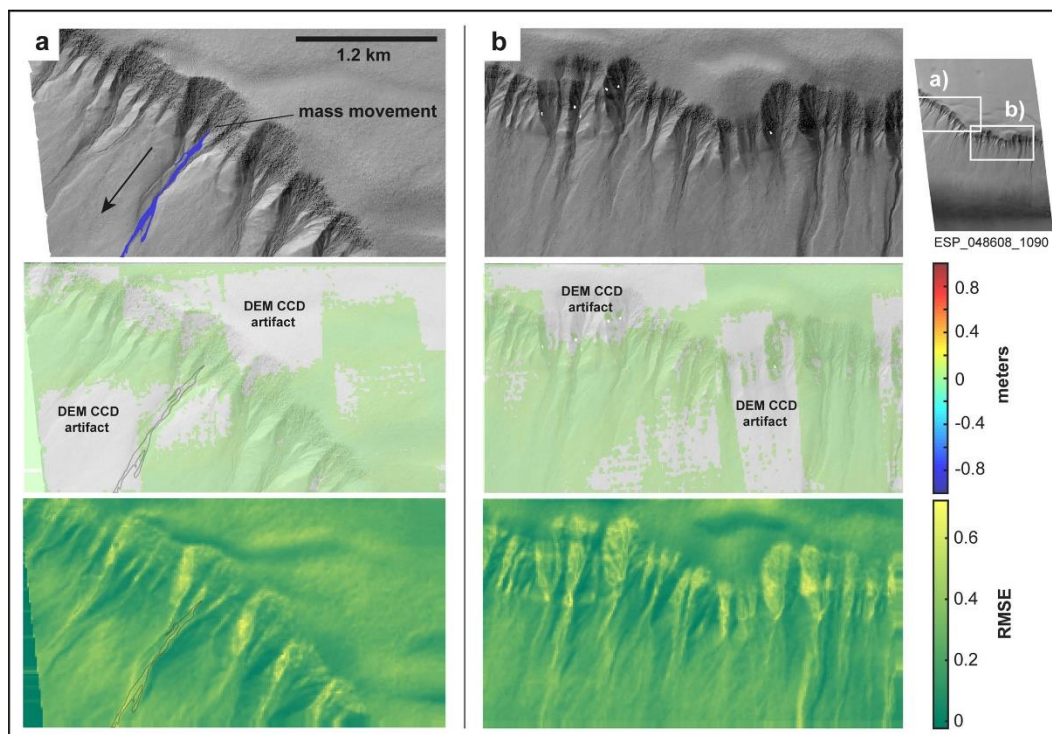


Figure 10: Displacement magnitude and associated correlation RMSE between HiRISE images PSP_005621_1090 and ESP_048608_1090 (MY 28 to 33, i.e., the image pair with the maximum temporal baseline) with focus on two different sites along the cliff of interest in region 11: **a)** the portion where activity occurred in MY 33 at L_S 277° (blue polygon, in the indicated direction) (Figure 4), and **b)** a series of gullies further east. Images have been taken before (MY 28) and after (MY 33) the activity of the gully. The accumulated displacement of the slope between MY 28 and 33 appears to be less than one pixel (~25 cm) or non-existent. Due to the occurrence of the flow and due to systematic noise introduced by CCD artifacts, coverage of the region of interest is incomplete. The correlation RMSE maps indicate areas in the images where matching accuracy has been slightly reduced, particularly in the shadowed portions of the gullies (western gully flanks). Overview based on HiRISE image ESP_048608_1090.

3.3. Timing of annual surface ice cover and gully activity, surface temperatures, and comparison to dark spots

Based on our large dataset of CTX, HRSC, and HiRISE images, we were able to correlate seasonal frost coverage with the annual activity of gullies. Using TES data we could correlate these trends with surface temperature. According to Raack et al. (2015), this seasonal frost cover is composed mainly of CO₂ ice with some minor contaminations of H₂O ice and dust. Figure 11 shows the seasonal trend in surface temperature with latitude combined with our observations of visible surface frost. Each latitude band has a similar temperature trend with temperatures stable at around 150 K until defrosting starts, the temperature then climbs relatively quickly and reaches a convex-up plateau extending over the summer. For latitudes between 72 and 76° S there is a slight precursor rise in surface temperature before the steep climb. The last image without surface frost

682 does not occur until $L_s \sim 30^\circ$ after the plateau is reached. For more equatorial latitudes the rise in
683 surface temperature is experienced earlier and is slightly more rapid with the surface frost
684 occurrence showing the same trend. At 75° S, the surface temperature plateau is reached at L_s
685 $\sim 280^\circ$, whereas at 67° S it is reached at $L_s \sim 240^\circ$.

686 Figure 12 shows the timing of the gully activity alongside observations of seasonal surface frost
687 cover from HiRISE. In almost all cases, the activity occurs at the very end of the surface defrosting.
688 The three exceptions are gully 3 in MY 29 and 31, and gully 7 in MY 31, where activity is earlier
689 in the year. These exceptions show the same type of activities compared to the others, but gully 3
690 is the only active gully in the study region orientated due north, which implies an earlier, more
691 intense sun exposure and earlier defrosting. This is the likely explanation for the relatively early
692 activity compared to the other active gullies. The active gully was investigated by Raack et al.
693 (2015) and shows clear headwall erosion of material in the source region (Figure 5). Gully 7 shows
694 an early block movement in MY 31 and this was the only active block movement whose timing
695 could be constrained in time. All other block movements appear in regions where a high-resolution
696 multi-temporal coverage was not available (see Supplementary Table 01). Therefore, whether
697 block movements systematically occur before the flow-like features in the study region could
698 neither be excluded nor confirmed.

699 Seasonal frost coverage of the study region was easy to identify. During winter and early beginning
700 of spring, the surface appeared relatively bright and dark defrosting spots are visible mainly on
701 dunes. This bright appearance is probably caused by the redeposition of CO_2 frost on top of the
702 generally translucent slab ice cover. Later, while the defrosting process is occurring (mid to end
703 of spring), only small bright icy patches on the generally defrosted surface are clearly visible. Dark
704 defrosting spots appear on all dark dunes within the study region.

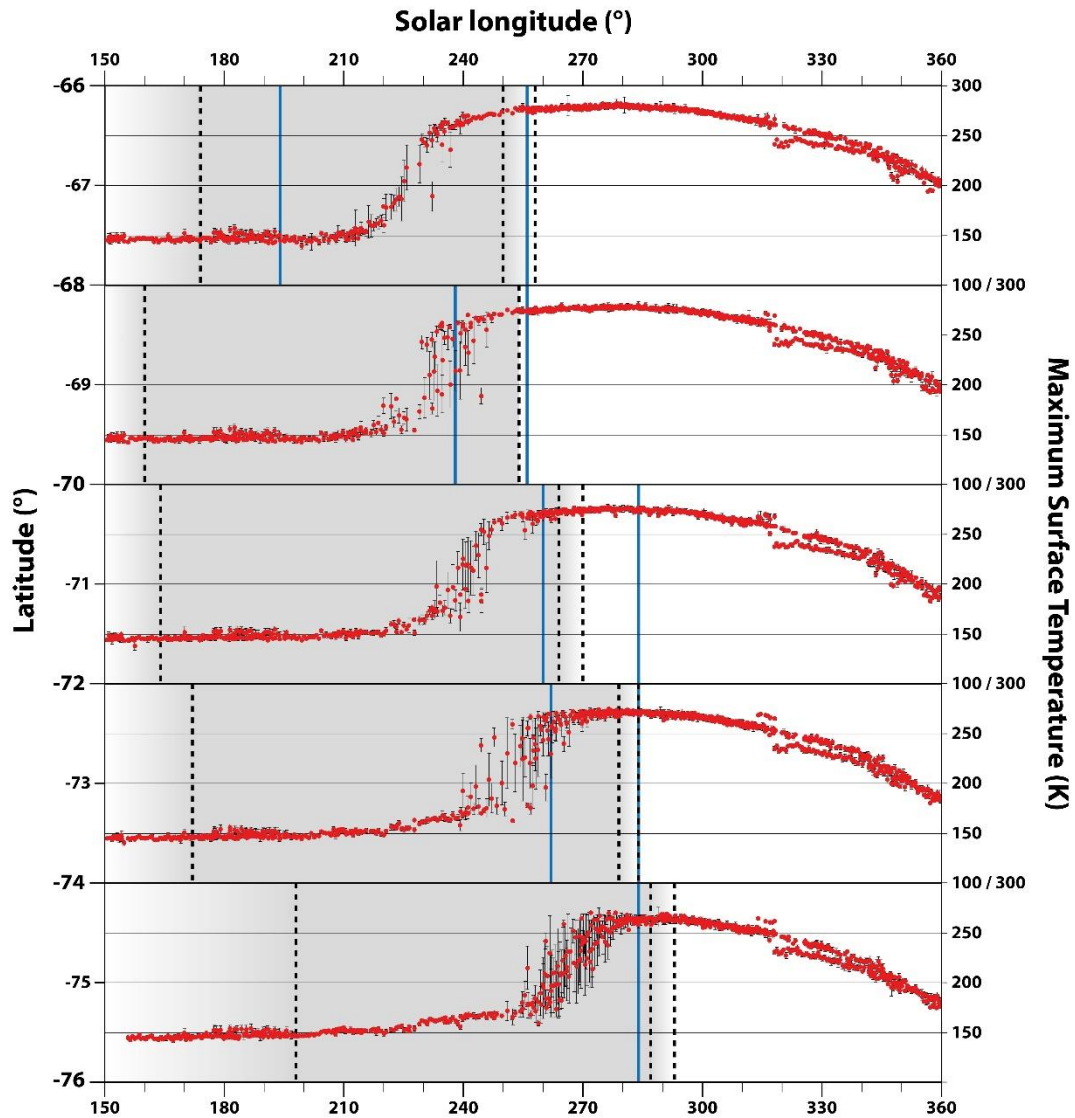
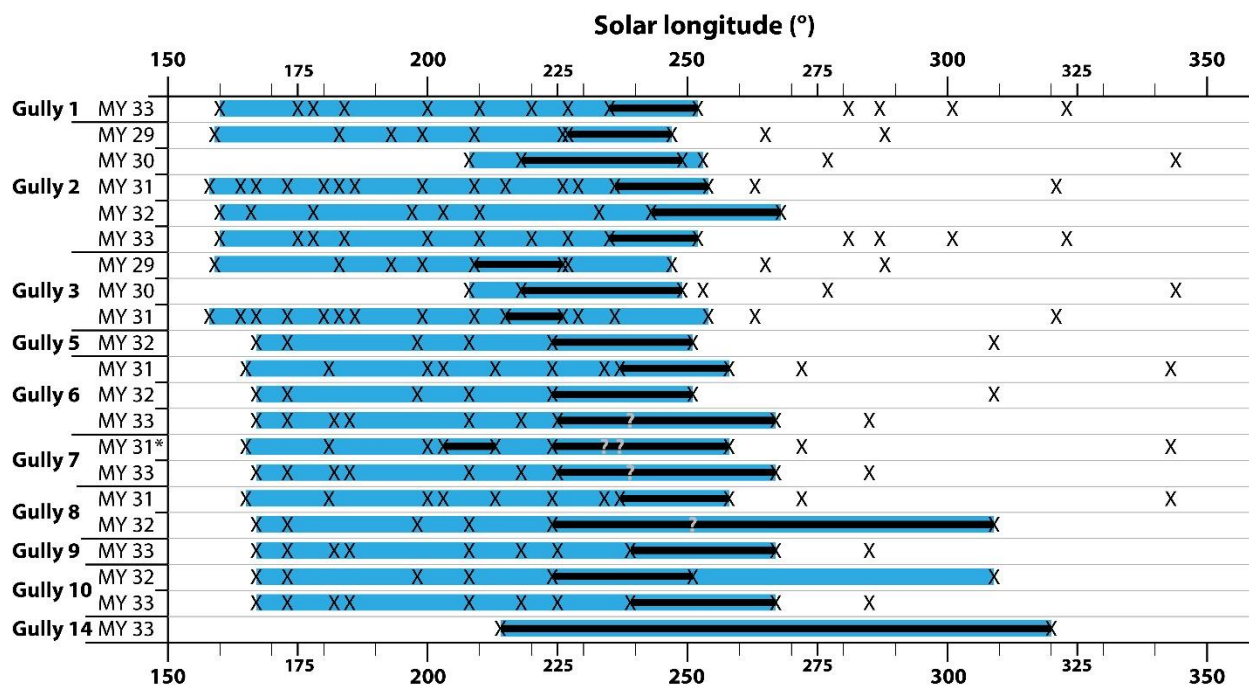


Figure 11: Schematic diagram of the average annual defrosting of the study region. Solar longitudes from end of winter (Ls 150° - 180°), spring (Ls 180° - 270°), to summer (Ls 270° - 360°) of the southern hemisphere vs. latitude of the study region (left, subdivided into areas of 2°) and vs. maximum surface temperatures (right, TES) of the study region within subdivided regions. The grey bar within each subdivision represents the surface defrosting observed on CTX datasets of MY 28-34. The first dashed black line represents the timing of the first available image (frosted surfaces), the second dashed black line represents the timing of the last image with identifiable patches of surface frost, and the third and last dashed black line represents the timing of the first

714 image without any surface frost. The blue lines represent the timing of defrosting observed on
715 HRSC imagery. The first blue line represents the timing of the last image with identified ice on
716 the surface, the second line represents the timing of the first image without any surface frost. The
717 red dots represent maximum daytime surface temperatures measured by TES of MY 24 to 26. The
718 individual dots represent the average of all taken TES measurements at the same time (same solar
719 longitude) with standard deviation (thin black “error” lines).



721 **Figure 12:** Diagram of 10 different gullies with contemporary flow-like features activity (except
722 gully 7 in MY 31, marked with an asterisk, where both activities within the year are related to
723 block movements), which could be narrowed down to an exact timing within one martian year
724 based on HiRISE imagery. All gullies are between -68.4° and -70.7° S (see Supplementary Table
725 01). The activity of the other 26 identified active gullies in the study region could not be
726 constrained within one martian year. Some of the 10 gullies show periodic activity within different
727 martian years (y-axis). The crosses represent single HiRISE images, as well as the grey question
728 marks of gullies 6 to 8 do. However, the question marks represent images where the identification

of changes in previous images could not be confirmed due to lower resolutions, atmospheric dust coverage, adverse insolation, and/or extensive surface albedo changes caused by surface defrosting. The blue bars represent the identified surface frost coverage from the beginning of surface frost (beginning of blue bar) to the first image without any identifiable surface frost (end of blue bar). Black bars represent identified activity from between the “before” and “after” HiRISE images.

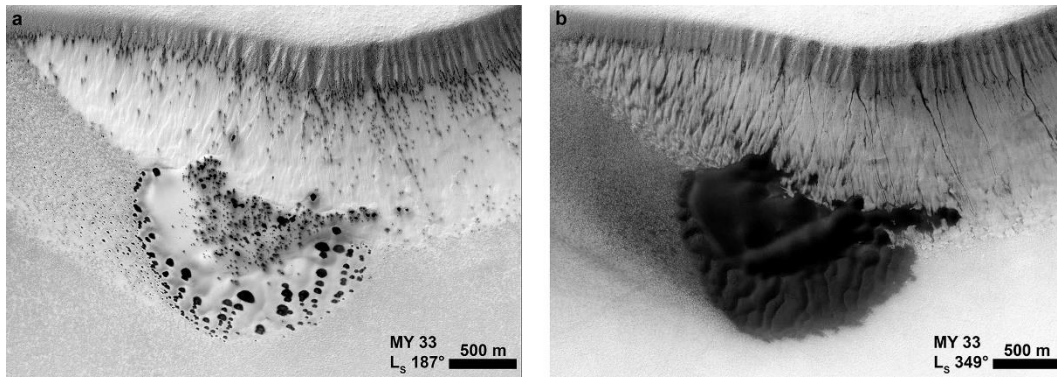


Figure 13: (a) A gullied slope with adjacent dark dune field in MY 33 during defrosting at the beginning of spring ($L_s 187^\circ$) with numerous dark defrosting spots. (b) The same location after complete defrosting with an ice-free surface during summer ($L_s 349^\circ$). Notice that the dark defrosting spots shown in (a) only occur in regions with a sandy surface (dark dune, windblown sand on the eastern side of the dune, and the gullied slope with preferentially loose material. HiRISE-images (a) EPS_046749_1085 and (b) EPS_050230_1080. North is up in all images.

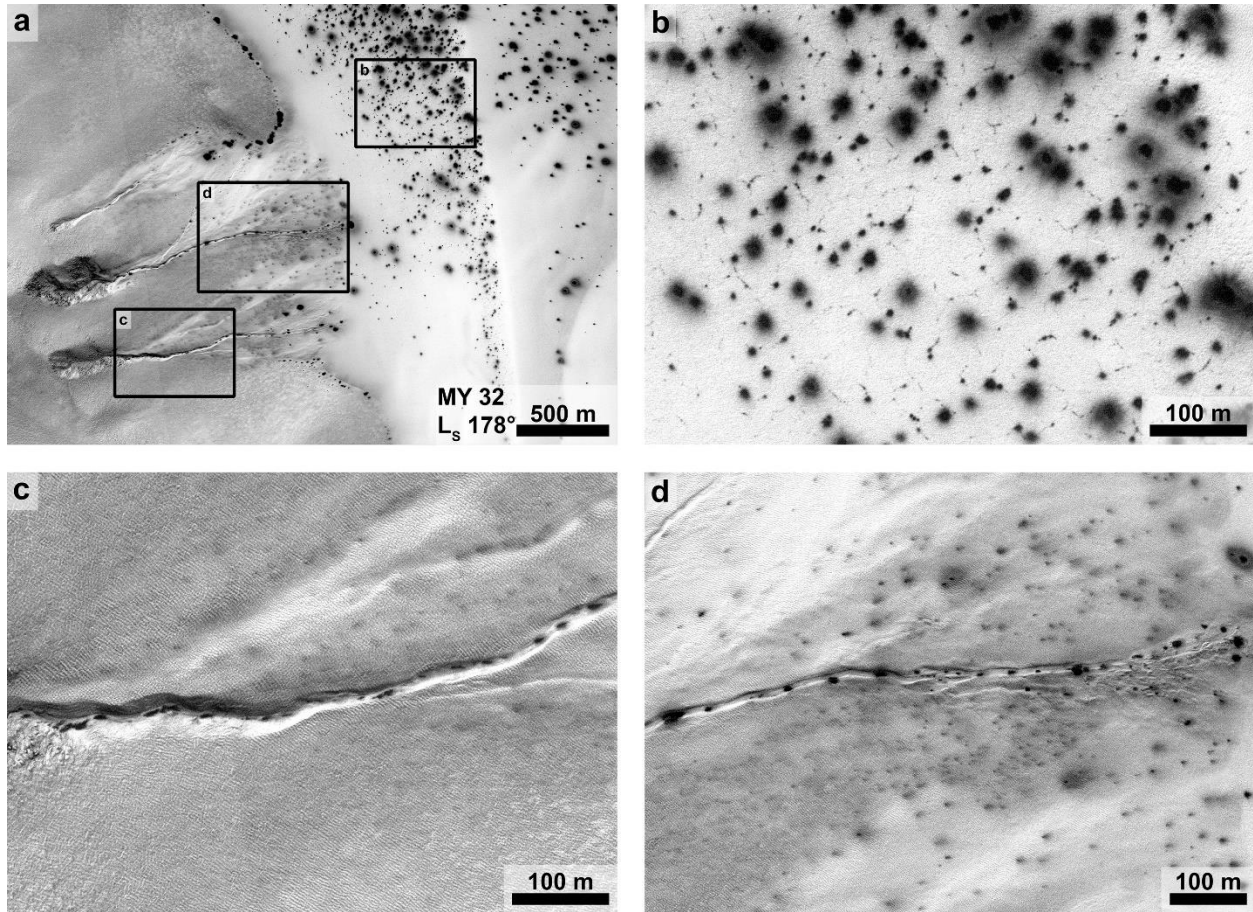


Figure 14: Examples of dark defrosting spots in the study region. (a) Overview of an east-facing slope with three gullies. The gully aprons run into a dune field, which is within a polar pit. (b) Detail of the dune crest with several dark defrosting spots as well as visible cracks in the slab ice. The image was taken at the end of winter/beginning of spring (L_s 178°) and the dune appears bright probably due to redeposition of CO_2 frost on top on the translucent seasonal CO_2 slab ice cover (comparable to dune field in Figure 8). (c) Detail of one of the gully channels and (d) one of the gully channels with adjacent apron. Dark spots are present within the gully channels and on the aprons, while they are absent on the adjacent hillslopes. This could be caused by the lack of fine material on the slopes, a lack of sufficiently sintered slab ice or different thermal contrasts. HiRISE-image ESP_037729_1115. North is up in all images.

4. Discussion

4.1. Dark spots and flow-like streaks

Prior and during the activity of the flow-features in the gullies in Sisyphe Cavi the appearance of dark spots and flow-like streaks are observed on the surface, which do not change the topography. To obviate possible confusion we named these small features emanating from dark defrosting spots “dark flow-like streaks”, while “dark flow-like features” refer to the present-day activity of gullies with observable sediment transport. The phenomenon of dark spots was first observed by Cantor et al. (2002) and is well described in the literature (e.g., Piqueux et al., 2003; Kieffer et al., 2006; Horváth et al., 2009; Hansen et al., 2010; Pilorget et al., 2011; Martínez et al., 2012; Jouannic et al., 2019). The dark spots are formed by basal sublimation of seasonal translucent slab-ice (Figure 13; e.g., Piqueux et al., 2003; Kieffer et al., 2006). The basal sublimation leads to overpressure under the ice, leading to the formation of cracks within the ice (see Figure 14b; Portyankina et al., 2012). Through these cracks degassing occurs and dust/sand particles are entrained and redeposited on the surface of the ice (e.g., Piqueux et al., 2003; Kieffer et al., 2006; Portyankina et al., 2012) (Figure 13, 14). If the surface is inclined, the sediment can move downslope forming dark flow-like streaks (e.g., Horváth et al., 2009; Kereszturi et al., 2009, 2010, 2011; Gardin et al., 2010; Hansen et al., 2010, 2012; Jouannic et al., 2019), which are observed in our study region during spring. Within the study region, dark spots are only observed on dark dunes and on gullies (non-active and active ones), particularly within the gully channel and on aprons (Figure 14). Based on the same timing of activity and very similar morphologic features (Figure 14), we infer that the same formation mechanism is responsible for the dark spots and flows in the study region, on dunes as well as in gullies. Thus, these two substrates may have similar properties that differ from the surrounding terrain in order to explain the fact that the dark spots/flows are only found

on the dunes and gullies. This implies that dunes, gully channels, and aprons are formed of fine grained material such as sand and dust, which can be mobilized. It could also imply that these substrates somehow favor the formation of slab ice and/or the basal heating.

Such dark flow-like streaks have been observed on other gullies, notably the linear gullies on the Russell crater megadune (Gardin et al., 2010; Jouannic et al., 2019) and also on classical gullies in Sisyphi Cavi by Dundas et al. (2019) or in the mid-latitudes by Costard et al. (2007). Dundas et al. (2019) presented a gully as an example for defrosting flows in a polar pit gully which was also investigated in our study. They did not detect changes in topography after the flow disappeared. However, our new observations reveal very small topographic changes, probably missed in the Dundas et al. (2019) study due to fewer available HiRISE images.

4.2. Dark flow-like features

We have shown that at the very end of defrosting of the seasonal CO₂ surface ice, flow-like features occur, which modify the topography of the gullies in Sisyphi Cavi. These flows run out onto slopes of 10-15° (Figure 8), hence require some degree of fluidization. Similar flow-like features have been observed in gullies imaged in the shadows of impact craters in three craters in the mid-latitudes (32-38° S; Dundas et al., 2019). As a consequence of the less frequent monitoring of gully-sites outside the polar regions, changes observed in mid-latitude martian gullies may also have happened over frost. However, this has not yet been documented in images because they were not captured at the right time and cadence. In contrast to the Sisyphi Cavi gullies, in the mid-latitudes flow-like features were only observed on south-facing slopes. The timing of activity in Sisyphi Cavi coincides with activity associated with linear gullies on martian sand dunes (Pasquon et al., 2016; Jouannic et al., 2019). However, in this case the activity seems to originate from the

frosted areas and propagate over unfrosted areas (Diniega et al., 2013; Jouannic et al., 2019) and again this activity is predominantly on south-facing slopes. Classic gullies on sand dunes have a more complex behavior with activity continuing throughout winter (Diniega et al., 2010; Pasquon et al., 2019a,b).

The flow-like features occur when the CO₂ seasonal deposit is becoming thin and discontinuous. This is also visible in the thermal datasets (Figure 11) where the temperature variability of the standard deviation during the sublimation phase is very high. This is the case when ice covered and non-ice covered surfaces are measured at the same time. The formation mechanism of dark flows via pressurized debris flows underneath the slab ice proposed by Pilorget and Forget (2016) is unlikely in Sisyphy Cavi. Raack et al. (2015) showed with spectral and thermal investigations and numerical modelling that the dark flows are on top of the ice and not underneath it, at least for the most active gully in Sisyphi Cavi and our additional image observations support this earlier work.

Instead, a modified Cedillo-Flores et al. (2011) model where relatively hot sediments are transported by sublimation of the CO₂ ices underneath the flow seems a more likely scenario. The fact that the deposits are preserved into the summer months leads us to the conclusion that either the underlying CO₂ surface frost is relatively thin and/or the dark flows are turbulent and consist of a mixture of some ice and dry material, which erodes the underlying thin surface frost. If large quantities of CO₂ ice were located either under or within the transported debris, their subsequent sublimation would disturb and change the morphology of the deposits over time. De Haas et al. (2019) calculated that only very small volumetric fractions of CO₂ (<<1%) are required to fluidize a flow, hence a thin surface frost should be adequate to fluidize the flow.

822 The number of active gullies in Sisyphi Cavi is a small proportion of the whole population: 7 of
823 25 sites are active, i.e., only 35 of 2,067 individual gullies on multi-temporal HiRISE-images
824 (about 1.7 %). This value is even lower when only flow-like features without block movements
825 are included ($n = 22$, which is about 1 %). Even though some of the gullies are active annually,
826 many only showed one or two events during the time of image acquisition. This shows that
827 contemporary activity of gullies in this region is rare. To-date, about 35 % of all gullies in the
828 study region have multi-temporal coverage. Some of them only have coverage by two multi-
829 temporal images, which makes a visual identification of changes even more challenging.

830 Active gullies in Sisyphi Cavi could have long recurrence times, similar to debris flows on Earth
831 (e.g., de Haas et al., 2015), but a longer baseline of observation would be needed to substantiate
832 this hypothesis. We found no topographic or other factor (e.g., differential movement of the
833 headwall) that could explain why certain gullies are active (often repeatedly) and others are not,
834 even within those gullies located at the same site. Similarly to debris flows, such events could be
835 limited by the union of sufficient accumulation of loose material (via jetting processes like dark
836 spots/flows?) and rare climatic events that put the system in motion. We now consider whether the
837 activity seen today, integrated over a long time period, could be sufficient to explain the whole
838 gully population in Sisyphi Cavi. The flow-like features that we observed have a sufficient runout
839 to transport material to the base of the gully-fans, hence are capable of explaining the spatial extent
840 of the gullies. Taking into account imaging bias, the flow-like features we observed have a range
841 and variety of orientations that suggest similar events could occur on the whole range of slope
842 orientations in Sisyphi Cavi, although more data would be needed in the under-imaged east-facing
843 orientations to verify this (Figure 9).

For gullies #1, #2, and #3 we calculated the area covered by deposits during the time of observation, which ranged between ~600 and ~2,800 m² per MY. Conservatively assuming a 0.5 m thickness for these deposits (Raack et al., 2015) results in volumes of between ~300 and ~1,400 m³ per MY. We used the publicly available HiRISE DTM derived from the stereo pair ESP_013097_1115 and ESP_013585_1115 to measure the alcove volumes of the gullies. We removed / masked the values of the DTM inside 19 alcoves and linearly interpolated over the gap then differenced with the original DTM (e.g., Conway and Balme, 2014) to find alcove volumes between 32,000 and 2,819,000 m³ (average 956,000 m³). Assuming a constant rate of activity, we find that whole gullies could be formed in decades to several tens of thousands of Mars years (~4,000 Mars years for an average alcove with an average level of activity). As cycles of obliquity have a dominant frequency of 120 ka, eccentricity 95 ka, and precession 51 ka (Ward, 1974; 1979; 1992), our estimated gully formation times fall into times when the climate would not have differed substantially from the present-day climate. Hence, it is realistic that processes similar to those active at the present-day could explain the formation of the entire gully-landform without invoking other mechanisms. However, some gully alcoves are filled with presumably aeolian sedimented ice-rich mantle material (e.g., Mustard et al, 2001; Raack et al., 2012; Figure 5). This ice-rich mantle appears uncratered and other studies estimated maximum ages of ~20 Ma for mid-latitudinal locations (Raack et al., 2012) and ~3-5 Ma near the poles (55-60° S) (Willmes et al., 2012). This suggests that gully formation has been ongoing over much longer timescales than recorded by the most recent active gullies, but could still be dependent on conditions similar to the present-day for their formation (indeed conditions conducive for mantle emplacement seem to be non-conducive for gully-formation).

4.3. Block movements

We could only constrain the timing of one of the 16 block movements observed during spring, prior to the activity of the flow-like features. Block movements were sometimes spatially associated with and sometimes independent of the flow-like features we observed. All movements occurred in the alcove areas of the gullies where slopes are typically $> 20^\circ$ (Figure 8) and were usually of a few meters, leaving no track. Sometimes the block just moved ~ 1 -2 meters, consistent with just toppling over. It is tempting to link these movements to the flows associated with the gullies, yet no blocks are found in the deposits and similar block movements have been reported in areas without gullies. Dundas et al. (2019) found block movements of meters to tens of meters on slopes of typically 25 - 35° in craters in the northern hemisphere of which the majority occurred in winter and two occurred in summer. Dundas et al. (2019) argued that because similar block movements are not observed at equatorial latitudes, some aspect of the seasonal cycle encourages these types of movement. They suggested that thermal contraction/expansion of underlying ground ice could disturb blocks or even slight changes in the ground ice distribution driven by seasonal temperature changes. They considered loading or other disturbances by the seasonal ice as less likely because some movements were observed in summer. Given that we only have the timing for one of the movements in our dataset, it is currently impossible to move beyond the hypotheses suggested by Dundas et al. (2019).

5. Conclusions

Based on various visual and thermal remote sensing data, especially high-resolution multi-temporal images, we identified and analyzed multiple contemporary active gullies within Sisyphe Cavi. On the basis of our study we conclude:

- (1) At least ~1.7 % of all gullies observed with HiRISE show present-day activity (flow-like features and/or block movements). This is a minimum value as some activity could be overlooked and the required number of multi-temporal images for a complete investigation in all martian years is not available for all regions. Nevertheless, the number of active flow-like features (about 1 % of all investigated gullies) is very low which shows that contemporary gully activity in Sisyphi Cavi is generally rare.
- (2) All observed gully activity took place during the end of spring at the end of the seasonal defrosting. During this season, the highest surface temperatures for a partially ice-covered surface were observed. During this time, dark defrosting spots on dunes and gullies were most prevalent.
- (3) The origin of the transported material are the alcoves and small layers on the flanks of gully channels. We made the first observations of headwall erosion of gully alcoves. Material accumulated within the gully channel and moved down in one catastrophic flow event.
- (4) The preferred triggering mechanism for present-day gully activity in Sisyphi Cavi are flows of dry material over seasonal slab ice (comparable to dark spots/flows). It is possible, that the material flowing on top of the ice eroded the underlying ice and formed a mixture of dry material and ice, which was then transported together downslope, fluidizing the flow. It is estimated that the ice thickness at the time of dark flow-like feature appearance was relatively thin, which is consistent with the observation that this activity is linked to the last defrosting stages. The triggering factor of the movement of blocks remains unclear due to the lack of multi-temporal images.
- (5) We found the orientation of active gullies to be broadly consistent with the general population and using volume balance arguments, calculated that some of the active gullies

could have been formed within decades to several tens of thousands of MY. This implies that the gullies in Sisyphe Cavi could have been formed in their entirety by processes similar to these active at the present day.

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Present-day gully activity in Sisyphi Cavi, Mars – Flow-like features and block movements

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Supplementary Material

Supplementary Table 01: List of all identified active gullies with associated region, specific coordinates, orientation, short description, and time of activity in the study region.

Gully	Region	Lon. (E) / Lat. (S)	Orienta tion	Description	Year active	Time span between activity
Gully 1	5	1.285° / -68.471°	109°	Large dark flow (Figure 3)	MY 33	26 sols
Gully 2	5	1.23° / -68.481°	113°	Dark flow	MY 29 MY 30 MY 31 MY 32 MY 33	31 sols 91 sols 27 sols 38 sols 26 sols
Gully 3	5	1.443° / -68.537°	352°	Large dark flow (Figure 5 and Raack et al., 2015)	MY 29 MY 30 MY 31	27 sols 91 sols 17 sols
Gully 4	5	1.68° / -68.512°	321°	Small dark flow	MY 28-31	2012 sols
Gully 5	10	-13.84° / -69.48°	232°	Small flow	MY 32	42 sols
Gully 6	10	-13.835° / -69.481°	200°	Very small changes	MY 31 MY 32 MY 33	33 sols 42 sols 65 sols
Gully 7	10	-13.826° / -69.493°	224°	Very small changes plus block movements [†]	MY 31 [†] MY 31 [†] MY 33	65 sols 16 sols 54 sols
Gully 8	10	-13.786° / -69.512°	198°	Very small changes	MY 31 MY 32	33 sols 133 sols
Gully 9	10	-13.71° / -69.525°	196°	Several small changes	MY 33	44 sols
Gully 10	10	-13.698° / -69.527°	208°	Some small changes	MY 32 MY 33	42 sols 44 sols
Gully 11	11	1.2° / -70.92°	216°	Largest activity (see Figure 4)	MY 32-33	673 sols
Gully 12	11	1.224° / -70.92°	229°	Very small changes plus large block movement [†] (see Figure 7)	MY 31-32 MY 32-33 [†]	673 sols 673 sols
Gully 13	11	1.392° / -70.949°	194°	Medium changes	MY 32-33	673 sols
Gully 14	12	4.292° / -70.678°	305°	Small dark flow	MY 32-33 MY 33	575 sols 166 sols
Gully 15	12	4.21° / -70.74°	297°	Medium dark flow	MY 29-32	2160 sols

Gully 16	14	3.161° / -71.203°	234°	Small changes	MY 32-33	1400 sols
Gully 17	14	3.186° / -71.204°	247°	Very small changes	MY 30-31	708 sols
Gully 18	14	3.205° / -71.212°	260°	Small changes	MY 28-33	3357 sols
Gully 19	14	3.17° / -71.288°	301°	Very small dark flow	MY 28-30	1163 sols
Gully 20	18	2.237° / -72.159°	301°	Medium changes	MY 29-32	2032 sols
Gully 21	18	2.206° / -72.17°	316°	Block movement	MY 29-32	2032 sols
Gully 22	18	2.203° / -72.17°	315°	Block movement	MY 29-32	2032 sols
Gully 23	18	2.193° / -72.175°	325°	Block movement	MY 32-33	634 sols
Gully 24	18	2.189° / -72.176°	262°	Block movement	MY 32-33	634 sols
Gully 25	18	2.19° / -72.177°	300°	Block movement	MY 29-32	2032 sols
Gully 26	18	2.184° / -72.178°	300°	Block movement	MY 29-32	2032 sols
Gully 27	20	3.724° / -72.172°	258°	Block movement	MY 31-33	2688 sols
Gully 28	20	3.724° / -72.173°	222°	Block movement	MY 29-30	709 sols
Gully 29	20	3.725° / -72.175°	293°	Block movement	MY 29-30	709 sols
Gully 30	20	3.745° / -72.182°	209°	Block movement	MY 29-30	613 sols
Gully 31	20	3.898° / -72.244°	255°	Small changes	MY 29-30 MY 30-33	709 sols 1969 sols
Gully 32	20	3.909° / -72.249°	224°	Block movement (in same gully, but different places)	MY 30-33	1969 sols
Gully 33	20	3.914° / -72.248°	236°	Block movement (in same gully, but different places)	MY 30-33	1969 sols
Gully 34	20	3.924° / -72.248°	249°	Small changes plus block movements	MY 30-33	1969 sols
Gully 35	20	3.943° / -72.253°	229°	Block movement	MY 29-30	709 sols

Supplementary Table 02: Slope angles of all investigated gullies in region 5 and 11 from the beginning of their alcoves, through their channels, above their aprons until the end of the general slope (Figure 8). Slope angles are reported as calculated over 100 m-long segments of the gully length. The last row of the table shows the overall average angle of the slope following the path of individual gullies. Active gullies are marked in bold.

Length (m)	Region 11						Region 5									
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
100	29°	33°	39°	43°	36°	37°	38°	36°	34°	36°	35°	15°	35°	50°	38°	42°
200	36°	45°	34°	38°	35°	32°	28°	29°	27°	26°	27°	15°	37°	44°	38°	31°
300	38°	34°	28°	30°	37°	37°	20°	20°	23°	29°	20°	13°	23°	23°	33°	22°
400	27°	25°	22°	24°	23°	26°	18°	18°	20°	20°	17°	13°	15°	18°	22°	17°
500	21°	21°	19°	19°	19°	14°	16°	15°	18°	19°	16°	12°	14°	14°	15°	16°
600	17°	16°	16°	12°	15°	12°	15°	14°	19°	15°	15°	11°	12°	14°	15°	12°
700	15°	13°	12°	10°	12°	16°	16°	16°	15°	16°	16°	11°	11°	13°	13°	15°
800	14°	12°	11°	11°	12°	11°	16°	16°	14°	15°	14°	12°	11°	13°	16°	15°
900	11°	11°	11°	12°	11°	12°	14°	15°	15°	19°	15°	11°	12°	13°	18°	15°
1000	13°	13°	12°	12°	14°	10°	13°	16°	15°	14°	14°	12°	12°	12°	19°	14°
1100	10°	12°	11°	10°	11°	11°	14°	14°	15°	14°	14°	11°	10°	11°	14°	13°
1200	12°	10°	11°	9°	9°	10°	15°	13°	16°	13°	20°	11°	9°	10°	13°	12°
1300		11°	11°	12°	12°	9°	14°	13°	15°	13°	13°	10°	11°	10°	12°	12°
1400		11°	11°	10°	8°	9°	12°	13°	14°	12°	14°	11°	10°	11°	12°	11°
1500		11°	12°	10°	10°	10°	13°	13°	14°	13°	12°	10°	11°	11°	11°	11°
1600		12°	9°	9°	10°	9°	11°	12°	13°	13°	13°	10°	10°	10°	10°	10°
1700		9°	14°	11°	11°	10°	10°	11°	13°	13°	9°	10°	10°	11°	10°	10°
1800		11°	7°	10°	11°	10°	11°	9°	13°	12°	9°	9°	10°	11°	10°	11°
1900		11°	11°	10°	10°	10°	10°	9°	12°	11°	7°	8°	9°	10°	9°	10°
2000		9°	12°	10°	11°	11°	13°	13°	11°	19°	2°	8°	7°	9°	7°	9°
2100		9°	11°	9°	10°	8°	19°	18°	10°	3°		6°	5°	8°		8°
2200		10°	8°	10°	9°	8°	25°	25°	8°			0°	3°			8°
2300		10°	9°	10°	10°	9°			5°			0°	6°			7°
2400			9°	10°	8°	9°							13°			
2500			8°	9°	9°	8°							12°			
2600			6°	9°	7°	8°										
2700			4°	6°	6°	7°										
2800				4°	3°	6°										
2900						5°										
	20°	16°	14°	14°	14°	13°	16°	16°	16°	16°	16°	10°	13°	16°	17°	14°

Supplementary Table 03: List of the HiRISE image pairs used for DTM generation, including their spatial resolution and their mean intersection error as a measure for DTM quality. Some of the listed DTMs have been used to orthorectify the HiRISE imagery used for DIC.

Timeframe	HiRISE pair	DTM spatial resolution (m/pix)	Mean intersection error (m)
2007 - 2011	ESP_023290_1090 PSP_005621_1090	2	0.62
2007 - 2016	ESP_048608_1090 PSP_005621_1090	1	0.25
2013 - 2015	ESP_030859_1090 ESP_039747_1090	3	0.87
2015 - 2016	ESP_039747_1090 ESP_048608_1090	0.5	0.48