New and recent gully activity on Mars as seen by HiRISE

Colin M. Dundas,[1] Alfred S. McEwen,[1] Serina Diniega,[2] Shane Byrne,[1]
and Sara Martinez-Alonso[3]

Received 15 October 2009; revised 14 January 2010; accepted 27 January 2010; published 7 April 2010.

[1] Fresh-appearing gully deposits are found at tens of sites in the southern hemisphere of Mars. These deposits have latitudinal and azimuthal dependences similar to the overall preferences of southern-hemisphere gullies, suggesting that most gullies can undergo such events. Definite changes are seen at ten sites, including two previously reported. These include visible modification of gully channels and aprons. Those formation intervals constrained to better than one Mars year tend to include winter and exclude summer, suggesting seasonal activity. This seasonal activity is consistent with proposed models for gully formation driven by CO_2 frost, although at least some of the new deposits are probably due to dry granular flow with no volatile involvement. As these deposits are capable of effecting distinct topographic changes to gully aprons and channels, they represent a significant component of recent gully evolution. **Citation:** Dundas, C. M., A. S. McEwen, S. Diniega, and S. Byrne (2010), New and recent gully activity on Mars as seen by HiRISE, *Geophys. Res. Lett.*, *37*, L07202, doi:10.1029/2009GL041351.

1. Background

[2] Gullies on Mars have been taken as evidence for significant amounts of liquid water in the recent past [*Malin and Edgett*, 2000]. As it is difficult to generate liquid water on the Martian surface, much work has been devoted to determining the process by which these gullies form. The theories most often considered include groundwater release [e.g. *Malin and Edgett*, 2000; *Mellon and Phillips*, 2001; *Heldmann and Mellon*, 2004; *Heldmann et al.*, 2007] and melting of snow at high obliquity [e.g., *Christensen*, 2003; *Bridges and Lackner*, 2006; *Dickson et al.*, 2007]. Alternative formation processes have also been considered, including melting of near-surface ground ice [*Costard et al.*, 2002], dry flows of eolian deposits [*Treiman*, 2003], or various CO_2-driven mechanisms [*Musselwhite et al.*, 2001; *Hoffman*, 2002; *Ishii and Sasaki*, 2004]. Recent work has favored snowmelt [e.g., *Williams et al.*, 2009; *Dickson and Head*, 2009].

[3] Observations by the Mars Orbiter Camera (MOC) over a period of years revealed two new bright deposits associated with gullies [*Malin et al.*, 2006]. This was initially taken as evidence of present-day groundwater release, but modeling of one deposit by *Pelletier et al.* [2008] indicated that it was consistent with a dry granular flow. *McEwen et al.* [2007a] noted four fresh-appearing bright deposits with little modification, and saw no orientation preference among the six examples. In order to better understand current gully activity, we examine recent gully deposits on Mars using images from the High Resolution Imaging Science Experiment (HiRISE) camera [*McEwen et al.*, 2007b] on Mars Reconnaissance Orbiter (MRO). Recent gully activity on Mars has concurrently been examined by *Harrison et al.* [2009], who suggested activity between autumn and spring and argued for liquid water activity.

2. Survey of Recent Gully Activity

[4] HiRISE images typically cover areas 5–6 km wide and up to tens of km long, with a pixel scale as small as 25 cm/pixel, allowing small changes to be seen. Most images include a three-color swath covering the central 1.2 km. The camera has a high signal-to-noise ratio (typically 200:1 over well-illuminated surfaces), which is valuable in detecting changes between images.

[5] Gullies are most abundant between 30°–50° latitude in each hemisphere [e.g., *Malin and Edgett*, 2000; *Heldmann and Mellon*, 2004; *Balme et al.*, 2006; *Bridges and Lackner*, 2006; *Dickson et al.*, 2007; *Heldmann et al.*, 2007]. For this study, we examined all HiRISE images acquired prior to MRO orbit 15000 with center latitudes between 20°–60° in each hemisphere. We also examined all other images that included the words "gully," "gullied" or "gullies" in the image description. We exclude dune gullies, which are discussed separately by *Diniega et al.* [2010].

[6] Since HiRISE images are not targeted randomly, biases may exist in this data set in latitudinal coverage, coverage of slope azimuth, season, etc. Such biases are likely inextricably part of the current HiRISE data set. MOC images could suffer from similar biases while larger-area HRSC images should have reduced biases; a study using both found similar results [*Balme et al.*, 2006], and so we do not consider these to be a fundamental problem.

[7] We searched for fresh deposits similar to those observed by *Malin et al.* [2006]. We defined these as features with distinct tone (bright, dark, or color) relative to other gully deposits or aprons at the same site, with minimal signs of modification such as ripples, polygons, craters, faults, or smeared edges. Examples are shown in Figure 1. Deposit freshness is gradational, requiring some qualitative judgment, and the rate of modification is likely site-dependent; nevertheless, this approach let us pick out the freshest deposits. These are usually morphologically distinct from the striated mass wasting textures commonly found on non-gullied steep slopes, although their planform often resembles

[1]Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona, USA.
[2]Program in Applied Mathematics, University of Arizona, Tucson, Arizona, USA.
[3]Department of Geological Sciences, University of Colorado at Boulder, Boulder, Colorado, USA.

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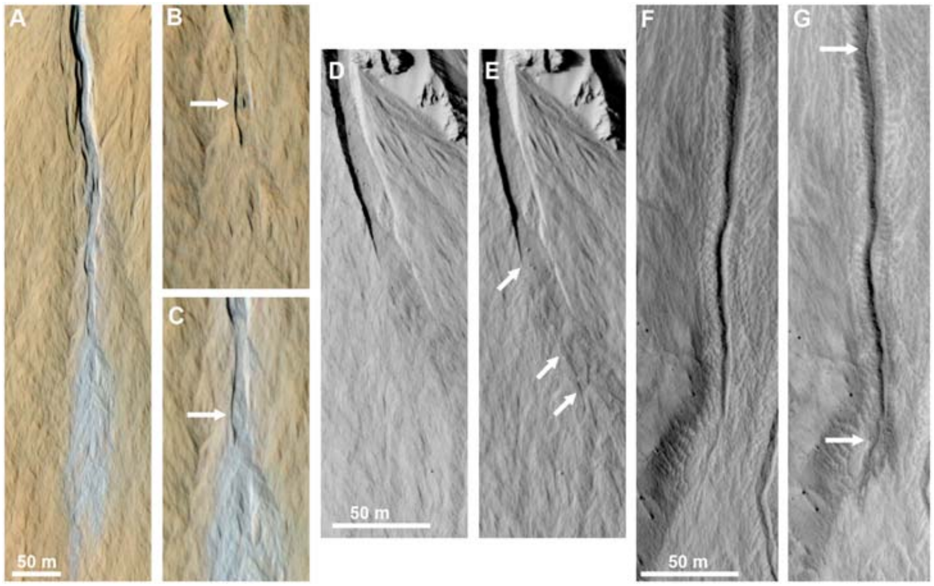

Figure 1. Recent gully activity on Mars. (a) A colorful new gully deposit. (b and c) Site of a ridge in the channel (arrowed), which is present in the earlier image (Figure 2b) but later absent (Figures 1a and 1c) due to burial and/or erosion. Color is stretched for contrast and differs slightly between Figure 1a and Figures 1a and 1c. (d and e) Changes in a gully channel and apron; same HiRISE image pair as Figures 1a–1c. From top to bottom: transported boulders, possible new ridge or channel erosion, and newly deposited ridge. PSP_004060_1440 (Figures 1b and 1d) was acquired at L_s 254 with an incidence angle of 43°. ESP_012024_1440 (Figures 1a, 1c, and 1e) was acquired at L_s 212, with an incidence angle of 57°; some apparent changes may be due to lighting geometry. Both are in Gasa Crater. (f and g) New gully deposit (lower arrow) and apparent channel incision (upper arrow). PSP_006261_1410 and ESP_014093_1410.

the (usually dark) slope streaks found on steep dust-mantled slopes. Where fresh deposits were identified, we examined any previous images from HiRISE, MOC and the MRO Context Camera (CTX) to determine if it was possible to constrain the formation time. Some images were considered non-constraints due to poor resolution or signal-to-noise.

3. Results

[8] We have identified fresh-looking deposits at nearly 50 sites in the southern hemisphere and a handful in the north; in several cases, more than one fresh-looking deposit is present at a given site. Most of the deposits noted are bright gully deposits (BGDs) rather than dark (DGDs), although bright deposits could simply be more distinctive, and this is only a relative classification. The deposits show a range of tones and thicknesses. The deposits are associated with gullies, although some are fine channels without the complete alcove-channel-apron morphology described by *Malin and Edgett* [2000]; in a few cases, similar features were found on non-gullied slopes.

[9] Southern-hemisphere fresh deposits occur at latitudes ranging from 29°–55°S. At each site we noted the facing directions of slopes with distinct deposits. The deposits poleward of 40°S show no obvious preferred orientation (with few examples), but the southern-hemisphere deposits equatorward of 40°S show a strong tendency to face the pole (Figure 2). Gullies are less abundant in the northern hemisphere, but we have found only four sites with comparable features there, two of which we consider marginal. The remaining two were both at relatively high latitude (48°–50°N).

[10] Including the two noted by *Malin et al.* [2006], we have noted ten sites with eleven or more definitely new deposits, all in the southern hemisphere. (These are not necessarily the youngest events, as temporal coverage of gully sites is highly varied.) These include a mix BGDs and DGDs, and span the entire latitude range of all fresh deposits. Table 1 gives information about each of these new deposits. Some less certain candidates were not included.

4. Discussion

[11] The results of this survey indicate an azimuthal dependence of recent gully activity, particularly for lower-latitude gullies. This is not particularly surprising, since gullies have a similar relationship between latitude and orientation [e.g., *Malin and Edgett*, 2000; *Heldmann and Mellon*, 2004; *Balme et al.*, 2006; *Dickson et al.*, 2007]. Mass wasting should preferentially occur on steeper slopes; large-scale steep slopes are most likely to face the equator in the southern mid-latitudes [*Kreslavsky and Head*, 2003]. This is the opposite of the tendency for these fresh deposits, but existing gullies might provide local very steep slopes, sufficient to initiate dry granular flows [*Kolb et al.*, 2010]. Even if the deposits all represent dry mass wasting, the association with gullies indicates that they are a relevant component of gully evolution.

[12] We have noted eleven new events in roughly ten years of observations; this is an incomplete record of gully activity over this timeframe, both because of very incomplete coverage in space and time and because some recent deposits may not be very distinct from their surroundings (or only distinct in HiRISE color swaths). The deposits often appear quite thin, but movement of material is significant in

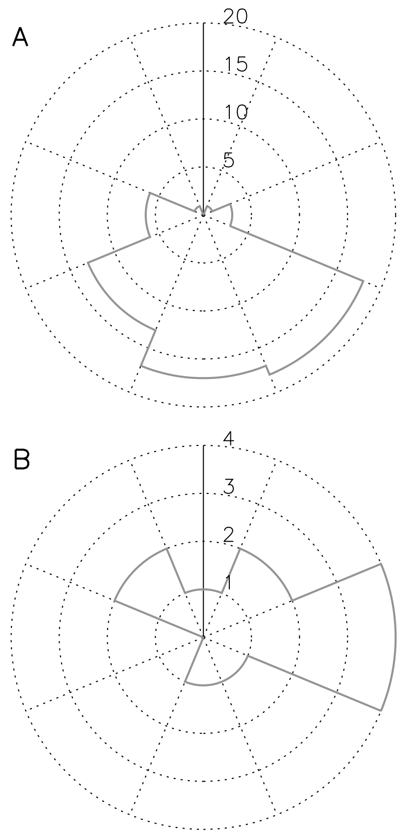

Figure 2. Rose diagram of the orientation of southern-hemisphere slopes with fresh gully deposits (a) equatorward and (b) poleward of 40°S. North-facing slopes are up. Those equatorwards of 40°S show a strong tendency to face the pole, consistent with the orientation of gullies at these latitudes. At a given site, a slope azimuth with multiple deposits is only counted once.

some cases. In Gasa Crater, we observe movement of meter-scale boulders and topographic changes in two separate channels and aprons (Figures 1a–1e). Therefore, transport of significant amounts of material from the alcove or upper channel to the apron is proceeding today. Possible erosion of fine inner channels is also observed (Figures 1f and 1g).

[13] Figure 3 shows the L_s ranges in which deposits could have formed for events with times known to better than one Mars year. The constraints are generally weak, but there is possible preference for winter activity; a span of eighty-eight degrees of L_s during late spring and summer is included in three or fewer intervals. Imaging of the southern hemisphere is minimized during winter due to poor lighting, which could cause observation intervals spanning the winter to be systematically longer and more likely to include a mass movement. To examine this possibility, we conducted a Monte Carlo simulation of imaging intervals. We picked pairs of image times using the HiRISE imaging frequency of "gully" targets from 20°–60°S to weight the relative timing. If the second L_s value was less than the first, we assumed that the interval wrapped around through L_s 0. Since a longer interval is more likely to include activity, we filter these pairs by assigning each a probability of inclusion proportional to its length. We then examined the nature of overlap of sets of nine intervals. Less than five percent of such trials produced an interval as long as eighty-eight degrees of L_s with three or fewer overlapping intervals, as observed in late spring/summer in Figure 3. The images of the deposits in Gasa Crater are overlapping and not inde-

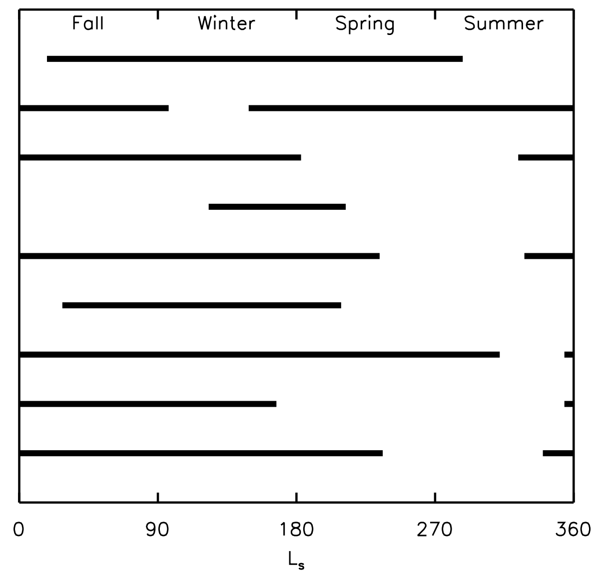

Figure 3. Timing constraints on gully activity for deposits with formation times known to better than one Mars year, ordered by latitude with poleward at the bottom (see Table 1).

Table 1. Observed New Gully Deposits

Latitude (°S)	Longitude (°E)	Last Image Before[a]	First Image After[a]	L_s Range[b]	Orientation	Type	Comment
29.1	181.8	P15_006893_1510	ESP_013578_1505	18/MY29–288/MY29	S	DGD	Channeled slope
34.4	172.3	PSP_001764_1455	PSP_009161_1450	149/MY28–97/MY29	S	DGD	In shadow; subsequently faded
35.7	129.4	PSP_005550_1440	ESP_011391_1440	324/MY28–183/MY29	S	DGD	Probably after 123/MY29
35.7	129.4	PSP_009901_1440	ESP_012024_1440	123/MY29–212/MY29	SW	BGD	Distinct in color
36.2	198.3	E11-03412	S05-01463	295/MY25–199/MY27	SE	BGD	*Malin et al.* [2006]
36.4	190.4	S12-02151	PSP_003649_1435	328/MY27–234/MY28	SE	DGD	
37.4	130.7	P16_007185_1425	B06_011958_1425	28/MY29–209/MY29	NE	BGD	Other changes possible
38.4	96.8	M04-04175	R14-02285	197/MY24–353/MY26	NW	BGD	*Malin et al.* [2006]
38.8	159.5	PSP_006261_1410	ESP_014093_1410	354/MY28–312/MY29	SW	DGD	Possibly between L_s 61-183
41.7	150.6	S14-00995	PSP_002200_1380	354/MY27–167/MY28	E	BGD	
54.6	17.5	S13-01357	PSP_003695_1250	340/MY27–236/MY28	S	DGD	Adjacent gully likely active between 253/MY24 and 234/MY26

[a]Prefixes PSP and ESP are HiRISE images, P and B are CTX, and M, E, R and S are MOC. CTX image IDs are abbreviated.
[b]MY is Mars Year using the numbering of *Clancy et al.* [2000].

pendent, but if only seven intervals were considered, such a long interval occurred just over ten percent of the time. These probabilities should be regarded with caution since repeat observations are generally not taken at random times in relation to previous images, but do suggest that seasonal imaging rates are unlikely to be solely responsible for the timing suggested by Figure 3. The possible winter timing is consistent with the timing of dune gully activity reported by *Diniega et al.* [2010]. This suggests that similar processes occur on both dune and slope gullies, and are influenced by volatiles.

[14] The latitudinal and azimuthal control of gully occurrence and implied requirement of volatiles has been taken as evidence for water. However, current gully activity shows similar trends, suggesting that similar activity can occur in most southern hemisphere gullies. The Martian mid-latitudes almost certainly lack liquid water under current conditions. Ground ice will sublimate before melting [*Mellon and Phillips*, 2001] and seasonal water frost should do likewise [*Ingersoll*, 1970], remnant snow from high obliquities is not plausible at current gully locations [*Williams et al.*, 2008], and radar sounding to ~11 km depth has so far not detected a water table [*Farrell et al.*, 2009]. *Hecht and Bridges* [2003] suggested that rapid warming after the disappearance of seasonal CO_2 frost could allow coexisting water frost to melt, but considered this unlikely to produce more than a trickle of liquid under current conditions; moreover, CO_2 frost at low latitudes disappears in late winter, when peak temperatures are still below the melting point.

[15] An alternate possibility is that the volatile responsible for gully formation and/or evolution is frost, likely CO_2. This has been proposed or noted in various forms [*Hoffman*, 2002; *Ishii and Sasaki*, 2004; *Balme et al.*, 2006; *Hugenholtz*, 2008], but has not been favored as a major process. CO_2 frost can be found on pole-facing slopes as far equatorward as ~30°S in the current climate [*Schorghofer and Edgett*, 2006]. Several mechanisms for such activity can be envisioned. *Hoffman* [2002] suggested lubrication by gas during sublimation, while *Ishii and Sasaki* [2004] proposed avalanching of CO_2 frost. A third possibility is frosted granular flow triggered by rock falls [*Hugenholtz*, 2008], in which frost reduces inter-particle friction. Frost could also serve as a trigger for dry granular flow. H_2O frost might produce some similar effects and is more widespread, but likely to be a much thinner layer. The possible seasonal timing seen here is consistent with these possible effects.

[16] The hypothesis that CO_2 frost drives some fraction of gully activity is consistent with the results presented here. The L_s range where activity is most likely includes the season of peak abundance of CO_2 frost, and centimeters of such frost can develop on pole-facing slopes at relatively low latitudes [*Schorghofer and Edgett*, 2006]. (Gully geometry also influences frost distributions [*Hecht and Bridges*, 2003; *Dickson and Head*, 2009].) Frosted granular flows have been documented on Earth [*Hugenholtz*, 2008, and references therein], as has erosion of talus by avalanches [*Luckman*, 1977]. Thus, significant amounts of CO_2 frost, which is likely on many slopes where gullies occur, could drive mass transport with distinct azimuthal control. Active CO_2 avalanching has been observed on high-latitude polar scarps, moving meter-scale blocks of ice [*Russell et al.*, 2008]. CO_2 frost is unlikely on some equator-facing slopes with recent deposits, but nothing about this hypothesis rules out the possibility that some deposits are due to dry granular flows [*Pelletier et al.*, 2008; *Kolb et al.*, 2010].

[17] Dry flow may be able to produce gully-like morphologies [*Shinbrot et al.*, 2004], and at least linear gully-like features have been reported on the Moon [*Bart*, 2007]. A few features resembling classic Martian gullies are seen at low latitudes (e.g., HiRISE images PSP_001376_1675 and PSP_010428_1745 [see also *Treiman*, 2003]). It is possible that these processes create some Martian gullies, and CO_2 frost processes cause the observed latitudinal and azimuthal variations.

[18] A component of CO_2 frost in gully evolution could also explain hemispheric differences in gully properties. Northern hemisphere gullies appear more degraded [*Heldmann et al.*, 2007] and are better preserved at higher latitude [*Bridges and Lackner*, 2006]. We have found much less evidence for recent activity in the northern hemisphere, although gullies are also less abundant there. The best northern examples are at relatively high latitude (~50°N), where seasonal frost is more likely. The orbital eccentricity of Mars currently causes greater temperature extremes in the southern hemisphere, favoring formation of CO_2 frost at lower latitudes [*Schorghofer and Edgett*, 2006]. Variation in the L_s of perihelion will cause the length of northern and southern seasons to change with a period of ~50 ka, and favor formation of CO_2 frost at lower latitudes in the northern hemisphere at other epochs.

5. Conclusions

[19] Martian gullies exhibit significant current and recent activity, including topographic changes on gully aprons and possible channel incision. A combination of upslope erosion, channel incision and apron deposition is sufficient to form gullies, and all may be occurring in the current climate. The latitudinal and orientation distribution and seasonal occurrence times suggest that CO_2 frost could be a component of the driving mechanism; more observations of gully activity to test the apparent seasonality would be valuable. None of these observations contradict the hypothesis that gullies are initiated by H_2O snowmelt or that this process drives a significant fraction of gully erosion. However, CO_2-driven processes could play a larger role than generally thought. Present-day CO_2 frost occurrence has latitudinal and azimuthal dependences that resemble those of gullies. Since the last possible deposition of mid-latitude snow at high obliquity, events such as those producing the observed deposits could have driven significant evolution of gullies through CO_2 frost processes, as well as dry granular flows. Since many gullies still appear very fresh, it is important to investigate to what extent these processes could account for the initiation and recent evolution of Martian gullies in the absence of liquid water.

[20] **Acknowledgements.** We thank the HiRISE, CTX and MOC teams for planning and acquiring the images used in this work. A number of images of possible recent deposits were suggested by the CTX team. Gwen Bart and an anonymous referee gave helpful reviews. This work was supported by NASA's Mars Data Analysis program, grant #NNX08AL08G, and the Mars Reconnaissance Orbiter project.

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S. Byrne, C. M. Dundas, and A. S. McEwen, Lunar and Planetary Laboratory, University of Arizona, 1541 E. University Blvd., Tucson, AZ 85721, USA. (colind@lpl.arizona.edu)

S. Diniega, Program in Applied Mathematics, University of Arizona, Tucson, AZ 85721, USA.

S. Martinez-Alonso, Department of Geological Sciences, University of Colorado at Boulder, UCB 399, Boulder, CO 80309, USA.