EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms (2012)
DOI: 10.1002/esp.3331

Shifting sands on Mars: insights from tropical intra-crater dunes

Paul E. Geissler,[1]* Nicholas W. Stantzos,[2] Nathan T. Bridges,[3] Mary C. Bourke,[4] Simone Silvestro[5] and Lori K. Fenton[5,6]
[1] US Geological Survey, Flagstaff, AZ, USA
[2] Northern Arizona University, Flagstaff, AZ, USA
[3] Applied Physics Laboratory, Laurel, MD, USA
[4] Planetary Science Institute, Tucson, AZ, USA
[5] SETI Institute, Mountain View, CA, USA
[6] NASA Ames Research Center, Moffett Field, CA, USA

Received 24 June 2011; Revised 11 September 2012; Accepted 17 September 2012

*Correspondence to: Paul E. Geissler, Center for Astrogeology, US Geological Survey, 2255 N. Gemini Drive, Flagstaff, AZ 86001, USA. E-mail: pgeissler@usgs.gov

ESPL
Earth Surface Processes and Landforms

ABSTRACT: Evidence for sand motion is found in repeated observations of sand dunes at three sites in the Martian tropics by the High Resolution Imaging Science Experiment on Mars Reconnaissance Orbiter. An eroding outcrop of layered sediments is identified as a possible source of the sand in Pasteur crater. Ancient layered sediments in Becquerel crater are actively being carved into flutes and yardangs by the blowing sands. Dunes in an un-named crater in Meridiani near the Mars Exploration Rover Opportunity landing site advanced as much as 50 cm over an interval of one Martian year. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: Mars; dunes; saltation

Introduction

The High Resolution Imaging Science Experiment (HiRISE) camera on Mars Reconnaissance Orbiter has been carrying out an orchestrated campaign to re-image sand dunes and other eolian features under similar lighting conditions at intervals of Martian years. Initial results of this survey show sand movement in many places on Mars, ranging from the tropics to the north polar erg (Silvestro *et al.*, 2010, 2011; Chojnacki *et al.*, 2011; Hansen *et al.*, 2011; Bridges *et al.*, 2012a, 2012b). So far, dune movement has been detected in 40 of the 64 qualifying HiRISE image pairs acquired by this campaign (Geissler *et al.*, 2012). The best documented dune field is at Nili Patera in Syrtis Major, where a series of HiRISE images has monitored sand motion at recurring intervals over a period of more than two Martian years. These images demonstrate frequent avalanches cascading down the slip faces of active dunes, and show the gradual advance of entire dunes as slip faces are overtaken by the faster ripples. A digital elevation model constrains the volumetric changes in the Nili Patera dune fields, allowing estimates to be made of the sand flux needed to produce the observed changes (Bridges *et al.*, 2012a). The results suggest sand fluxes on order of several cubic meters per meter per year, similar to sand fluxes in Victoria Valley, Antarctica (Bridges *et al.*, 2012a).

The confirmation that Martian sands are mobile in the present environment solves some old puzzles, explaining how Martian dark regions manage to clean themselves after dust storms, for example (e.g. Geissler, 2005). But it also raises new questions. First, where are the sources of the sand? Repeated impacts onto the surface must eventually destroy the saltating sand grains by comminution and abrasion. What supplies the sand needed to replace the destroyed grains and balance the attrition? Second, what are the implications of the blowing sands for actively altering the Martian landscape through erosion by sandblasting or deposition of eolian sediments?

In this report we focus on three tropical sites with verifiable surface changes caused by windblown sand. These sites are all intra-crater dune deposits in the Arabia Terra/Meridiani Planum region but they are separated by up to 2000 km and lie in different terrain with distinctly different settings (Figure 1). The landing site of the Mars Exploration Rover (MER) Opportunity lies in this region, so we have observations from the surface to help interpret the orbital images. These examples allow us to examine the effects of modern sand motion on dunes and ripples and investigate the implications for the present day geological environment.

Approach

The dune fields chosen for this study were deliberately targeted for repeat imaging because of the ease of visibility of the dark dunes contrasting with bright bedrock or soil substrate. These sites were examined for changes using pairs of map-projected images straight from the HiRISE processing pipeline (Eliason *et al.*, 2007). The bedform changes were first identified by blinking between the image pairs and recorded on a reduced-scale (browse) image. From these sites, specific examples were chosen for further study and measurement. Cropped subimages depicting these sites were next prepared. These subimages

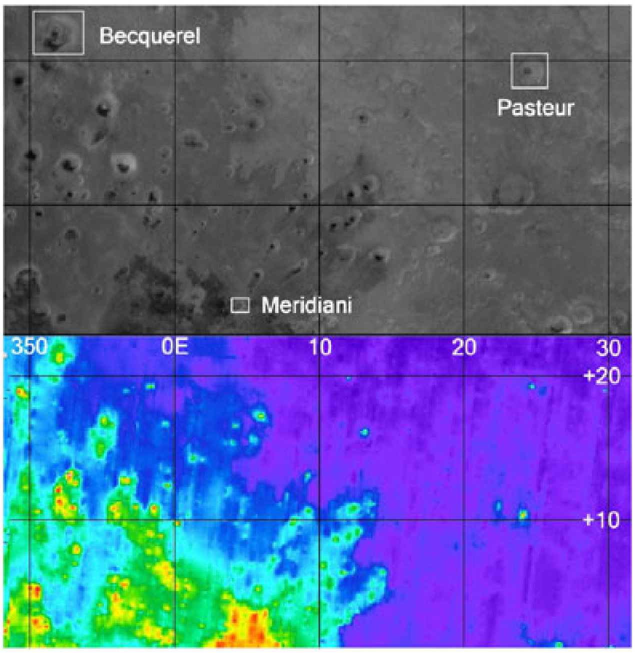

Figure 1. Locations of the study sites. (Top) Locations outlined on Mars Global Surveyor (MGS) Mars Orbiter Camera (MOC) visible reflectance from Malin Space Science Systems. (Bottom) MGS Thermal Emission Spectrometer (TES) thermal inertia from Christensen *et al.* (2001); color coding: purples range from 40 to 60 $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$, reds reach as high as 480 $\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$.

were co-registered using the US Geological Survey (USGS) Integrated Software for Imagers and Spectrometers (ISIS) processing package, based on the terrain surrounding the sand dunes after first masking out (setting to null) the changeable features. The earlier subimage of each pair was finally subtracted from the later subimage, allowing us to determine the dimensions of the changes from the pixel scale (i.e. the known ground dimensions of an image element).

Pasteur Crater

Pasteur crater is located at 24·7° E, 19·4° N, in a generally dust-covered region of eastern Arabia with relatively high albedo and low thermal inertia. The intra-crater dune deposits consist of small, isolated, dark barchans up to 100 m in breadth clustered in the southwest quarter of the crater (Figure 2). The sparse dunes are found sheltered in the lee of topographic obstacles and in depressions such as small craters. The dune orientations indicate that they formed from north-easterly winds. The dark dunes overlie bright soils made up of dust and transverse aeolian ridges (TARs), older eolian deposits that may be armored against erosion by a skin of coarse grained rock fragments (Zimbelman and Williams, 2007; Balme *et al.*, 2008; Sullivan *et al.*, 2008). Bright streaks extend downwind from the dunes, suggesting that the dusty surface brightens when it is disturbed by the saltating sand (Figure 2). Changes in the sand dunes were observed over one Martian year between December 11, 2006 and November 2, 2008 in HiRISE images PSP_001756_1995 and PSP_010643_1995. Although most of the dunes remained unaltered, changes were detected in at least 25 sites in the ~157 km^2 area targeted. No changes were seen in the TARs.

Close-up examination (Figure 3) shows that these changes cannot be ascribed to deposition or removal of a dust coating, but rather require local sand motion in a south-westerly direction. New dark patches appear adjacent to spots that brightened during the same interval, indicating that the dark sand has blown downwind. In many places the sand has banked up against the upwind flanks of the immobile TARs. Streaks show where sand has blown from one deposit to another.

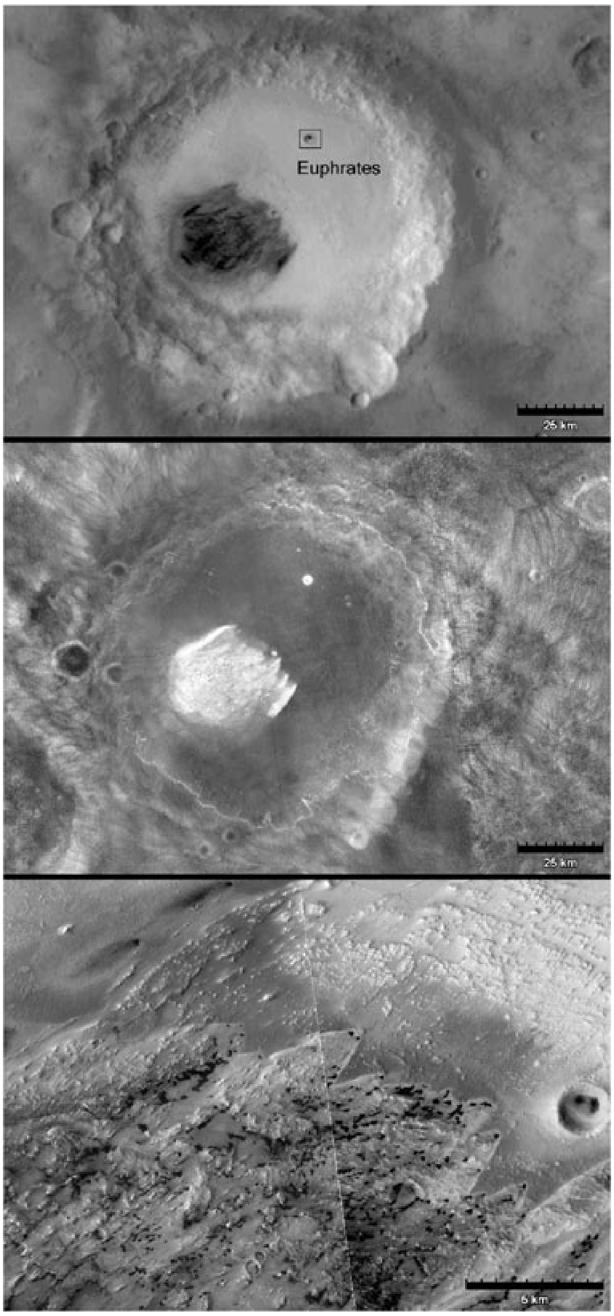

Figure 2. Pasteur crater dunes. (Top) MGS MOC visible reflectance. (Middle) Mars Odyssey THEMIS night-time temperatures. (Bottom) Dark dunes and bright wind streaks in CTX images B03_010643_1998_XN_19N335W (left) and P14_006503_1995_XN_19N335W (right).

The presence of active dunes in Pasteur crater is surprising because of the crater's isolated location in Arabia Terra, in the center of a vast region that is covered by a thick mantle of dust. The dust cover stabilizes the surface surrounding Pasteur, preventing any mobile materials from saltating into the crater. The nearest external sources of sand lie hundreds of kilometers upwind of Pasteur, and no wind streaks or other evidence of recent sand transport into Pasteur can be seen. Without replenishment, the active dunes in Pasteur crater would rapidly blow away and disappear. While many other craters in Arabia Terra contain dune fields of trapped sands that appear to have blown

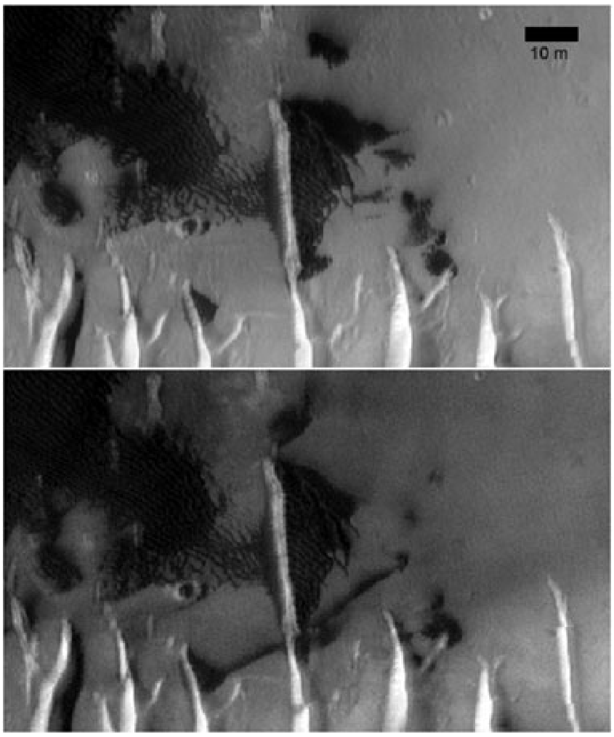

Figure 3. Sand motion in Pasteur crater. (Top) HiRISE image PSP_001756_1995, December 11, 2006. (Bottom) PSP_010643_1995, November 2, 2008.

in from outside the crater, the Pasteur crater dunes are interesting because they appear to arise from a local source within Pasteur crater itself. The small crater Euphrates, upwind of the dunes at 24·8° E, 19·8° N, contains layered sediments that have collected a pool of dark sand at the base of the deposit (Figure 4). The dark bands within the layered deposit could be eroding to generate the sands in Euphrates and elsewhere within Pasteur. While it is possible that these sands simply blew in from elsewhere and were temporarily trapped in Euphrates, we note that sand deposits are absent from the small crater at 25·3° E, 19·4° N, which is also within Pasteur and is similar in size to Euphates but lacks a comparable night-time thermal signature (see again Figure 2). Close examination of Figure 4 shows evidence for mass wasting that directly links the sand shed by the layered deposit to the pool of sand at its base. The layered deposit in Euphrates may itself be made up of eolian sediments, sands that were deposited in a past epoch and are being resurrected again now. Euphrates is approximately 400 m deep according to MOLA measurements and is 2·8 km across, so if it were once filled to its total volume of ~1 km^3 it could easily account for all of the sand in Pasteur crater (estimated at 0·03 km^3).

Many of the bedrock features in Pasteur are elongated in a north-easterly direction. These elongated knobs resemble yardangs, features produced by eolian erosion, but the alternative explanation of a structural trend in the bedrock cannot be ruled out. Interpretation is difficult here because the bedrock is covered with dust.

Becquerel Crater

Becquerel crater is located at 352·2° E, 22·1° N in a region of western Arabia Terra with intermediate albedo and thermal inertia (Figure 5). Becquerel is particularly interesting because a deposit of bright layered sedimentary rock is found near the southern rim of the crater. Southerly trending wind streaks cross the surface of the layered deposit, which is sculpted into knobs and yardangs (Figure 6; see also Rossi *et al.*, 2009). Dark dunes are clustered along the northern and southern margins of the layered deposit, presumably providing the source of the dark streaks.

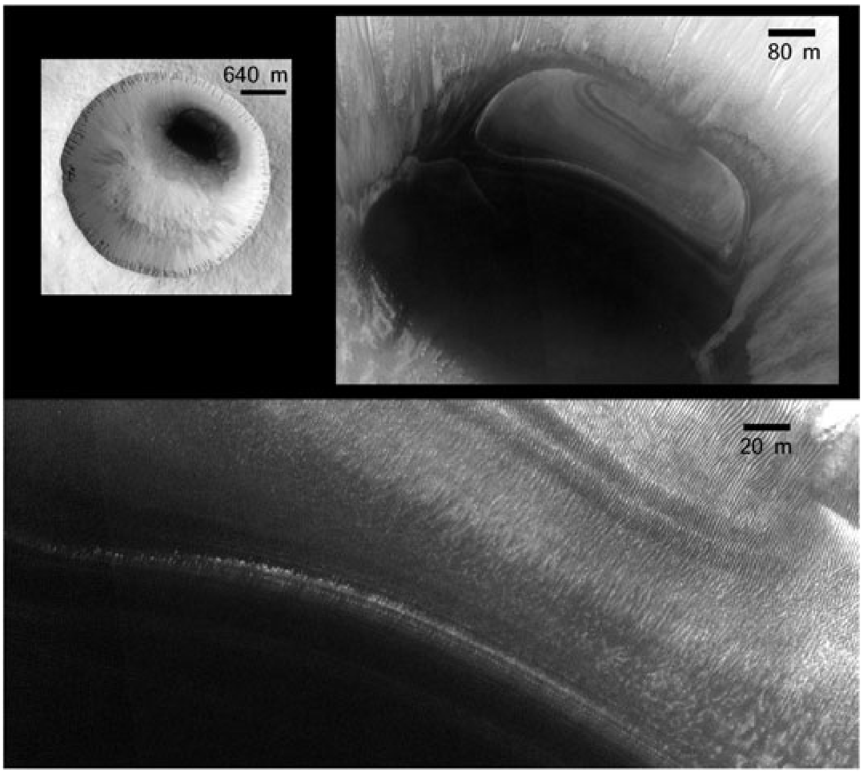

Figure 4. Euphrates crater, a possible source of the Pasteur crater sands. Downslope motion is apparent in the bottom cut-out where the dark sediments drape over the lowermost bright bands as the layered deposit sheds sand. HiRISE image PSP_007004_2000.

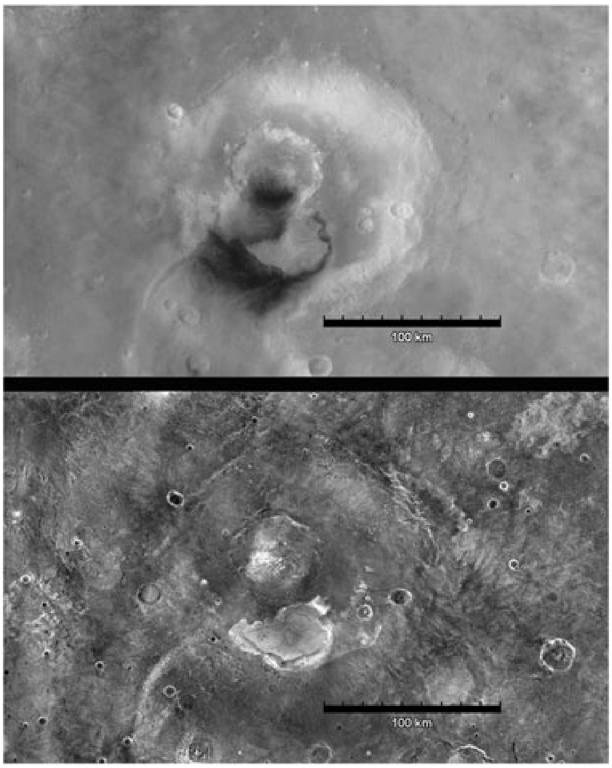

Figure 5. Becquerel crater context. (Top) MGS MOC visible reflectance. (Bottom) Mars Odyssey THEMIS night-time temperatures.

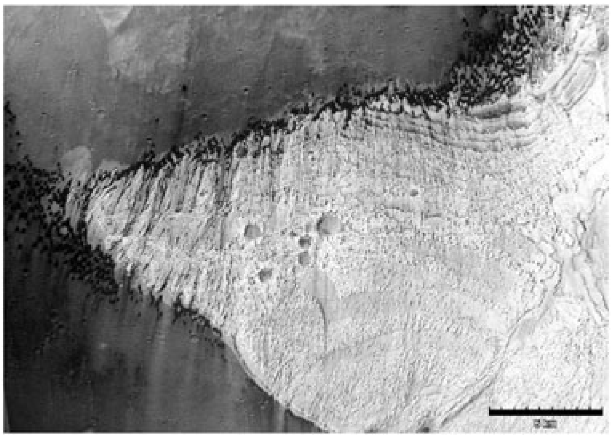

Figure 6. Eolian erosion of ancient layered sediments in Becquerel crater. CTX image P19_008495_2015_XN_21N008W.

The orientation of the barchans indicates that they were formed by northerly winds. Changes in the distribution of the sand with respect to the layered deposits were observed over two Martian years between November 24, 2006 and September 5, 2010, documented by HiRISE images PSP_001546_2015 and ESP_019268_2015. The most obvious changes occurred along the margins of the dunes and in the pattern of ripples atop the dunes (Figure 7). The ripples shifted almost 2 m to the south-southwest over this interval, an advance of ~1 m/Martian year. Only the ripples perpendicular to the wind direction changed position. Nearby, crestlines also advanced as ripples climbed the backs of isolated barchans and cascaded down the slip faces.

These observations suggest that the sands in Becquerel are currently mobile and actively contribute to the sandblasting that has evidently eroded the layered deposit. The effectiveness of the erosion suggests that the layered deposit is made up of soft rock, perhaps the last remnant of a formerly more extensive unit that will someday disappear entirely. In contrast, the crater rim rock is not as deeply scoured by the sandblasting, and appears to be more resistant to erosion than the softer layered deposit. No local sources of sand have been identified in Becquerel crater. The dark sands to the north (upwind) of the layered deposit appear to have blown in from outside of Becquerel crater. Erosion of the layered sediment itself may contribute to the local sand supply.

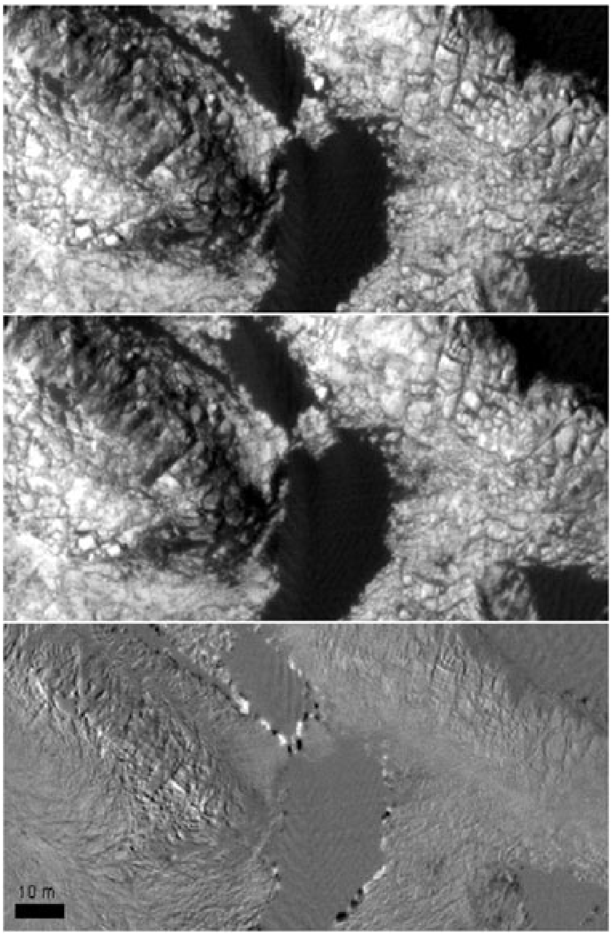

Figure 7. Dune changes in Becquerel crater. (Top) PSP_001546_2015, November 24, 2006. (Middle) ESP_019268_2015, September 5, 2010. (Bottom) Difference image (white spots show places that brightened during this interval, black spots places that darkened).

Meridiani

The third site is another intra-crater dune deposit in an un-named crater located at 4·7° E, 3·1° N on the margin of low albedo, high thermal inertia terrain in Meridiani Planum (Figure 8). The dunes are situated in the western half of the crater (Figure 9), on bright bedrock which is complexly fractured and convoluted. The orientation of the coalescing barchans suggests that they were shaped by north to north-easterly winds. The dunes are sorted by size with the largest (up to 575 m across) upwind. Changes were observed over one Martian year between January 25, 2008 and January 29, 2010 in HiRISE images PSP_007018_1830 and ESP_016459_1830. Many conspicuous changes took place at the edges of the dunes and in the pattern of ripples on the surface of the sand dunes (Figure 10). Ripples in this location shifted up to a maximum of 2 m over a period of one Martian year, however the average movement was closer

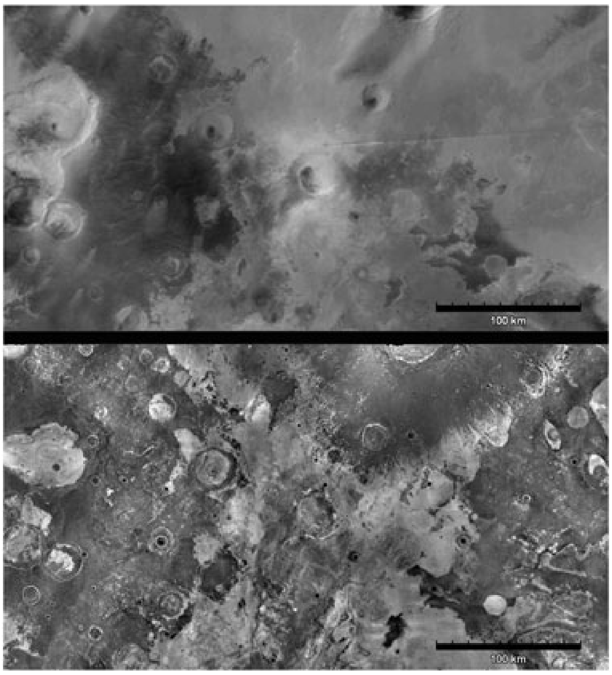

Figure 8. Meridiani dunes context. (Top) MGS MOC visible reflectance. (Bottom) Mars Odyssey THEMIS night-time temperatures.

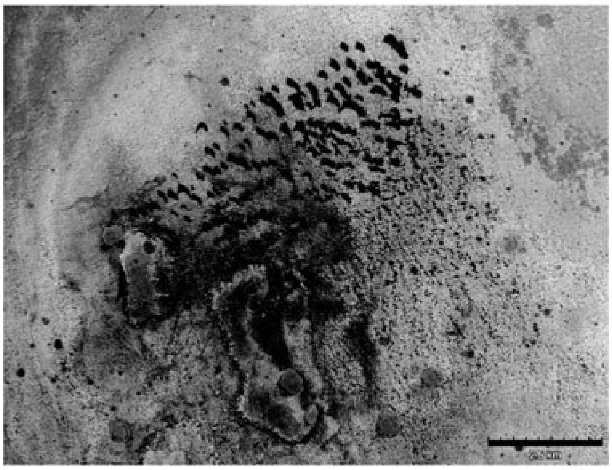

Figure 9. Sand dunes and eroded mesas in Meridiani. Portion of CTX image B17_016459_1831_XN_03N355W.

to 50 cm. The slip face of one of these dunes advanced approximately 25–50 cm during this interval, as measured against the bedrock (Figure 8). No local sand sources could be identified within the crater; the sands may have blown into the crater from larger intra-crater deposits upwind, northeast of the site.

Downwind of the dunes, the fractured bedrock is eroded into flat-topped mesas bounded by steep scarps. The circular plan of some of the smaller mesas makes us suspect that they may be inverted impact craters. Most of the mesas are steepest on their eastern scarps and grade more gently towards the west. In many places, the eastern edges of the mesas are undercut by erosion, producing vertical and overhanging cliffs. We suggest that these mesas were shaped by eons of sandblasting that continues today.

Discussion

These results are consistent with the surface observations of the MER Opportunity, which documented sand movement at Meridiani Planum in MI and Pancam images (Herkenhoff *et al.*, 2006; Geissler *et al.*, 2008, 2010). The detection of sand movement by HiRISE in this region provides some confidence that the orbital observations can be used to discern the mobility of sands elsewhere on Mars. Active sand dunes have been spotted in several other sites in Meridiani and western Arabia Terra (Silvestro *et al.*, 2011). HiRISE observations have already detected changes in the sand dunes at Endeavor crater, near Opportunity's current location (Chojnacki *et al.*, 2011). Surface observations from Opportunity show that the Meridiani sands actively modify the landscape, scouring settled dust and sandblasting the soft bedrock (Sullivan *et al.*, 2005; Geissler *et al.*, 2010). Blowing sand is blamed for carving the alcoves in the serrated rim of Victoria crater and other craters nearby (Geissler *et al.*, 2008; Grant *et al.*, 2008).

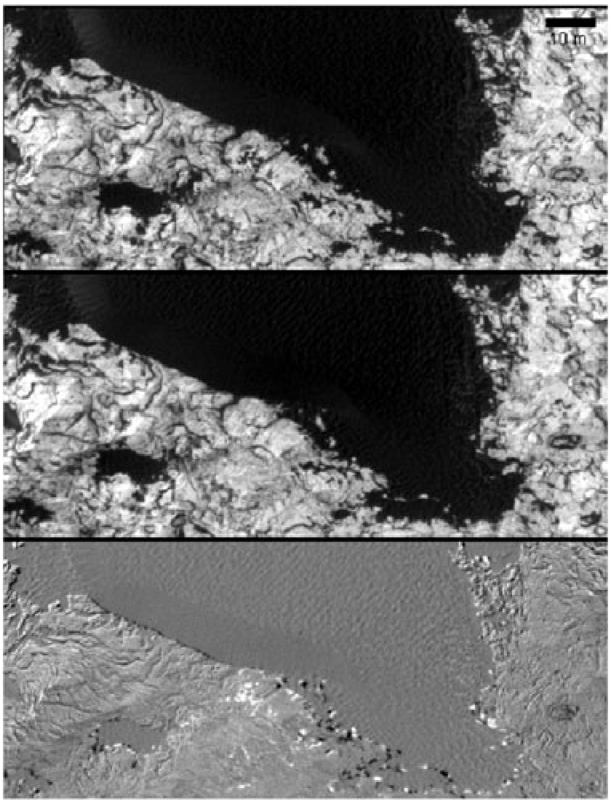

Figure 10. Meridiani. (Top) PSP_007018_1830, January 25, 2008. (Middle) ESP_016459_1830, January 29, 2010. (Bottom) Difference image (white spots show places that brightened during this interval, black spots places that darkened).

Although we are still in the early stages of the HiRISE survey, the detection of sand movement both in the tropics of Mars and in the north polar erg (Bourke *et al.*, 2008; Hansen *et al.*, 2011) suggests that Martian dunes are active globally. Only the surfaces and margins of the dunes are visibly mobile, but it is highly unlikely that the interiors of the tropical dunes are cemented by volatiles. The blowing sands actively alter the Martian landscape, exposing ancient strata and eradicating young features such as rover tracks. New sources of sand must be available to replace the restless grains as they are ground into dust. Local sources are suspected in many places on Mars (e.g. Tirsch *et al.*, 2011). The specific sites examined here offer some insights into possible sand sources and sinks, and demonstrate the effectiveness of eolian erosion and deposition in the Martian tropics.

Conclusions

The recent detection of active sand saltation on Mars raises a number of new questions. It is not yet known why some locations display obvious changes while others do not. Exactly when the changes take place is unclear, as is whether the changes are gradual or episodic. The implications of the activity for the evolution of the sand grains and their impact on the landscape are poorly understood. Our studies of three specific examples yield the following insights:

1. HiRISE observations show that sand mobility is widespread in the Martian tropics. All three of the sites described earlier were targets chosen for easy visibility of the dark dunes contrasting with the background of bright bedrock or soil. This suggests that sand movement may be common elsewhere on Mars but is simply more difficult to detect. Together with recent evidence for dune changes in the north polar erg (Bourke *et al.*, 2008; Hansen *et al.* 2011; Bridges *et al.*, 2012b), these observations suggest that Martian sand is mobile globally.
2. Even in active sites, most sand dunes show no changes detectable to HiRISE over a Martian year. The dunes are clearly on the move, however, if only slowly. Dune slip faces are advancing at rates of up to ~50 cm per Martian year in an exceptional example in Meridiani. The small ripples formed on top of the dunes shift up to 2 m per season, overtaking the crestlines and avalanching down the slip faces. In contrast, no changes were observed among the older transverse aeolian ridge deposits.
3. Fresh supplies of sand have recently been generated by erosion of layered sediments in Pasteur crater and possibly in Becquerel. Such sources of sand are needed to account for the attrition of saltating sand grains.
4. Blowing sands actively alter the landscape of Mars. The light toned layered deposits in Becquerel crater have been deeply sculpted by eolian erosion. The steep scarps of mesas in Meridiani were shaped by saltating grains. The rim of Victoria crater was chewed up by sands escaping the crater to form the dark streaks now decorating the crater's rim. Sandblasting appears to be the most effective agent of erosion in the Martian tropics today.

Acknowledgments—The efforts of the science and operations teams of both MER and HiRISE in acquiring these data are gratefully acknowledged. Figures 1, 2, 5, 6, and 9 were prepared with JMARS software from Arizona State University. Thoughtful comments from Robert Sullivan and another reviewer helped improve the scholarship of this article. S. Silvestro is supported by a grant from the NASA Mars Data Analysis program (NNH09ZDA001N).

References

Balme M, Berman DC, Bourke MC, Zimbelman JR 2008. Transverse Aeolian Ridges (TARs) on Mars. *Geomorphology* **101**: 703–720. DOI. 10.1016/j.geomorph.2008.03.011

Bourke MC, Edgett KS, Cantor BA. 2008. Recent aeolian dune change on Mars. *Geomorphology* **94**: 247–255. DOI. 10.1016/j.geomorph.2007.05.012

Bridges, NT, Ayoub F, Avouac JP Leprince S, Lucas A, and Mattson S. 2012a. Earth-like sand fluxes on Mars. *Nature* **485**(7398): 339–342, 485. DOI. 10.1038/nature11022

Bridges NT, Bourke MC, Geissler PE, Banks ME, Colon CM, Diniega S, Golombek MP, Hansen CJ, Mattson S, McEwen AS, Mellon MT, Stantzos N, Thomson BJ. 2012b. Planet-wide sand movement on Mars. *Geology* **40**: 31–34. DOI. 10.1130/G32373.1

Chojnacki M, Burr DM, Moersch JE, Michaels TI. 2011. Orbital observations of contemporary dune activity in Endeavor crater, Meridiani Planum, Mars. *Journal of Geophysical Research (Planets)* **116**: 20. DOI. 10.1029/2010JE003675

Christensen PR, Bandfield JL, Hamilton VE, Ruff SW, Kieffer HH, Titus TN, Malin MC, Morris RV, Lane MD, Clark RL, Jakosky BM, Mellon MT, Pearl JC, Conrath BJ, Smith MD, Clancy RT, Kuzmin RO, Roush T, Mehall GL, Gorelick N, Bender K, Murray K, Dason S, Greene E, Silverman S, Greenfield M. 2001. Mars Global Surveyor Thermal Emission Spectrometer experiment: investigation description and surface science results. *Journal of Geophysical Research* **106**: 23823–23871. DOI. 10.1029/2000JE001370

Eliason E, Castalia B, Becker C, Anderson A, Sides S. 2007. Software Interface Specification for HiRISE Reduced Data Record Products, JPL Document Number D-32006. http://hirise.lpl.arizona.edu/pdf/HiRISE_RDR_SIS.pdf

Geissler PE. 2005. Three decades of Martian surface changes. *Journal of Geophysical Research (Planets)* **110**: 23. DOI. 10.1029/2004JE002345

Geissler PE, Banks ME, Bridges NT, Silvestro S, the HiRISE Science Team. 2012. HiRISE Observations of Sand Dune Motion on Mars: Emerging Global Trends, Third International Planetary Dunes Workshop, June 2012, Flagstaff, AZ.

Geissler PE, Johnson JR, Sullivan R, Herkenhoff K, Mittlefehldt D, Fergason R, Ming D, Morris R, Squyres S, Soderblom L, Golombek M. 2008. First in situ investigation of a dark wind streak on Mars. *Journal of Geophysical Research (Planets)* **113**: 16. DOI. 10.1029/2008JE003102

Geissler PE, Sullivan R, Golombek M, Johnson JR, Herkenhoff K, Bridges N, Vaughan A, Maki J, Parker T, Bell J. 2010. Gone with the wind: eolian erasure of the Mars Rover tracks. *Journal of Geophysical Research (Planets)* **115**. DOI. 10.1029/2010JE003674

Grant JA, Wilson SA, Cohen BA, Golombek MP, Geissler PE, Sullivan RJ, Kirk RL, Parker TJ. 2008. Degradation of Victoria crater, Mars. *Journal of Geophysical Research (Planets)* **113**. DOI. 10.1029/2008JE003155

Hansen CJ, Bourke M, Bridges NT, Byrne S, Colon C, Diniega S, Dundas C, Herkenhoff K, McEwen A, Mellon M, Portyankina G, Thomas N. 2011. Seasonal erosion and restoration of Mars' northern polar dunes. *Science* **331**: 575–578. DOI. 10.1126/science.1197636

Herkenhoff K, Squyres S, Arvidson RE, Bell JF III, Cabrol NA, Chapman M, Ehlmann B, Franklin B, Gaddis L, Geissler P, Greeley R, Grotzinger J, Johnson J, Jolliff B, Keszthelyi L, Knoll A, Lanagan P, Lee E, Maki J, McLennan S, Ming D, Mullins K, Rice J, Richter L, Sims M, Soderblom L, Spanovich N, Springer R, Sucharski R, Sullivan R, Weitz C, Athena Science Team. 2006. Overview of Athena Microscopic Imager Results, 37th Lunar and Planetary Science Conference, Abstract #1816.

Rossi AP, Pondrelli M, Hauber E, Baliva A, Michael G, Ori GG, Pompilio L, Parente M, Ivanov A, Neukum G. 2009. Stratigraphic Architecture and Structural Control on Sediment Emplacement in Becquerel Crater (Mars), 40th Lunar and Planetary Science Conference, Abstract #1588.

Silvestro S, Fenton LK, Vaz DA, Bridges NT, Ori GG. 2010. Ripple migration and dune activity on Mars: evidence for dynamic wind processes. *Geophysical Research Letters* **37**: L20203. DOI. 10.1029/2010GL044743

Silvestro S, Vaz DA, Fenton LK, Geissler PE. 2011. Active aeolian processes on Mars: a regional study in Arabia and Meridiani Terrae. *Geophysical Research Letters* **38**: L20201. DOI. 10.1029/2011GL048955

Sullivan R, Arvidson R, Bell JF, Gellert R, Golombek M, Greeley R, Herkenhoff K, Johnson J, Thompson S, Whelley P, Wray J. 2008. Wind-driven particle mobility on Mars: insights from MER observations at "El Dorado" and surroundings at Gusev crater. *Journal of Geophysical Research* **113**: E06S07. DOI. 10.1029/2008JE003101

Sullivan R, Banfield D, Bell JF, Calvin W, Fike D, Golombek M, Greeley R, Grotzinger J, Herkenhoff K, Jerolmack D, Malin M, Ming D, Soderblom LA, Squyres SW, Thompson S, Watters W, Weitz CM, Yen A. 2005. Aeolian processes at the Mars Exploration Rover Meridiani Planum landing site. *Nature* **436**: 58–61. DOI: 10.1038/nature03641

Tirsch D, Jaumann R, Pacifici A, Poulet F. 2011. Dark aeolian sediments in Martian craters: composition and sources. *Journal of Geophysical Research* **116**. DOI: 10.1029/2009JE003562

Zimbelman JR, Williams SH. 2007. An Evaluation of Formation Processes for Transverse Aeolian Ridges on Mars, Seventh International Conference on Mars, Lunar and Planet, Pasadena, CA.