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Dune migration and slip face advancement in the Rabe Crater dune field, Mars

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[1] Eight overlapping images of a dune slip face in Rabe Crater (35°E, 44°S) from the Mars Global Surveyor Mars Orbiter Camera show changes interpreted to be multiple grainflow events that would indicate present-day sand saltation and dune migration. New occurrences of these features appear sporadically throughout late southern summer and early fall, and then no further changes occur throughout winter. By the following summer the pattern of old streaks had been almost completely covered by new dark streaks. Assuming that this activity is typical from year to year, migration rates are estimated to be on the order of 1–2 cm per martian year, produced by south to southeasterly winds that blow mostly during the southern spring and early summer. This slow migration rate is consistent with a present-day sediment state that is either transport or availability limited. **Citation:** Fenton, L. K. (2006), Dune migration and slip face advancement in the Rabe Crater dune field, Mars, *Geophys. Res. Lett.*, *33*, L20201, doi:10.1029/2006GL027133.

1. Introduction

[2] Wind-sculpted features are common on much of the surface of Mars, indicating the importance of aeolian processes in shaping the landscape and responding to climate-driven changes in wind circulation [e.g., *Ward et al.*, 1985; *Malin and Edgett*, 2001]. In particular, active sand dunes would reflect present-day prevailing winds, whereas dormant sand dunes would record wind patterns from older wind regimes that are now defunct. On Earth, active and partially active dunes readjust to changing winds on timescales of years to centuries. In order to describe the sediment state of martian dunes and better understand the role aeolian processes have played in forming the sedimentary landscape, it is important to establish the activity level of martian dunes. This work reports on slip face avalanches in the dune field in Rabe Crater (35°E, 44°S) that change little within a single Mars year, but greatly from one year to another. This potential evidence for grainflow provides the first migration rate calculation for an active dune on Mars.

2. Background

[3] Despite the pervasive presence of dunes on Mars [*Ward et al.*, 1985, *Mullins et al.*, 2005] and high resolution imaging, it has been difficult to find evidence for dune activity.

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[4] Comparisons between Mars Global Surveyor Mars Orbiter Camera (MGS MOC) Narrow Angle images and Viking Orbiter images of dunes [*Edgett*, 2000; *Malin and Edgett*, 2001] and megaripple-like bedforms [*Zimbelman*, 2000] indicate no detectable movement over a span of 21 terrestrial years. Despite numerous efforts, there have been no reports of dune movement within overlapping MOC images [*Edgett*, 2002; *Williams et al.*, 2003; *Williams*, 2006; *Schatz et al.*, 2006]. As others have noted, it is possible that the observed dunes are indeed migrating, but at a rate too slow to be detected in the time between image acquisitions, especially given their limited spatial resolution. This may be in part because the migration rate of terrestrial dunes scales inversely with their height [*Bagnold*, 1941]. For example, the compound and complex crescentic dunes of the Algodones dune field in southern California are roughly the same size and type as those in this study, but their measured migration rate has been estimated at only 0.08 m yr^{-1} [*Sweet et al.*, 1988]. Such a low migration rate would be quite difficult to detect from spacecraft images.

[5] There are other reasons why dune migration may not be observed. In some cases, dune morphology indicates that more than one wind has shaped the dunes within a given dune field, leading to reversing, longitudinal, and star dunes. Under incident winds from multiple directions, these dunes can extend downwind in a direction roughly parallel to the resultant wind direction, or simply pile up under two or more convergent winds [e.g., *McKee*, 1979]. If the martian dunes of these forms are currently influenced by the same wind regime in which they formed, then they will not migrate downwind in the fashion of more straightforward barchans and transverse dunes. As a result, active dunes can be difficult to recognize if they do not migrate.

[6] Dune migration occurs under a combination of two processes: grainfall and grainflow. Sand grains lifted into saltation or suspension are carried over the brink of a dune slip face, and settle out on the slip face as grainfall deposits. As grainfall sands accumulate not far down the brink of the slip face, the slope eventually oversteepens and avalanches down the slip face as grainflow deposits [e.g., *Anderson*, 1988]. On Earth, the grainflow events take the shape of 3–4 cm thick tongues of sand that extend from near the slip face brink to the toe of the dune [*Lancaster*, 1995].

[7] Although dune movement has not yet been observed, there is evidence of both aeolian and erosional activity on dune slopes. Slip face avalanching on martian dunes has been noted and attributed to grainflow [*Malin and Edgett*, 2001; *Fenton et al.*, 2003], although some of these features have been attributed to mass wasting [*Fenton et al.*, 2003]. Other features on dune slip faces have been interpreted as erosional [*Mangold et al.*, 2003; *Bourke*, 2005]. Some relatively bright materials in Proctor Crater have been

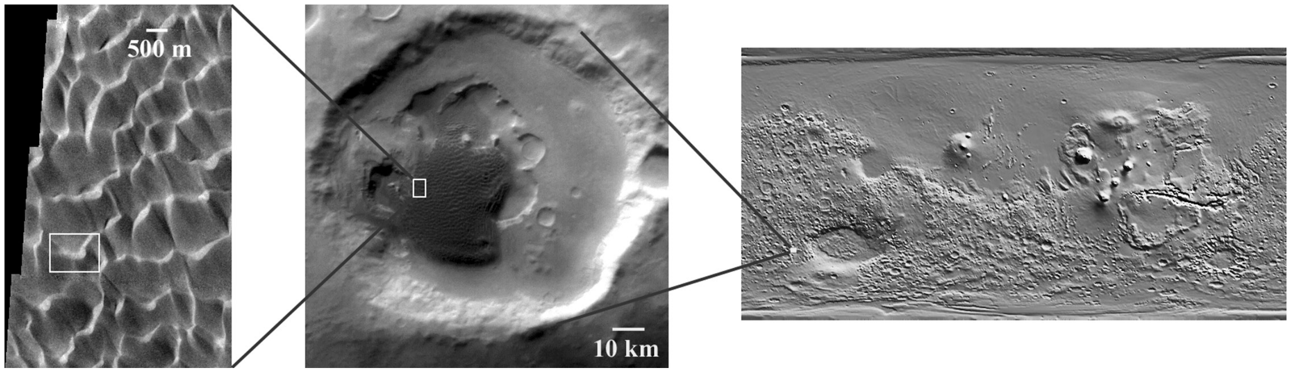

Figure 1. The study area is a dune outlined in white (THEMIS VIS image V01048003), located in the Rabe Crater dune field (MOC Wide Angle M21/01007), in Noachis Terra of the southern highlands of Mars. North is to the top.

shown to seasonally shift from one dune slope to another, suggesting that some loose material is currently shifting back and forth in response to the wind [*Fenton et al.*, 2005]. From these studies, it is clear that sand movement occurs on the slopes of many martian dunes, however, strong evidence for dune migration is still lacking.

3. Study Area and Method

[8] Rabe Crater is a ~100 km diameter crater located in Noachis Terra, not far west of Hellas Planitia. It contains one of the largest dune fields in the region, with dimensions of roughly 50 km × 35 km. The dune field is mostly composed of barchanoid and transverse dunes, with most slip faces oriented to the northwest (see Figure 10f and related discussion of *Fenton* [2005]). Because of this morphology, they are the type of dunes expected to migrate downwind, rather than extend downwind or accumulate in place. Thus migration should occur if dune sand is available for saltation (e.g., not indurated or frozen) and the wind stress climbs above the saltation threshold. Unlike most dune fields in Noachis Terra, the dunes of Rabe Crater are dominated by a single dune-forming wind (from the southeast). Mars season is defined by degrees in solar longitude (L_s) from 0°–360°, and L_s = 0° defines the northern vernal equinox. Martian years are numbered according to *Clancy et al.* [2000], who defined Mars Year 1 as beginning on April 11, 1955 (Ls = 0°). Thus Mars Years 24, 25, and 26 span the terrestrial years 1998–2000, 2000–2002, and 2002–2004, respectively.

[9] Because the dune field is so large, it has been repeatedly targeted by the MGS MOC team. As a result, there are individual dunes that have repeat coverage. This work focuses on one dune that was imaged no fewer than eight times from 1999 through 2002, spanning one and a half martian years from Mars Years (MY) 24 through 26. Figure 1 shows the location of this dune within the dune field. All MOC Narrow Angle and THEMIS VIS images used in this study were processed and sinusoidally projected to the same central longitude using the Integrated Software for Imagers and Spectrometers (ISIS) [*Eliason et al.*, 2001].

4. Results

[10] Figure 2 shows eight MOC Narrow Angle views of the same dune slip face, which dips down to the northwest (up and left). Images M07/03187, E13/00810, and E22/00190 are of limited spatial extent or were stretched until only the slip face was visible, so missing spaces are underlain by the processed and projected THEMIS image V01048003. To the right of each image is a drawing of the slip face brink and toe, as well as lines indicating the more prominent dark streaks that appear on the slip face.

[11] New major streaks appear in black, while successive drawings show older streaks in gray, with new minor additions as black dotted lines. New streak lines were drawn in only where new darker lines running more than halfway from the slip face brink to its toe appeared in successive images. Some changes in contrast may not be new streaks, but rather older streaks that briefly show more contrast than in the previous image. An example of a potentially false (albeit faint) new streak event is pointed out in the fourth frame. Because it is not clear whether or not they are newly formed dark streaks, they have not been considered as such in this study.

[12] Many dark streaks are apparent in the first frame. A prominent bright area between dark streaks is marked with a short arrow. This gap between streaks persists from the first through the sixth frame, nearly an entire martian year. The gap, however, is not present in the seventh and eighth frames. Most of the dark streak pattern has greatly shifted in the latter part of Mars Year 25, indicating a high formation rate between frames 6 and 7, or from midwinter through summer (see Figure 3). Minor new dark streaks appear in the second, third, and eighth frames, suggesting that their formation rate is persistent but slow from late summer through fall. No new features are apparent in the fourth through sixth frames, indicating no activity in early winter.

5. Discussion

[13] These dark streaks are interpreted here as grainflow events. They share the same morphology as typical terrestrial grainflows, having a characteristic straight, narrow shape that runs from slip face brink to toe. These features are distinct from sinuous gullies observed in dunes [*Mangold et al.*, 2003] and fan-shaped erosional features [*Bourke*, 2005], both of which are interpreted to be erosional features formed by the melting of water ice trapped in the dunes.

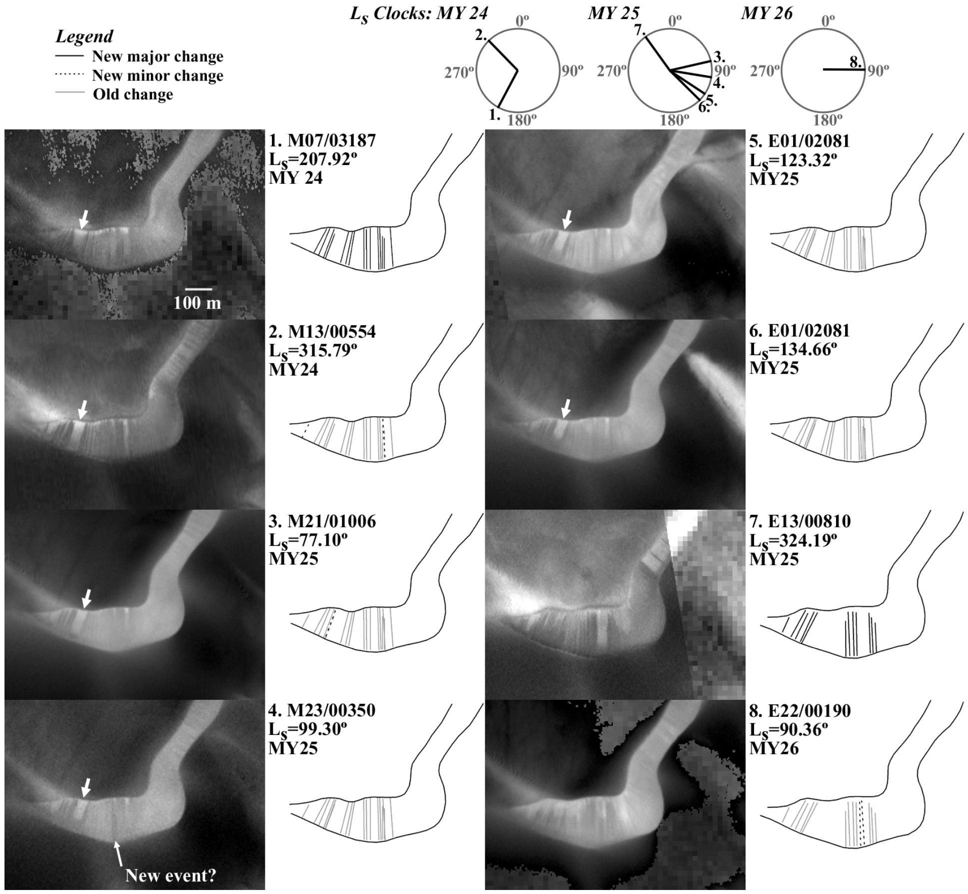

Figure 2. Portions of eight MOC Narrow Angle frames located on the same dune in Rabe Crater, showing the slip face studied here. The slip face dips down to the upper left: the windward slope (high ground) is on the bottom right and low ground is on the upper left. To the right of each frame are drawings showing major dark streak additions, minor dark streak additions, and pre-existing dark streaks. The three L_s "clocks" illustrate the timing of the MOC frames across three martian years. Short white arrows indicate a broad bright region on the slip face that persists throughout the first six frames but disappears in the seventh and eighth. The longer white arrow indicates an example of a (faint) potential new dark streak that is not considered an event because it does not obscure any new bright slip face areas with respect to the previous frame. North is to the top.

[14] The Rabe Crater dark streaks are also morphologically distinct from slope streaks interpreted as dust avalanches. *Sullivan et al.* [2001] describe the slope streaks as bright or dark features with acute upslope ends and digitate downslope terminations, often curving to follow slight variations in terrain and varying in width with a tendency to widen downslope. Each of these characteristics is at variance with the straight single-lobed dark streaks on the dune slip faces in this work. Furthermore, 95% of the slope streaks in one study were located in low thermal inertia areas ($I < 130$ J m^{-2} K^{-1} s$^{-1/2}$), and all were located within or near high albedo, low thermal inertia "continents" in the low northern latitudes [*Schorghofer et al.*, 2002]. In contrast, the low albedo dune sand of Rabe Crater is located far from these regions, and it has a thermal inertia greater than 300 J m^{-2} K^{-1} s$^{-1/2}$ [*Mellon et al.*, 2000]. Given these differing thermal characteristics it is unlikely that enough dust is present on the Rabe Crater dunes to produce dust avalanching slope streaks.

[15] The dark streaks are visible because they are superimposed on a relatively bright slip face. Such a distinct difference in tone between slip face and grainflow is

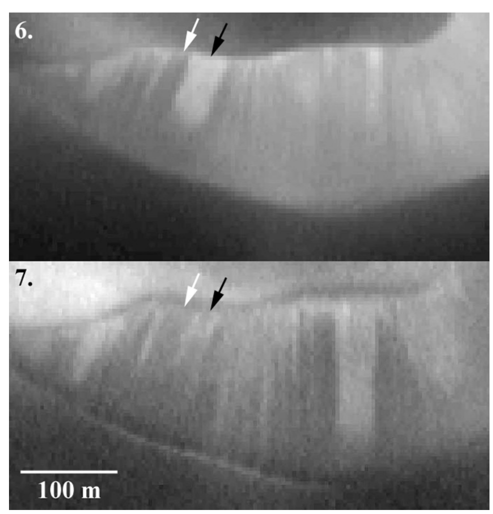

Figure 3. Part of MOC Narrow Angle frames 6 and 7 from Figure 2, highlighting major changes in dark streaks on the dune slip face. Black arrows indicate an area with significant change; white arrows indicate an area that may not have changed. North is to the top.

unusual on terrestrial dunes. It is possible that relatively bright fallout from dust storms thinly mantles the dunes, only to be subsequently buried or cast into suspension by new grainflow events. If this is the case, then dust fallout would have occurred before the first frame in Mars Year 24, and possibly again before the seventh frame in Mars Year 25. The global dust storm of 2001 occurred at $L_s \approx 185°$ in MY 25, between the sixth and seventh frames, so it is possible that the new dark streaks in the seventh frame are only visible because of dust settling from this storm.

[16] There is an apparent loss of contrast in winter images (frames 3, 4, 5, 6, and 8). TES surface temperatures of the Rabe Crater floor show winter daytime temperatures (acquired during the same time of day as MOC Narrow Angle images) cold enough for water frost to form, but too warm for CO_2 frost (see Figure 4). It is possible that water frost accumulation is partially obscuring the underlying dark streaks. In this case, the frost could also be preventing new dark streaks from forming, effectively rendering the dunes inactive during the winter. However, the solar incidence angle increases during the southern winter as the martian subsolar point reaches into the northern latitudes. It is also likely that a higher sun angle contributes to the apparent loss of contrast.

[17] If martian grainflows are similar in thickness to terrestrial grainflows, then each dark streak visible in the MOC images is ~3–4 cm thick [*Lancaster*, 1995]. Dark streaks are visible on dune slip faces throughout most of the eight MOC images included in this study, indicating that these streak-forming events are occurring at least in this portion of the dune field. Assuming that the grainflow events observed in these eight images is typical, and that roughly half of each slip face each year is covered by new grainflow events, then the dunes in this portion of the dune field migrate at a rate of 1–2 cm MY^{-1} towards the northwest. Other parts of the dune field (not shown) do not display this kind of activity, so the dune field may be described as partially active. Because wind accelerates more up the slopes of large dunes relative to small dunes (especially those located within dune fields, as opposed to those isolated from one another), some terrestrial dune fields are defined as partially active because the wind is only strong enough to move sand on the tops of the larger dunes [e.g., *Lancaster*, 1985]. It is possible that the same effect is keeping the largest dunes in the Rabe Crater dune field active and allowing the smaller and low-lying dunes to remain dormant.

[18] The low observed migration rate is consistent with either an availability or transport limited sediment state (using concepts described by *Kocurek and Lancaster* [1999]), although the presence of the large dune field indicates that the sediment state was probably vastly different at some point in the past. If migration rates this slow are typical of martian dune fields, then the reason for the lack of observed dune movement by other researchers is now apparent: as suggested by many, the dunes simply move too slow for changes to be apparent in orbiter images on a decadal timescale with resolutions lower than tens of centimeters per pixel.

[19] Small fan-like erosional features smaller than but similar to the Kaiser Crater fans described by *Bourke* [2005] are present in the Rabe Crater dune field, a few of which are within a few kilometers of the dune described in this work (not shown). If the Rabe Crater dunes are indeed active, then they must migrate at a rate slow enough that these erosional features can form and persist. A dune's reconstitution time is described as the time required for a dune to migrate one wavelength (one dune length) [*Lancaster*, 1995]. The dunes in this portion of the Rabe Crater dune field are ~900 m in length. At a rate of 1–2 cm MY^{-1}, these dunes would require 45,000–90,000 MY (85,000–170,000 terrestrial years) to move one wavelength. This timescale is likely long enough to allow erosional fans to form, and if the dune migration rate is constant then it may be considered an upper limit on their age.

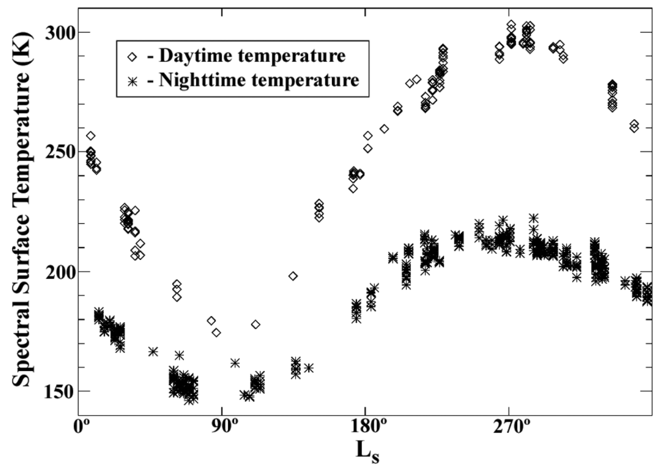

Figure 4. Spectrally derived temperatures from the floor of Rabe Crater, divided into daytime and nighttime measurements. Daytime temperatures do not dip below 170 K during the winter, indicating that obscuration by CO_2 frost is not likely responsible for the loss of contrast on the slip face of the dune in Figures 2 and 3. Remaining candidates are water frost and the low wintertime solar incidence angle.

6. Conclusion

[20] Seventeen prominent dark streaks have been observed to form on a slip face in Rabe Crater in Noachis Terra on Mars. These dark streaks are interpreted as grainflow events, sand avalanches that form by the oversteepening of dune slip faces under incident winds of saltation strength. The greatest number of new dark streaks formed in an interval between midwinter and midsummer, suggesting that southern spring is a season with persistent high-stress winds blowing from the south to southeast. Fewer new dark streaks formed in the late summer and fall; none appeared during the winter.

[21] These grainflow events lead to an estimated migration rate of 1–2 cm MY^{-1} to the northwest and a dune reconstitution time of 45,000–90,000 MY. If this migration rate is typical of martian dunes, then it is unlikely that movement of dunes will be detected by image comparison within the current era of spacecraft observation. However, the sediment state of martian dunes is probably spatially variable, so the migration rates of the Rabe Crater dunes may not be representative of dunes outside of Noachis

Terra. The observed grainflow events and erosional features indicate that the dune field is only seasonally and partially active, limited from further activity by (1) low drift potential caused by weak winds that are unable to transport much sand and/or (2) sand that is unavailable for transport (e.g., it is indurated, frosted, or frozen). These two possibilities, or a combination of them, indicate that the Rabe Crater sediment state is transport or availability limited.

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References

Anderson, R. S. (1988), The pattern of grainfall deposition in the lee of aeolian dunes, *Sedimentology*, *35*, 175–188.

Bagnold, R. A. (1941), *The Physics of Blown Sand and Desert Dunes*, 265 pp., CRC Press, Boca Raton, Fla.

Bourke, M. C. (2005), Alluvial fans on dunes in Kaiser Crater suggest niveo-aeolian and denivation processes on Mars, *Lunar Planet. Sci.*, *XXXVI*, Abstract 2373.

Clancy, R. T., B. J. Sandor, M. J. Wolff, P. R. Christensen, M. D. Smith, J. C. Pearl, B. J. Conrath, and R. J. Wilson (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, *J. Geophys. Res.*, *105*(E4), 9553–9571.

Edgett, K. S. (2000), New views of Mars eolian activity, materials, and surface properties: Three vignettes from the Mars Global Surveyor Mars Orbiter Camera, *J. Geophys. Res.*, *105*(E1), 1623–1650.

Edgett, K. S. (2002), Low-albedo surfaces and eolian sediment: Mars Orbiter Camera views of western Arabia Terra craters and wind streaks, *J. Geophys. Res.*, *107*(E6), 5038, doi:10.1029/2001JE001587.

Eliason, E. M., J. A. Anderson, J. M. Barrett, K. J. Becker, T. L. Becker, D. A. Cook, L. A. Soderblom, T. L. Sucharski, and K. T. Thompson (2001), ISIS Image processing capabilities for MGS/MOC imaging data, *Lunar Planet. Sci.*, *XXXII*, Abstract 2081.

Fenton, L. K. (2005), Potential sand sources for the dune fields in Noachis Terra, Mars, *J. Geophys. Res.*, *110*, E11004, doi:10.1029/2005JE002436.

Fenton, L. K., J. L. Bandfield, and A. W. Ward (2003), Aeolian processes in Proctor Crater on Mars: Sedimentary history as analyzed from multiple data sets, *J. Geophys. Res.*, *108*(E12), 5129, doi:10.1029/2002JE002015.

Fenton, L. K., A. D. Toigo, and M. I. Richardson (2005), Aeolian processes in Proctor Crater on Mars: Mesoscale modeling of dune-forming winds, *J. Geophys. Res.*, *110*, E06005, doi:10.1029/2004JE002309.

Kocurek, G., and N. Lancaster (1999), Aeolian sediment states: Theory and Mojave Desert Kelso Dune field example, *Sedimentology*, *46*, 505–516.

Lancaster, N. (1985), Variations in wind velocity and sand transport rates on the windward flanks of desert sand dunes, *Sedimentology*, *32*, 581–593.

Lancaster, N. (1995), *Geomorphology of Desert Dunes*, Routledge, Boca Raton, Fla.

Malin, M. C., and K. S. Edgett (2001), Mars Global Surveyor Mars Orbiter Camera: Interplanetary cruise through primary mission, *J. Geophys. Res.*, *106*(E10), 23,429–23,570.

Mangold, N., F. Costard, and F. Forget (2003), Debris flows over sand dunes on Mars: Evidence for liquid water, *J. Geophys. Res.*, *108*(E4), 5027, doi:10.1029/2002JE001958.

McKee, E. D. (1979), Introduction to a study of global sand seas, in *A Study of Global Sand Seas*, *U.S. Geol. Surv. Prof. Pap.*, *1052*, 1–19.

Mellon, M. T., B. M. Jakosky, H. H. Kieffer, and P. R. Christensen (2000), High-resolution thermal inertia mapping from the Mars Global Surveyor Thermal Emission Spectrometer, *Icarus*, *148*, 437–455.

Mullins, K. F., R. K. Hayward, T. N. Titus, M. C. Bourke, and L. K. Fenton (2005), Mars digital dune database: A quantitative look at the geographic distribution of dunes on Mars, *Lunar Planet. Sci.*, *XXXVI*, Abstract 1986.

Schatz, V., H. Tsoar, K. S. Edgett, E. J. R. Parteli, and H. J. Herrmann (2006), Evidence for indurated sand dunes in the Martian north polar region, *J. Geophys. Res.*, *111*, E04006, doi:10.1029/2005JE002514.

Schorghofer, N., O. Aharonson, and S. Khatiwala (2002), Slope streaks on Mars: Correlations with surface properties and the potential role of water, *Geophys. Res. Lett.*, *29*(23), 2126, doi:10.1029/2002GL015889.

Sullivan, R., P. Thomas, J. Veverka, M. Malin, and K. E. Edgett (2001), Mass movement slope streaks imaged by the Mars Orbiter Camera, *J. Geophys. Res.*, *106*(E10), 23,607–23,633.

Sweet, M. L., J. Nielson, K. Havholm, and J. Farrelley (1988), Algodones dune field of southeastern California: Case history of a migrating modern dune field, *Sedimentology*, *35*, 939–952.

Ward, A. W., K. B. Doyle, P. J. Helm, M. K. Weisman, and N. E. Witbeck (1985), Global map of eolian features on Mars, *J. Geophys. Res.*, *90*(B2), 2038–2056.

Williams, K. K. (2006), Are Martian dunes migrating? A planet-wide search for dune movement, *Lunar Planet. Sci.*, *XXXVII*, Abstract 2322.

Williams, K. K., R. Greeley, and J. R. Zimbelman (2003), Using overlapping MOC images to search for dune movement and to measure dune heights, *Lunar Planet. Sci.*, *XXXIV*, Abstract 1639.

Zimbelman, J. R. (2000), Non-active dunes in the Acheron Fossae region of Mars between the Viking and Mars Global Surveyor eras, *Geophys. Res. Lett.*, *72*(7), 1069–1072.

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