EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **37**, 1120–1125 (2012)

Published online 11 May 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.3243

Cross-sectional profiles of sand ripples, megaripples, and dunes: a method for discriminating between formational mechanisms

James R. Zimbelman,[1]* Steven H. Williams[2] and Andrew K. Johnston[1]
[1] Center for Earth and Planetary Studies, National Air and Space Museum, MRC 315, Smithsonian Institution, Washington, DC, USA
[2] Education Division, National Air and Space Museum, MRC 310, Smithsonian Institution, Washington, DC, USA

Received 25 April 2011; Revised 7 February 2012; Accepted 8 March 2012

*Correspondence to: James Zimbelman, CEPS/NASM/ MRC 315, Smithsonian Institution, Washington, DC, USA, 20013-7012. E-mail: zimbelmanj@si.edu

ESPL
Earth Surface Processes and Landforms

ABSTRACT: Cross-sectional profiles of sand ripples, megaripples, and sand dunes provide a useful tool for discriminating between formation by ripple and dune processes. Feature width, defined as the basal break in slope along the profile to either side of the crest, represents a good standard for comparison of profile attributes across more than three orders of magnitude. Aspect ratio (height/width) as a function of log width separates measurements into clusters representing differing mechanisms of formation. Scaling both height and distance for individual profiles by feature width facilitates comparison of profile shapes across three orders of magnitude in width. The data presented here should prove useful for evaluating possible mechanisms of origin for aeolian features observed remotely, including on planetary bodies. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: topography; sand ripples; granule ripples; megaripples; reversing dune; transverse dunes

Introduction

Differing processes active in the generation and propagation of aeolian bedforms create similar, but quite distinct bedforms; ripples and dunes represent two of the most common aeolian landforms observed in desert environments. Topographic profiles of terrestrial sand ripples, megaripples, and small sand dunes were measured perpendicular to the crest of each feature, in order to evaluate their usefulness as a tool for discriminating between formation mechanisms of ripples and dunes when applied to transverse aeolian bedforms that are observed remotely, as is necessary for aeolian features imaged on other planets.

Background

Sand ripples have intrigued researchers for many years, leading to several explanations for the typical spacing evident in most sand ripples. Bagnold (1941, p. 62, 150) considered the length scale represented by the ripple wavelength as the physical manifestation of a 'characteristic path' of sand grains constrained by the height reached by the majority of the saltating grains. In contrast to the Bagnold view, Sharp (1963) concluded that since ripples begin as small-amplitude, short-wavelength features, the ripples must evolve to a steady state form where ripple wavelength depends primarily on ripple amplitude and the angle at which the saltating grains impact the bed. Anderson (1987) developed an analytical model for the initiation of sand ripples caused by small perturbations of the sand surface; perturbations grow by the influence of low-velocity grains ejected from the impact of high-velocity saltating grains, a process he termed 'reptation'. Numerical modelling (Anderson and Haff, 1988; Werner and Gillespie, 1993; Stam, 1996; Yizhaq *et al.*, 2004; Manukyan and Prigozhin, 2009) and experiments (Seppala and Linde, 1978; Andreotti *et al.*, 2006) have shown that when both saltation and reptation processes are considered, fast-moving (small) ripples overtake and merge with slower (larger) forms, which eventually produces an average overall wavelength following a decline in the dispersion of wavelengths.

For aeolian sands with a bimodal size distribution, Bagnold (1941, pp. 153–156) noted that the coarse grains tend to concentrate at the crest of large ripples (which he called 'ridges', to distinguish them from normal sand ripples) as a result of rolling or shoving the coarse particles through the impact of saltating sand, a process also called 'impact creep' (Greeley and Iversen, 1985, p. 17). Sharp (1963) described 'granule ripples' with a concentration of grains >1 mm over a core that is mostly medium to fine sand with only occasional coarse grains; he described the 'ripple index' (RI = wavelength/height) in which sand ripples have RI of 18 to 20, while granule ripples generally have RI ≤15. Greeley and Iversen (1985, pp. 154–155) use the term 'megaripple' for aeolian bedforms larger than sand ripples, which encompass both Bagnold's 'ridges' and Sharp's 'granule ripples'. Particles 1 to 2 mm in diameter are described as coarse sand while particles 2 to 4 mm are termed granules in the sedimentary literature (Wentworth, 1922; Siever, 1988, p. 49), but large aeolian ripples coated with very coarse sand over fine sand often are referred to as 'granule ripples' (Sharp, 1963). Megaripples have been investigated in various deserts (Yizhaq, 2004; Yizhaq *et al.*, 2009; Isenberg *et al.*, 2011), including features where coarse surface particles attain pebble sizes (Weir, 1962; de Silva *et al.*, 2011). Granule ripples of 3 to 10 cm height were observed to move several centimetres within hours (Zimbelman *et al.*, 2009) during a strong wind event at Great Sand Dunes National Park and Preserve, CO (Madole *et al.*, 2008), consistent with a previous study that documented movement of 1-cm-high granule ripples at White Sands National Monument, NM (Jerolmack *et al.*, 2006).

Bagnold (1941) described certain attributes that can help to differentiate between ripple and dune formational mechanisms; dunes usually have a slip face dominated by avalanche processes (p. 189) whereas ripples lack what can be called a true slip face, and ripples have the coarsest particles at their crest with the finest particles in the intervening troughs whereas the opposite is true for dunes (p. 145). Wilson (1972a, 1972b) documented three distinct scales for aeolian landforms; ripples (wavelength 0.01 to 10 m, which includes granule ripples at the large end), dunes (wavelength ~10 to 500 m), and draas (wavelength ~0.7 to 5.5 km). Wavelength is the most commonly used attribute to describe the horizontal scale across a field of aeolian features, but it is less useful when considering individual bedforms within a spatially variable field of features. The overlap between large ripples and small dunes near 10 m wavelength can be addressed through particle size; dunes consist mostly of fine sand (<0.2 mm diameter) whereas large ripples have surface particles >1 mm in diameter, with no transitional features observed to occur between the two groups (Wilson, 1972a). Scaling of bedforms is important to a wide variety of modelling efforts related to aeolian features (Werner and Gillespie, 1993; Van Dijk *et al.*, 1999; Momiji *et al.*, 2000; Schwammle and Herrmann, 2004; Baas, 2007; Pelletier, 2009; Parteli *et al.*, 2011). The goal of the present work is to identify measurable attributes that can aid in evaluating likely formational mechanisms for features that could be either large ripples or small dunes, particularly when it is not possible to sample the sediment size of the feature (which is the case for nearly all planetary aeolian investigations).

Methodology

Several procedures were used to measure the topography across aeolian features whose dimensions range over more than three orders of magnitude. A simple but elegant procedure for generating detailed profiles of sand ripples (Werner *et al.*, 1986) was used for active sand ripples. The technique involves taking a photograph (perpendicular to the surface) of the shadow cast by a straight edge (oriented perpendicular to the sand ripple crests) along with the shadow cast by a gnomon of known height; similar triangles applied to the shadows from both the straight edge and the gnomon allows determination of the height across the ripples with a precision comparable with the size of the sand grains (Werner *et al.*, 1986). The Werner technique was applied to a high-resolution contrast-stretched digital image taken at GSDNPP on 9/18/02; the resulting measurements along the straight edge shadow were reproducible to better than the size of a single sand grain, ~0.2 mm. The oblique illumination in the shadow images resulted in calculated heights with a vertical precision much better than that of the shadow measurements themselves, likely <0.1 mm (see Figure S1, Supplementary Material).

Profiling of megaripples, with wavelengths of up to several metres, required an approach very different from that of the straight edge shadow technique. After some experimentation, a technique was settled upon where relief was measured relative to a laser line projected above the feature. A standard carpenter's laser level was mounted on a tripod and pointed above the megaripple so that the vertical distance could be measured from the beam to a tape laid along the survey line, plus any dip angle present along the laser beam itself (Figure S2, Supplementary Material). Megaripples of a metre or more in horizontal width could be adequately documented with points spaced 10 cm apart. The measuring rod included a bubble level to maintain verticality during each measurement. The reproducibility of the measurements was limited mostly by the size of the laser spot on the ruler; the measurements obtained using the laser line technique are reproducible to <0.5 cm, both vertically and horizontally, over lengths up to 15 m (Figures S3 and S4). Surveyed measurements for 18 megaripples were obtained at GSDNPP (September, 2002 to 2005), plus six additional surveyed megaripples from the Kelso Dunes (Sharp, 1966), the Coachella Valley (Katra *et al.*, 2009), and the Ibex Dunes (Zimbelman and Williams, 2007a), all located in southern California (February, 2002 and 2003). Photogrammetry produced digital elevation models (DEMs) of megaripples in the Negev Desert, Israel (Yishaq, 2008; Yizhaq *et al.*, 2009; Isenberg *et al.*, 2011); profiles derived from DEMs of megaripples are published in these two references.

Megaripples at the northern end of Rodgers Dry Lake (Playa), California (part of the Edwards Air Force Base) were visited briefly during a NASA-sponsored field trip in October of 2001. Unlike the megaripples described above, the largest ripples at Edwards (visible in Figure 10 of Ward, 1979) had surface coatings of pebbles (~0.4 to 1.2 cm in diameter) over a silt-clay interior; very little sand-sized material was present either on or within these features. An inclinometer and tape provided some basic dimensional information, but the laser line technique was not available here. Following a search for other possible pebble-coated megaripples, the Coyote Playa near Barstow, California (Weir, 1962), was visited in February of 2002; the laser line technique was used to survey a pebble-coated megaripple with a silt-clay interior, very similar to the Edwards features. In June of 2003, a laser line survey was obtained across megaripples at the top of the Mono Domes near Mono Lake, California, which consisted of obsidian pebbles over sand-granule cores (Williams *et al.*, 2003). Recently, pebble-coated megaripples have been reported in the Puna of Argentina (de Silva *et al.*, 2011); here the pebbles consist of both pumice and lithic fragments.

Profiling of sand dunes involved a Differential Global Positioning System (DGPS), to collect surveyed points across both active and stabilized transverse dunes. Trimble 4800 and R8 DGPS systems provide point locations that are reproducible to <2 cm horizontal and <4 cm vertical (Zimbelman and Johnston, 2001, 2002). Stabilized transverse dunes were surveyed near Parker, Arizona and in Rice Valley, California (February, 2003; Figures S5 and S6), and active transverse dunes were surveyed near Sand Mountain, Nevada (April, 2004; Figure S7). Recent results indicate that 'transverse aeolian ridges' (TARs) on Mars (Wilson and Zimbelman, 2004) are quite similar in profile shape to reversing sand dunes on Earth (Zimbelman, 2010); this motivated an effort to obtain 6 DGPS surveys of reversing dunes at GSDNPP (July, 2009; Figure S8), three DGPS surveys of reversing dunes at the Oregon Dunes near Lakeside, Oregon (June, 2010), and four laser ranger-inclinometer surveys of a large reversing dune at the Bruneau Dunes, Idaho (April, 2009). Reproducibility of the laser ranging measurements is <0.3 m horizontal, which translates to <0.15 m vertical. Published profile data were also utilized for transverse dunes (Nickling *et al.*, 2002; Bourke *et al.*, 2009), reversing dunes (McKenna Neuman *et al.*, 1997; Walker, 1999; Lancaster *et al.*, 2002), and very large (draa) dunes in western China (Hugenholtz and Barchyn, 2010; Yang *et al.*, 2011).

Results

Sand ripples have a distinctive profile shape (Figure 1); the stoss (upwind) side has a gentle slope leading to a rounded crest located about two-thirds of the distance along the ripple width, with a slope to the lee of the crest that is roughly three times steeper than the stoss side. In contrast to sand ripples, both granule and pebble-coated megaripples are more nearly symmetric in shape, often with sharp crests (Figure 2). The coarse particles protect the underlying fine sediments from removal by saltating sand, allowing these features to grow to sizes substantially larger than sand ripples. Stabilized transverse sand dunes examined here (Figure 3) have a vertical height that is <3 m, regardless of their horizontal scale. Reversing dunes have very symmetric profile shapes, with very sharp crests (Figure 4); bimodal winds tend to cause these dunes to grow vertically rather than horizontally, resulting in significant overall relief. Nature produces variations between profiles, yet the overall profile shape remains broadly consistent within groups distinguished by formation process (Figures S9 and S10).

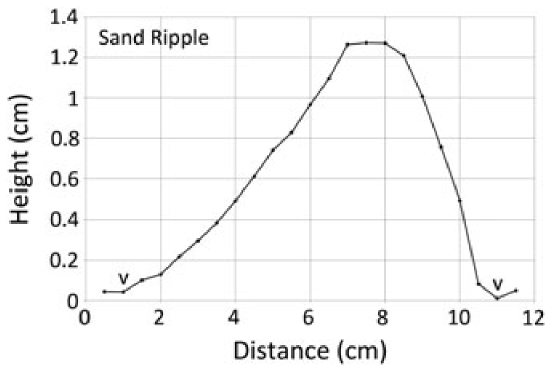

Figure 1. Profile across a sand ripple at GSDNPP, 9/18/03, derived from the shadow technique of Werner *et al.* (1986). Wind was from the left. Precision of each point is <0.2 mm, comparable with the size of the plotted symbols. 'v' indicates basal break in slope used to determine feature width (see text). Vertical exaggeration is 5.4 ×.

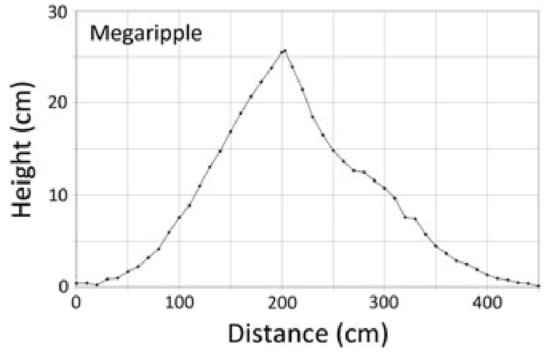

Figure 2. Profile across a coarse-sand-granule-coated megaripple at GSDNPP, 9/20/02. Wind was from the left. Precision of each point is <0.5 cm, smaller than the size of the plotted symbols. See text for explanation of the laser line profiling technique. Vertical exaggeration is 9.0 ×.

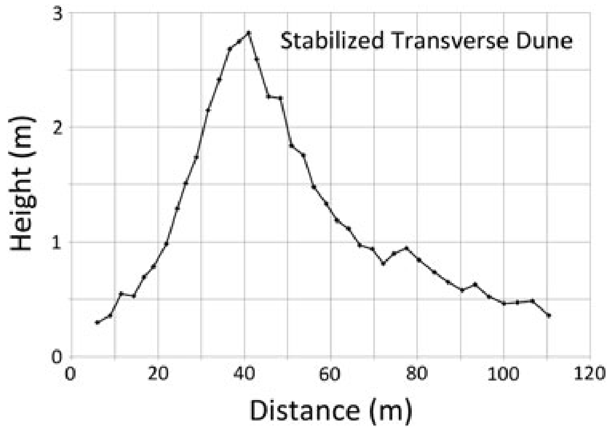

Figure 3. DGPS profile across a stabilized transverse sand dune near Parker, AZ, 2/19/03. Wind was from the left. Precision of each point is <4 cm, smaller than the size of the plotted symbols. See text for explanation of profiling technique. Vertical exaggeration is 27 ×.

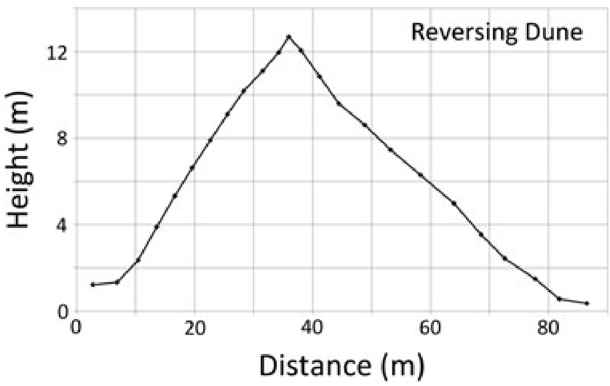

Figure 4. DGPS profile across a reversing sand dune at GSDNPP, 7/30/09. Reversing dunes experience opposing bimodal winds. Precision of each point is <4 cm, smaller than the size of the plotted symbols. See text for explanation of profiling technique. Vertical exaggeration is 3.7 ×.

Several methods were explored to portray the most significant aspects derived from the profile data. In order to make comparisons of features of diverse sizes, measurements were scaled by different parameters; average wavelength was used first, but the natural variability of widely separated features like dunes led to significant scatter within the data; height was tried, but it is the most difficult dimension to measure remotely; feature width was finally determined to be the best parameter for scaling individual profile results (Zimbelman and Williams, 2007b). Width is defined here as the distance between basal breaks in slope on either side of the crest (Figure 1); breaks in slope typically correspond to visual indications of the 'edge' of a feature in the field. Even when the topographic breaks are subtle or gradual, visual inspection of profile data is preferable to visual 'appearance' since it is often difficult to determine width from visual imaging data alone. The scaled data cluster by formation mechanism groups on a plot of height/width as a function of log width (Figure 5); Table S1 lists the data used in making Figure 5. The true size of each bedform is represented by width while the vertical axis portrays the feature aspect ratio (height/width). Wavelength has historically been used to represent the horizontal scale of aeolian features, which works well for fields of uniformly spaced features, but wavelength has little meaning for individual features variably separated from their neighbours. Aspect ratio is comparable with the inverse of RI for uniformly spaced sand ripples or megaripples, but it is now also meaningful for individual dunes where RI is not applicable.

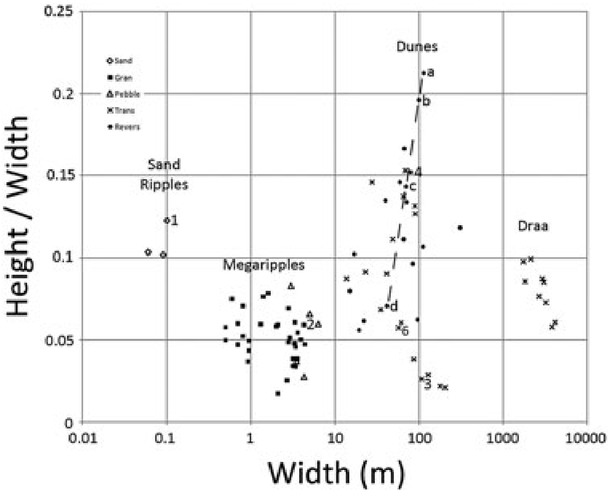

Figure 5. Scatter plot of feature height scaled by feature width, shown as a function of feature width using a logarithmic scale. Labels right of some symbols correspond to profiles shown in figures (indicated by the figure number), plus surveys along a single large reversing dune at Bruneau Dunes, Idaho (letters). See text for discussion. All data shown here are listed in Table S1 of the Supplementary Material.

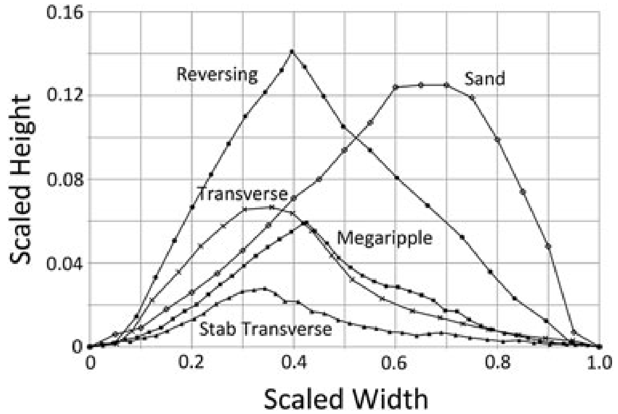

Figure 6. Profiles of aeolian features where both height and width are scaled by feature width (feature widths: 0.10 m for sand, 4.30 m for megaripple, 52.56 m for active transverse dune, 83.74 m for reversing dune, and 89.51 m for stabilized transverse dune). Four of the profiles are from data shown in Figures 1 to 4. Precision of each point is roughly comparable with the size of the plotted symbols; the uncertainty is largest (0.0002 in scaled units) for the sand profile. Recent wind is from the left for all profiles. Vertical exaggeration is 4.1 × .

The surveyed attributes segregate into four main clusters (Figure 5): sand ripples, megaripples (where pebble ripples represent the largest examples in the cluster), dunes (stabilized and active transverse dunes, and reversing dunes), and draa. The clusters in Figure 5 are essentially the same as those identified by Wilson (1972a,1972b), except that megaripples (aspect ratios 0.02 to 0.08) are distinct from sand ripples (aspect ratios 0.10 to 0.12). The dunes cluster is a mixture of transverse dunes with aspect ratios between 0.02 and 0.15, and reversing dunes with aspect ratios from 0.05 to 0.22. The aspect ratio for a single large reversing dune at Bruneau Sand Dunes decreased by a factor of three when profiles progressed from the largest part of the dune toward one end, with only minimal change in width (points a to d in Figure 5); this is less likely the effect of total sand volume available than it is the cumulative duration of exposure to bimodal winds. This trend is broadly consistent with two subclasses for transverse dunes; vegetation-stabilized transverse dunes have aspect ratios <0.04 while active transverse dunes have aspect ratios >0.05. Draa, the largest aeolian bedforms (Wilson, 1972a, 1972b; Lancaster, 1988), have aspect ratios (0.05 to 0.10) that overlap megaripples and dunes, but their width >1000 m clearly distinguishes them from smaller features.

Discussion

When both height and distance of surveyed profiles are normalized by the feature width, the shapes of feature profiles are preserved while also allowing comparisons to be made over multiple scales in width (Figure 6). Interestingly, profile uncertainties for the survey techniques used here are roughly comparable when scaled by feature width: scaled precisions are ~0.002 for sand ripples, ~0.001 for granule and pebble ripples, and ~0.0002 for DGPS measurements of sand dunes. Rounded crests are a distinctive characteristic of sand ripples and both active and stabilized transverse dunes, while megaripples and reversing dunes have relatively sharp crests. Even more important, the scaled height of sand ripples and reversing dunes is twice that of megaripples and active transverse dunes, while stabilized transverse dunes have scaled heights that are half that of either megaripples or active transverse dunes. These results indicate that the combination of both the aspect ratio (Figure 5) and the scaled profile shape (Figure 6) present useful clues for distinguishing between the formational mechanisms of aeolian features (Zimbelman *et al.*, 2010).

Measured profiles of selected terrestrial aeolian features were compared with profiles obtained from photoclinometry transects across portions of two High Resolution Imaging Science Experiment (HiRISE; McEwen *et al.*, 2007) images of Mars, using the width-scaling procedure described above (Zimbelman, 2010). The HiRISE profiles show that Martian 'transverse aeolian ridges' (TARs; Wilson and Zimbelman, 2004; Balme *et al.*, 2008; Berman *et al.*, 2011) have remarkably symmetric profiles, and TARs with heights <0.5 m closely matched the profiles of (granule-coated) megaripples (Figure 8 of Zimbelman, 2010) while TARs with heights >1 m matched profiles of two reversing dunes (Figure 4 of Zimbelman, 2010). Additional measurements of TARs from HiRISE images are underway (Shockey and Zimbelman, in revision), and it is anticipated that the field data presented here will be quite helpful for future efforts to distinguish between megaripples and sand dunes on Mars. It is not anticipated that either the reduced gravity or the reduced atmospheric pressure on Mars (compared with Earth) should greatly alter the shape of aeolian bedforms on the two planets, except perhaps their overall size, since sand grain trajectories will be much longer on Mars than on Earth (Greeley and Iversen, 1985, pp. 94–98).

Conclusions

Measurement of cross-sectional profiles of sand ripples, megaripples, and sand dunes provides a useful tool for discriminating between formation by ripple and dune processes. Feature width, defined as the basal break in slope along the profile to either side of the crest, represents a good measure for comparison of profile attributes over widely differing scales. Aspect ratio (height/width) as a function of log width separates profile measurements into clusters representing differing mechanisms of formation. Scaling both height and distance for individual profiles by feature width facilitates comparison of profile shapes across three orders of magnitude in feature width. Both approaches could also aid efforts to derive mathematical models of both ripple and dune processes. The data presented here should prove helpful for evaluating possible mechanisms of the origin for aeolian features observed remotely, as in the case of studying aeolian bedforms on Mars.

Acknowledgements—This work was supported primarily by funds from the Becker and Walcott portions of the Smithsonian Endowments. Additional support for some of the work came from NASA Mars Data Analysis Program grant NNX08AK90G. Comments by M. Balme, an anonymous reviewer, and the special issue Editor were very helpful during revision of this manuscript.

Supporting Information

Supporting information may be found in the online version of this article.

References

Anderson RS. 1987. A theoretical model for aeolian impact ripples. *Sedimentology* **34**: 943–956.

Anderson RS, Haff PK. 1988. Simulation of eolian saltation. *Science* **241**: 820–823.

Andreotti B, Claudin P, Pouliquen O. 2006. Aeolian sand ripples: experiment study of fully developed states. *Physical Review Letters* **96**: L028001. DOI: 10.1103/PhysRevLett.96.028001

Baas ACW. 2007. Complex systems in Aeolian geomorphology. *Geomorphology* **91**: 311–331. DOI: 10.1016/j.geomorph.2007.04.012

Bagnold RA. 1941. *The Physics of Blown Sand and Desert Dunes*. Chapman and Hall/Methuen and Company: London.

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

Berman DC, Balme MR, Rafkin SCR, Zimbelman JR. 2011. Transverse aeolian ridges (TARs) on Mars II: distributions, orientations, and ages. *Icarus* **213**: 116–130. DOI: 10.1016/j.icarus.2011.02.014

Bourke MC, Ewing RC, Finnegan D, McGowan HA. 2009. Sand dune movement in the Victoria Valley, Antarctica. *Geomorphology* **109**: 148–160. DOI: 10.1016/j.geomorph.2009.02.028

de Silva SL, Zimbelman JR, Bridges N, Scheidt S, Viramonte JG. 2011. The coarsest gravel ripples on Earth? Preliminary observations and interpretations. Lunar and Planetary Science XLII, Abstract 2421, Lunar and Planetary Institute, Houston, Texas.

Greeley R, Iversen JD. 1985. *Wind as a Geological Process on Earth, Mars, Venus, and Titan*. Cambridge University Press: New York.

Hugenholtz CH, Barchyn TE. 2010. Spatial analysis of sand dunes with a new global topographic dataset: new approaches and opportunities. *Earth Surface Processes and Landforms* **35**: 986–992. DOI: 10.1002/esp.2013

Isenberg O, Yizhaq H, Tsoar H, Wenkart R, Karnieli A, Kok JF, Katra I. 2011. Megaripple flattening due to strong winds. *Geomorphology* **131**: 69–84. DOI: 10.1016/j.geomorph.2011.04.028

Jerolmack DJ, Mohrig D, Grotzinger JP, Fike DA, Watters WA. 2006. Spatial grain size sorting in eolian ripples and estimation of wind conditions on planetary surfaces: application to Meridiani Planum, Mars. *Journal of Geophysical Research* **111**: E12S02. DOI: 10.1029/2005JE002544

Katra I, Scheidt S, Lancaster N. 2009. Changes in active eolian sand at northern Coachella Valley, California. *Geomorphology* **105**: 277–290. DOI: 10.1016/j.geomorph.2008.10.004

Lancaster N. 1988. The development of large aeolian bedforms. *Sedimentary Geology* **55**: 69–89.

Lancaster N, Nickling WG, McKenna Neuman C. 2002. Particle size and sorting characteristics of sand in transport on the stoss side of a small reversing dune. *Geomorphology* **43**: 233–242.

Madole RF, Romig JH, Aleinikoff JN, VanSistine DP, Yacob EY. 2008. On the origin and age of the Great Sand Dunes, Colorado. *Geomorphology* **99**: 99–119. DOI: 10.1016/j.geomorph.2007.10.006

Manukyan E, Prigozhin A. 2009. Formation of Aeolian ripples and sand sorting. *Physical Review E* **79**: 031303.

McEwen AS, Eliason EM, Bergstrom JW, Bridges NT, Hansen CJ, Delamere WA, Grant JA, Gulick VC, Herkenhoff KE, Keszthelyi L, Kirk RL, Mellon MY, Squyres SW, Thomas N, Weitz CM. 2007. Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE). *Journal of Geophysical Research* **112**: E05S02. DOI: 10.1029/2005JE002605

McKenna Neuman C, Lancaster N, Nickling WG. 1997. Relations between dune morphology, air flow, and sediment flux on reversing dunes, Silver Peak, Nevada. *Sedimentology* **44**: 1103–1113.

Momiji H, Carretero-Gonzalez R, Bishop SR, Warren AW. 2000. Simulation of the effect of wind speedup in the formation of transverse dune fields. *Earth Surface Processes and Landforms* **25**: 905–918.

Nickling WG, McKenna Neuman C, Lancaster N. 2002. Grainfall processes in the lee of transverse dunes, Silver Peak, Nevada. *Sedimentology* **49**: 191–209.

Parteli EJR, Andrade JS, Hermann HJ. 2011. Transverse instability of dunes. *Physical Review Letters* **107**: 188001. DOI: 10.1103/PhysRevLett.107.188001

Pelletier JD. 2009. Controls on the height and spacing of eolian ripples and transverse dunes: a numerical modeling investigation. *Geomorphology* **105**: 322–333. DOI: 10.1016/j.geomorph.2008.10.010

Schwammle V, Herrmann HJ. 2004. Modelling transverse dunes. *Earth Surface Processes and Landforms* **29**: 769–784.

Seppala M, Linde K. 1978. Wind tunnel studies of ripple formation. *Geografiska Annaler* **60**: 29–42.

Sharp RP. 1963. Wind ripples. *Journal of Geology* **71**: 617–636.

Sharp RP. 1966. Kelso Dunes, Mojave Desert, California. *Geological Society of America Bulletin* **77**: 1045–1074.

Shockey KM, Zimbelman JR. In revision. Transverse Aeolian Ridges as seen in HiRISE images. *Earth Surface Processes and Landforms*.

Siever R. 1988. *Sand*. W.H. Freeman and Company: New York.

Stam JMT. 1996. Migration and growth of aeolian bedforms. *Mathematical Geology* **28**: 519–536.

Van Dijk PM, Arens SM, Van Boxel JH. 1999. Aeolian processes across transverse dunes. II. Modeling the sediment transport and profile development. *Earth Surface Processes and Landforms* **24**: 319–333.

Walker I. 1999. Secondary airflow and sediment transport in the lee of a reversing dune. *Earth Surface Processes and Landforms* **24**: 437–448.

Ward AW. 1979. Yardangs on Mars: evidence of recent wind erosion. *Journal of Geophysical Research* **84**: 8147–8166.

Weir JE. 1962. Large wind-ripple marks near Coyote Lake (dry), California. *Geological Society of America Bulletin* **73**(7): 39.

Wentworth CK. 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology* **30**: 377–392.

Werner BT, Gillespie DT. 1993. Fundamentally discrete stochastic model for wind ripple dynamics. *Physical Review Letters* **71**: 3230–3233.

Werner BT, Haff PK, Livi RP, Anderson, RS. 1986. Measurement of eolian ripple cross-sectional shape. *Geology* **14**: 743–745.

Williams SH, Zimbelman JR, Peterfreund AR, Greeley R. 2003. Over two decades at Mono Domes: slow changes to potential analogs to Martian Aeolian bedforms. Abstract 107–10, Geological Society of America Abstracts with Program **35**, 128.

Wilson I. 1972a. Sand waves. *New Scientist* **53**: 634–637.

Wilson I. 1972b. Aeolian bedforms: their development and origins. *Sedimentology* **19**: 173–210.

Wilson SA, Zimbelman JR. 2004. The latitude-dependent nature and physical characteristics of transverse aeolian ridges on Mars. *Journal of Geophysical Research* **109**: E10003. DOI: 10.1029/2004JE002247

Yang X, Scuderi L, Liu T, Paillou P, Li H, Dong J, Zhu B, Jiang W, Jochems A, Weissmann G. 2011. Formation of the highest sand dunes on Earth. *Geomorphology* **135**: 108–116. DOI: 10.1016/j.geomorph.2011.08.008

Yizhaq H. 2004. A simple model of Aeolian megaripples. *Physica A* **338**: 211–217. DOI: 10.1016/j.physa.2004.02.044

Yizhaq H. 2008. Aeolian megaripples: mathematical model and numerical simulations. *Journal of Coastal Research* **24**: 1369–1378. DOI: 10.2112/08A-0012.1

Yizhaq H, Balmforth NJ, Provensale A. 2004. Blown by wind: nonlinear dynamics of aeolian sand ripples. *Physica D* **195**: 207–228. DOI: 10.1016/j.physd.2004.03.015

Yizhaq H, Isenberg O, Wenkart R, Tsoar H, Karnieli A. 2009. Morphology and dynamics of Aeolian mega-ripples in Nahal Kasuy, southern

Israel. *Israel Journal of Earth Sciences* **57**: 149–165. DOI: 10.1560/IJES.57.3-4.149

Zimbelman JR. 2010. Transverse aeolian ridges on Mars: first results from HiRISE images. *Geomorphology* **121**: 22–29. DOI: 10.1016/j.geomorph.2009.05.012

Zimbelman JR, Johnston AK. 2001. Improved topography of the Carrizozo lava flow: implications for emplacement conditions. In *Volcanology in New Mexico. New Mexico Museum of Natural History and Science Bulletin* **18**: 131–136.

Zimbelman JR, Johnston AK. 2002. New precision topographic measurements of the Carrizozo and McCartys basalt flows, New Mexico. In *New Mexico Geological Society Guidebook*, 53rd Field Conference, White Sands, New Mexico: 121–127.

Zimbelman JR, Williams SH. 2007a. Eolian dunes and deposits in the western United States as analogs to wind-related features on Mars. In *The Geology of Mars: Evidence from Earth-Based Analogs*, Chapman M (ed). Cambridge University Press: Cambridge; 232–264.

Zimbelman JR, Williams SH. 2007b. Dunes versus ripples: topographic profiling across terrestrial examples, with application to the interpretation of features on Mars. *EOS, Transactions of the American Geophysical Union* **88**(23): Abstract P34A-07.

Zimbelman JR, Irwin RP, Williams SH, Bunch F, Valdez A, Stevens S. 2009. The rate of granule ripple movement on Earth and Mars. *Icarus* **203**: 71–76. DOI: 10.1016/j.icarus.2009.03.033

Zimbelman JR, Williams SH, Johnston AK. 2010. Cross-sectional profiles of ripples, megaripples, and dunes: a method for discriminating between formational mechanisms. In Second International Planetary Dunes Workshop, LPI Contribution No. 1552: 76–77. Lunar and Planetary Institute, Houston.