Seasonality of present-day Martian dune-gully activity

Serina Diniega[1*], Shane Byrne[2], Nathan T. Bridges[3], Colin M. Dundas[2], and Alfred S. McEwen[2]
[1]Program in Applied Mathematics, The University of Arizona, Tucson, Arizona 85721, USA
[2]Lunar and Planetary Laboratory, The University of Arizona, Tucson, Arizona 85721, USA
[3]Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland 20723, USA

ABSTRACT

Martian slope gullies are argued to be evidence for recent liquid water flow on the surface of Mars. To explain the source of water, a wide range of environmental conditions and processes has been invoked. However, a lack of information about the environmental context or timing of gully activity makes it difficult to evaluate the theories. Here, we present new observations of extensive gully modification over the past 6 Mars years within dune gullies with slope-gully morphology. Observed activity within 18 gullies in 7 dune fields constrains timing to winter, which is consistent with observed slope-gully activity. These observations show that fluvial processes are unlikely to cause present-day Martian dune-gully activity, and imply that CO_2 frost accumulation may play the dominant role.

INTRODUCTION

Martian slope gullies found on crater walls and other slopes have been the subject of many studies aimed at understanding their evolution mechanism(s), and the implications such mechanisms have for the Martian environment. Based on morphological similarities with terrestrial water-carved gullies, it has been suggested that these features were formed by fluvial erosion with liquid water from groundwater aquifers (Malin and Edgett, 2000; Mellon and Phillips, 2001; Heldmann and Mellon, 2004; Malin et al., 2006), snowmelt (Christensen, 2003; Dickson et al., 2007; Williams et al., 2009), or melting ground ice (Costard et al., 2002). Others have suggested that seasonal volatile condensates, such as water frost (Bridges and Hecht, 2002) or CO_2 frost (Hoffman, 2002; Ishii et al., 2006; Hugenholtz, 2008), or dry flow (Treiman, 2003) are involved. New gully deposits have been identified (Malin et al., 2006; McEwen et al., 2007; Dundas et al., 2010), and formation models have shown that their morphology is not inconsistent with dry granular flow (Pelletier et al., 2008; Kolb et al., 2009). Some studies have concluded that significant gully formation occurred during past times of high obliquity (Costard et al., 2002; Balme et al., 2006; Dickson et al., 2007; Williams et al., 2009), while others use gully activity as evidence of present-day water flow (Malin et al., 2006). In this study, we show that gullies located on dunes and similar in morphology to slope gullies (i.e., composed of an alcove, channel, and apron) have undergone significant modification—including apron extension and alcove/channel formation and widening—over the past 6 Mars years. This dune-gully activity appears restricted to winter, which is consistent with observed slope-gully activity (on nondune surfaces; Dundas et al., 2010).

This study focuses only on dune gullies that resemble slope gullies (Fig. 1; classified as type II/III by Reiss et al. [2007]). Martian dune gullies also have various other morphologies (e.g., the type I dune gully [Reiss et al., 2007]: a long, leveed, generally sinuous channel with a terminal pit) that are often found in close proximity to each other.

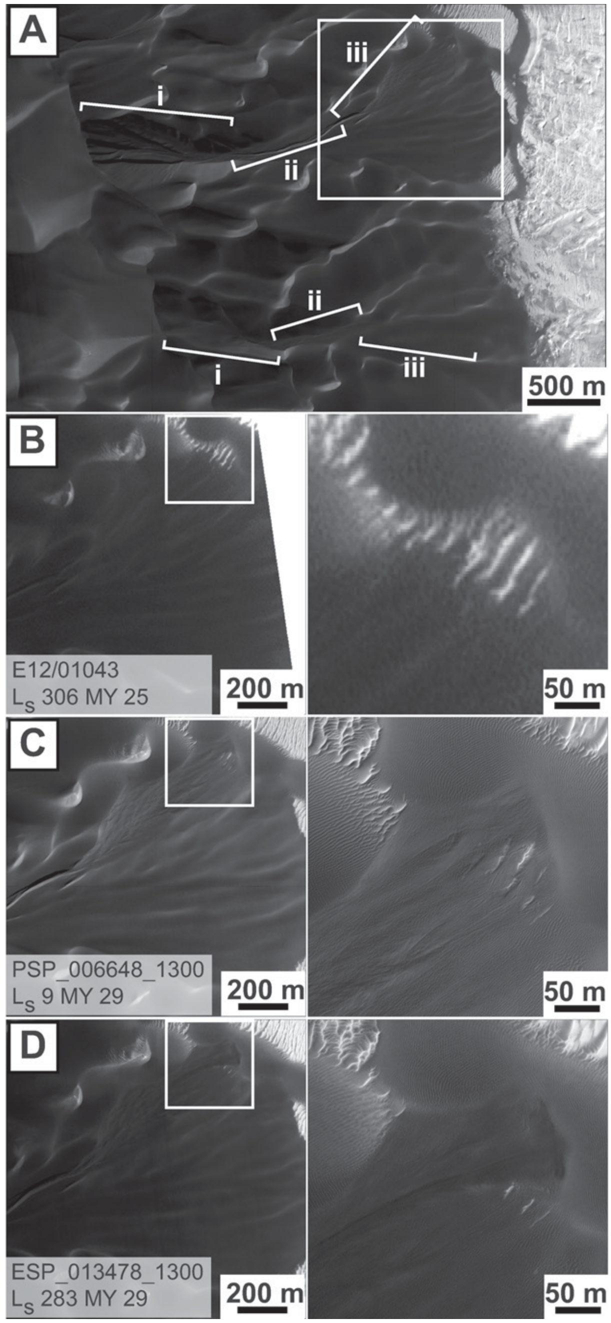

Figure 1. Dune gullies composed of (i) alcove, (ii) channel, and (iii) apron, in Matara crater dune field (49.5°S, 34.9°E). (A) Overview image (PSP_006648_1300) showing two gullies—bottom gully is heavily degraded and top gully is sharply defined and currently active, as shown in inset (and further insets below). (B) In 2002, bright bed forms were visible at foot of debris apron. Those bed forms were increasingly covered in 2007 (C) and 2009 (D), and most recent deposit exhibits albedo and texture signatures. MY—Mars Year, as defined by Clancy et al. (2000).

OBSERVATIONS

Dune gullies were identified using High-Resolution Imaging Science Experiment (HiRISE), Context Camera (CTX), and Mars Orbital Camera (MOC) images. We relied primarily on HiRISE images because their high resolution (0.25–0.5 m/px) and signal-to-noise ratio were needed to

*E-mail: serina@math.arizona.edu.

identify the generally small-scale (a few hundred meters long), low-contrast features on dark dune surfaces. Images were found based on HiRISE image description (included "dune"), inspection of probable dune locations (e.g., intracrater, low-albedo regions) in the global MOC wide-angle mosaic, and consultation of the Mars Global Digital Dune Database (65S-65N; Hayward et al., 2007).

We inspected over 250 HiRISE and 200 MOC/CTX images of 161 dune fields in the southern hemisphere (0°S–80°S). Gullies were found in 19 dune fields (see the GSA Data Repository[1]), which were almost all located between 40°S and 60°S (Fig. 2A), poleward of the majority of slope gullies: 30°S–50°S (Balme et al., 2006; Dickson et al., 2007). This is partly due to a latitudinal bias in the locations of long, steep dune slopes: the few dune fields located 0°S–30°S are generally composed of small, isolated barchans, and many dune fields poleward of 55°S have subdued relief. Many dune fields had only lower-resolution images or incomplete coverage, so that the number of sites identified as containing gullies and gully activity is a lower limit.

Of the observed 19 gullied dune fields, 12 contain gullies imaged with HiRISE. Of these, only 7 dune fields in the Hellespontus-Noachis region contained sufficient overlap with atmospherically clear HiRISE images for initial identification of gully activity. Through comparisons between overlapping HiRISE, MOC, and CTX images, we identified the timing of morphological changes (i.e., debris apron extension [Fig. 1] and alcove/channel formation or widening [Figs. 3A and 3B]) within an image pair. We identified timing of changes within 7 gullies (see the Data Repository) and changes within 3 gullies have been constrained to a period shorter than a Mars year (Fig. 2B).

We observed that areas with recent deposition often were sharply bounded with a relatively low albedo and disorganized texture with no resolvable ripples (Figs. 1C, 1D, and 3D; nearby dune and apron surfaces had uniform albedo and well-defined ripples of 2–4 m wavelength). Inspection of later images confirmed that these albedo and textural signatures fade, perhaps due to dust cover or saltation (although these areas still lacked resolvable ripples). These signatures were used to identify gully activity in sites without clear morphological changes. In total, we tracked activity within 18 gullies within 7 fields during 6 Mars years (see the Data Repository).

We found two active dune gullies in Matara crater (49.5°S, 34.9°E), within a 16-km-diameter, densely packed mound of barchan and transverse dunes. Activity within one gully was previously noted in 2005 (http://photojournal.jpl.nasa.gov/catalog/PIA04290); more recent activity includes alcove/channel widening and apron extension (second gully in Fig. 2B). The second active gully within Matara crater provides the clearest example of slope gully–type morphology, with a 1-km-long, 300-m-wide, steep-walled alcove, >1-km-long, 30-m-wide channel system, and >1-km-long apron (Fig. 1). Average slope (using a 75 m/pixel digital elevation model [DEM] generated from High-Resolution Stereo Camera images from orbit 2430) from dune crest to apron tip is 12°, with steeper portions (20°–30°) found near the channels. The alcove contains regions with different ripple patterns, indicating multiple erosional events. The entwined channels incised into the lower alcove and across the debris apron have various amounts of infilling, and the debris apron contains multiple overlapping deposits, each of which has its own ripple pattern and wavelength. The debris apron that appears to emanate from the northernmost and deepest channel lacks resolvable ripples, and the apron extent, albedo, and surface texture have changed at least twice since 2002 (Fig. 1; third gully in Fig. 2B). Other examples of gully modification include a newly formed 5-m-wide channel in Proctor field and apron deposition in Kaiser field (Fig. 3).

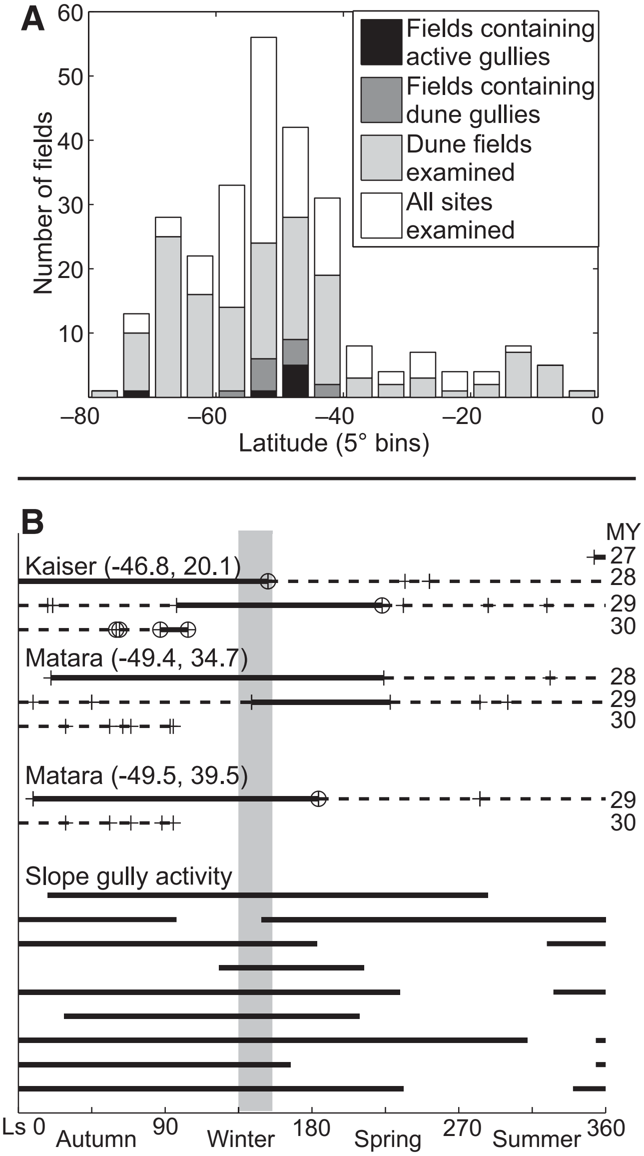

Figure 2. Spatial and temporal distribution of observed gully activity. A: Histogram showing latitudinal distribution of observed dune gullies and dune-gully activity. B: Plot showing timing of definitive morphological changes within dune gullies (upper lines) and bright/dark deposit formation within slope gullies (lower lines; Dundas et al., 2010). Also shown are spans where no changes were observed within dune gullies (dashed lines) and times that albedo and textural signatures of recent activity were visible (circles). Compared High-Resolution Imaging Science Experiment (HiRISE) and Context Camera (CTX) dune-gully images are denoted with plus signs. Peak CO_2 frost accumulation dates within midlatitudes (shaded region) are based on studies at 35°S (Schorghofer and Edgett, 2006) and 60°S (Kelly et al., 2006). Latest HiRISE images were taken at Ls 105 MY 30.

No gully activity was observed to occur from mid-spring through summer (Ls 230–353; Ls 0–360 encompass a Mars year, with Ls 0 at the southern autumnal equinox), and there were several examples of inactivity during autumn (Ls 353–60) and early spring (Ls 190–230). Conversely, the winter season is common to all periods containing definitive morphological gully changes—during 3 Mars years and in three different fields. This implies a common seasonality for dune-gully activity that is further

[1]GSA Data Repository item 2010286, locations of observed dune gullies, and MOC, CTX, and HiRISE images used to track dune gully activity, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

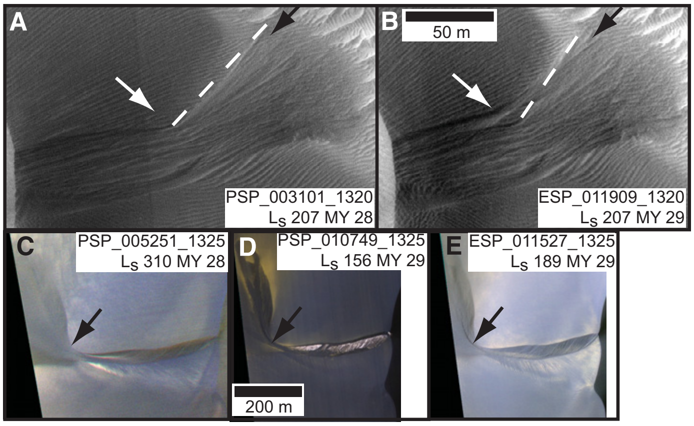

Figure 3. Additional examples of dune-gully modification. A–B: Within Proctor crater dune field (47.8 S, 30.7 E), 5-m-wide channel has formed and debris apron has extended. C–E: Within Kaiser crater dune field (47.2 S, 19.5 E), this dune gully has new apron deposition, briefly creating albedo and textural signatures of recent activity. Lines and arrows within image groups show common locations and are included to aide landform comparison.

supported by albedo and textural signatures of recent activity (22 observations within 13 gullies in 5 fields; see the Data Repository), which are visible only in images taken between Ls 140–250 during the previous 5 Mars years. During the current Mars year, albedo and texture changes have appeared since late autumn (Ls 60–104 so far) within dune gullies in Kaiser crater (46.7°S, 20.1°E; including first gully in Fig. 2B), and this suggests movement of material from the alcove/channels onto the apron. The latest image also shows apron extension (Fig. 2B).

DISCUSSION

The similar appearance, geologic setting, latitudes, and timing of activity of all dune gullies argue for a common modification mechanism. Because the observed activity includes significant apron, channel, and alcove modification and is consistent in timing with changes observed within slope gullies (Dundas et al., 2010) (Fig. 2B), this mechanism appears to relate to general present-day gully activity. Using our observations and knowledge about the structure of sand dunes, we evaluate proposed gully modification mechanisms.

Hypotheses involving subsurface reservoirs of liquid erupting through the surface (Malin and Edgett, 2000; Mellon and Phillips, 2001; Gaidos, 2001) are not supported in the geological setting of this study, because there is no reason that a liquid should be stored within or intrude into a dune and then be extruded from high-elevation locations. We would instead expect gullies to form near the bottom of dune slopes and to see other evidence of extrusions from a ground reservoir within interdune troughs.

An alternate theory is that the melting of ground ice could cause gully formation, based on morphological similarities with periglacial debris flows in Greenland (Costard et al., 2002) and denivation fans on Antarctic dunes (Bourke, 2005). Under present Martian conditions, however, ground ice will only melt through insolation or geothermal activity, and is likely to sublimate before melting (Mellon and Phillips, 2001). Insolation-driven melting (Hecht, 2002) is improbable because the observed gully activity is occurring during winter, when CO_2 frost is present (temperatures below 150 K). Geothermal activity would cause bottom-up melting, yielding subsurface water reservoirs; this is also inconsistent with the observed seasonality and lack of evidence of geothermal activity in these regions (Christensen et al., 2003).

It has also been proposed that sunlight penetrating through surface snowpacks could initiate gully development (Christensen, 2003; Dickson et al., 2007), but this mechanism is also at odds with the observed seasonality. It is unlikely that a snowpack that accumulated during high-obliquity periods (Christensen, 2003; Williams et al., 2009) could remain insulated for the 400 k.y. since the last period of high obliquity, especially near the crests of dark dunes, and a buried snow layer within a dune faces the same difficulties in melting as described for ground ice.

Recent modeling studies have shown that some morphological aspects of recently formed slope-gully deposits are consistent with dry granular flow (Pelletier et al., 2008; Kolb et al., 2009). Initiation mechanisms for dry flows, such as strong winds, may potentially mediate a seasonal control on gully activity. Further studies are needed to determine whether such a mechanism is viable and consistent with observed dune-gully locations, latitudes, and characteristics.

Our observations of gully activity and characteristics are most consistent with gully modification mechanisms driven by seasonal CO_2 frost. Such processes are hypothesized to be influential in other mass-wasting events (Russell et al., 2008), and slope-gully orientation distributions are consistent with a frost deposition–driven gully formation mechanism (Balme et al., 2006; Dundas et al., 2010). Models and observations of frost accumulation in the southern midlatitudes show that CO_2 frost accumulation continues through late winter (~Ls 150; Kelly et al., 2006; Schorghofer and Edgett, 2006), which coincides with our observed timing of activity within midlatitude dune gullies and slope gullies (Dundas et al., 2010; Fig. 2B). Peak frost accumulation within a gully will also depend on local geometry and thermophysical properties; images show that frost preferentially accumulates within gully alcoves/channels (e.g., Fig. 3D). This may account for the slightly later timing (Ls 190–220) observed for channel elongation within one type I dune gully (Russell crater: 54.5°S, 12.7°E); this activity has been attributed to seasonal melting of water frost (Reiss et al., 2010), but CO_2 frost–driven processes may be active within these features (Hansen et al., 2007), and HiRISE and CRISM data show that CO_2 frost was present in the gullies immediately preceding their activity. Frost accumulation continues through ~Ls 200–250 (Kelly et al., 2006; Aharonson et al., 2004) at higher latitudes, which again coincides with observations of activity: albedo and textural signatures of recent activity were observed ~Ls 300 within a dune field at 70°S, and possible slope-gully activity was observed Ls 240–260 at 71°S (Hoffman, 2002).

Hypothesized CO_2 frost–driven gully formation mechanisms include the entrainment of surficial material in frost avalanches (Ishii et al., 2006), initialization of material transport by the energetic release of sublimating CO_2 (Hoffman, 2002; Hansen et al., 2007), or increased fluidity and mobilization of mass-wasting flows through the reduction of dynamic interparticle friction (Hugenholtz, 2008). Quantitative model studies are needed to estimate the viability of these mechanisms. Modeling studies and observational surveys are also needed to determine expected gully morphologies and runout lengths/volume of transported material, as well as provide constraints on probable locations of gully modification in the past and present climate. Topography data are necessary inputs to these models, but the availability of high-resolution DEMs has been limited. A 1 m/pixel Kaiser dune DEM (constructed using HiRISE images from orbits 6899 and 6965) shows dune slopes of 20° and slopes of 15° within the dune gullies' alcove and channels; more high-resolution topography data from HiRISE stereo imaging is forthcoming.

If present-day gully activity is driven by frost processes, we might expect to see a hemispheric difference in the midlatitudes because the southern hemisphere currently experiences a longer winter season (Aharonson et al., 2004; Schorghofer and Edgett, 2006) and thus experiences more frost accumulation (in contrast, the high-latitude regions of both hemispheres—outside the study area of this paper—receive abundant seasonal frost). In examining all northern midlatitude dune fields (13 fields, 25°N–65°N [Hayward et al., 2007]; 7 HiRISE and 25 MOC/CTX images), we found far fewer dune gullies: a few small (~100 m length; all <200 m) dune gullies were found in only one field (Lyot crater: 50.2°N, 28.7°E). The longer winter season switches between hemispheres with a period of 50 k.y. as the argument of Mars' perihelion precesses, so frost-driven gully activity could have been more prevalent in the northern midlatitudes during earlier epochs. The lack of dune gullies in the northern midlatitudes suggests that dune field activity has erased evidence of dune gullies during the past tens of thousands of years, leaving only the larger and more robust slope gullies (Heldmann et al., 2007). This time scale of dune field activity is consistent with the lack of craters on these dunes (and all other Martian dunes; Bourke et al., 2010), even at HiRISE resolution.

CONCLUSION

Although we do not rule out a role for fluvial processes in past dune-gully activity, our observations imply that dune-gully formation is ongoing today and that current activity is subject to seasonal control. CO_2 frost accumulation appears to be the most likely driver for this activity. Because these dune gullies are similar in morphology to slope gullies, and consistent in the timing of observed activity, we hypothesize that CO_2 frost may play a major role in present-day general gully formation and modification.

ACKNOWLEDGMENTS

We thank Rose Hayward for her assistance with the Mars Global Digital Dune Database. Diniega was supported by a National Atmospheric and Space Administration (NASA) Harriett G. Jenkins Predoctoral Fellowship Project (JPFP) Fellowship.

REFERENCES CITED

Aharonson, O., Zuber, M.T., Smith, D.E., Neumann, G.A., Feldman, W.C., and Prettyman, T.H., 2004, Depth, distribution, and density of CO_2 deposition on Mars: Journal of Geophysical Research, v. 109, p. E05004, doi: 10.1029/2003JE002223.

Balme, M., Mangold, N., Baratoux, D., Costard, F., Gosselin, M., Masson, P., Pinet, P., and Neukum, G., 2006, Orientation and distribution of recent gullies in the southern hemisphere of Mars: Observations from High Resolution Stereo Camera/Mars Express (HRSC/MEX) and Mars Orbiter Camera/Mars Global Surveyor (MOC/MGS) data: Journal of Geophysical Research, v. 111, p. E05001, doi: 10.1029/2005JE002607.

Bourke, M.C., 2005, Alluvial fans on dunes in Kaiser crater suggest niveo-aeolian and denivation processes on Mars: Proceedings of the 36th Lunar and Planetary Science Conference, 14-18 March, League City, Texas, abstract 2373.

Bourke, M.C., Lancaster, N., Fenton, L.K., Parteli, E.J.R., Zimbelman, J.R., and Radebaugh, J., 2010, Extraterrestrial dunes: An introduction to the special issue on planetary dune systems: Geomorphology, v. 121, p. 1–14, doi: 10.1016/j.geomorph.2010.04.007.

Bridges, N.T., and Hecht, M.H., 2002, Mars polar gully modification and possible formation from condensed volatiles: Eos (Transaction, American Geophysical Union), Fall Meeting supplement, v. 83, Abstract P72C-10.

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

Christensen, P.R., and 21 others, 2003, Morphology and composition of the surface of Mars: Mars Odyssey THEMIS results: Science, v. 300, p. 2056–2061, doi: 10.1126/science.1080885.

Clancy, R.T., Sandor, B.J., Wolff, M.J., Christensen, P.R., Smith, M.D., Pearl, J.C., Conrath, B.J., and Wilson, R.J., 2000, An intercomparison of ground-based millimeter, MGS TES, and *Viking* atmospheric temperature measurements: Seasonal and interannual variability of temperatures and dust loading in the global Mars atmosphere: Journal of Geophysical Research, v. 105, p. 9553–9572, doi: 10.1029/1999JE001089.

Costard, F., Forget, F., Mangold, N., and Peulvast, J.P., 2002, Formation of recent Martian debris flows by melting of near-surface ground ice at high obliquity: Science, v. 295, p. 110–113, doi: 10.1126/science.1066698.

Dickson, J.L., Head, J.W., and Kreslavsky, M., 2007, Martian gullies in the southern mid-latitudes of Mars: Evidence for climate-controlled formation of young fluvial features based upon local and global topography: Icarus, v. 188, p. 315–323, doi: 10.1016/j.icarus.2006.11.020.

Dundas, C.M., McEwen, A.S., Diniega, S., Byrne, S., and Martinez-Alonso, S., 2010, New and recent gully activity on Mars as seen by HiRISE: Geophysical Research Letters, v. 37, p. L07202, doi: 10.1029/2009GL041351.

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

Hansen, C.J., et al., 2007, HiRISE observations of Mars' southern seasonal frost sublimation: Proceedings of the 38th Lunar and Planetary Science Conference, 12–16 March, Houston, Texas, abstract 1906.

Hayward, R.K., Mullins, K.F., Fenton, L.K., Hare, T.M., Titus, T.N., Bourke, M.C., Colaprete, A., and Christensen, P.R., 2007, Global Digital Dune Database and initial science results: Journal of Geophysical Research, v. 112, p. E11007, doi: 10.1029/2007JE002943.

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

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

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

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

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

Ishii, T., Miyamoto, H., Sasaki, S., and Tajika, E., 2006, Constraints on the formation of gullies on Mars: A possibility of the formation of gullies by avalanches of granular CO_2 ice particles: Proceedings of the 37th Lunar and Planetary Science Conference, 13–17 March, Houston, Texas, abstract 1646.

Kelly, N.J., Boynton, W.V., Kerry, K., Hamara, D., Janes, D., Reedy, R.C., Kim, K.J., and Haberle, R.M., 2006, Seasonal polar carbon dioxide frost on Mars: CO_2 mass and columnar thickness distribution: Journal of Geophysical Research, v. 111, E03S07, doi:10.1029/2006JE002678.

Kolb, K.J., Pelletier, J.D., and McEwen, A.S., 2009, Modeling the formation of bright slope deposits associated with gullies in Hale crater, Mars: Implications for recent liquid water: Icarus, v. 205, p. 113–137, doi: 10.1016/j.icarus.2009.09.009.

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

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

McEwen, A.S., and 32 others, 2007, A closer look at water-related geologic activity on Mars: Science, v. 317, p. 1706–1708, doi: 10.1126/science.1143987.

Mellon, M.T., and Phillips, R.J., 2001, Recent gullies on Mars and the source of liquid water: Journal of Geophysical Research, v. 106, p. 23,165–23,180, doi: 10.1029/2000JE001424.

Pelletier, J.D., Kolb, K.J., and Kirk, R.L., 2008, Recent bright gully deposits on Mars: Wet or dry flow?: Geology, v. 36, no. 3, p. 211–214, doi: 10.1130/G24346A.1.

Reiss, D., Jaumann, R., Kereszturi, A., Sik, A., and Neukum, G., 2007, Gullies and avalanche scars on Martian dark dunes: Proceedings of the 38th Lunar and Planetary Science Conference, 12–16 March, Houston, Texas, abstract 1993.

Reiss, D., Erkeling, G., Bauch, K.E., and Hiesinger, H., 2010, Evidence for present day gully activity on the Russell crater dune field, Mars: Geophysical Research Letters, v. 37, p. L06203, doi: 10.1029/2009GL042192.

Russell, P., Thomas, N., Byrne, S., Herkenhoff, K., Fishbaugh, K., Bridges, N., Okubo, C., Milazzo, M., Daubar, I., Hansen, C., and McEwen, A., 2008, Seasonally active frost-dust avalanches on a north polar scarp of Mars captured by HiRISE: Geophysical Research Letters, v. 35, p. L23204, doi: 10.1029/2008GL035790.

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

Treiman, A.H., 2003, Geologic settings of Martian gullies: Implications for their origins: Journal of Geophysical Research. Planets, v. 108, p. 8031, doi: 10.1029/2002JE001900.

Williams, K.E., Toon, O.B., Heldmann, J.L., and Mellon, M.T., 2009, Ancient melting of mid-latitude snowpacks on Mars as a water source for gullies: Icarus, v. 200, p. 418–425, doi: 10.1016/j.icarus.2008.12.013.

Manuscript received 9 April 2010
Revised manuscript received 23 June 2010
Manuscript accepted 29 June 2010

Printed in USA