Geology

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Geology 2012;40;31-34
doi: 10.1130/G32373.1

Notes

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ABSTRACT

Prior to Mars Reconnaissance Orbiter data, images of Mars showed no direct evidence for dune and ripple motion. This was consistent with climate models and lander measurements indicating that winds of sufficient intensity to mobilize sand were rare in the low-density atmosphere. We show that many sand ripples and dunes across Mars exhibit movement of as much as a few meters per year, demonstrating that Martian sand migrates under current conditions in diverse areas of the planet. Most motion is probably driven by wind gusts that are not resolved in global circulation models. A past climate with a thicker atmosphere is only required to move large ripples that contain coarse grains.

INTRODUCTION

Dunes and ripples (collectively termed bedforms) are abundant and widespread on Mars, with concentrations surrounding the north polar layered deposits, within craters and other depressions that trap sediment, and as isolated patches on the plains. Initially discovered in 0.1–1-km-pixel scale Mariner 9 images in 1971 (McCauley, 1973), Martian bedforms have been studied with progressively higher-resolution cameras, including the Mars Orbiter Camera (MOC, 1997–2006) (Malin and Edgett, 2001) and the High Resolution Imaging Science Experiment (HiRISE; 2006 to the present) (Bridges et al., 2007). HiRISE, on the Mars Reconnaissance Orbiter (MRO), has a pixel scale as low as 25 cm, compared to the MOC minimum of 1.4 m, and shows fine-scale details on these sand features, including superposed secondary ripples on dunes not discernable at coarser spatial resolution.

The abundance of sand on Mars attests to ancient mechanisms capable of producing large volumes of clastic particles, and winds of sufficient strength and frequency to move and collect them into extensive deposits. However, the presence of the Martian bedforms is at odds with surface meteorological measurements and climate models that indicate that winds capable of moving sand (termed threshold winds) are infrequent in the ~6 mbar atmosphere (Arvidson et al., 1983; Almeida et al., 2008). This view of limited Martian sand transport in the current climate had been supported by orbital observations indicating no movement at scales down to a few meters (Zimbelman, 2000; Malin and Edgett, 2001). However, with increasing resolution and temporal baselines, details have emerged. For example, MOC images hinted at migration, even if not showing it directly, with some dunes exhibiting brink rounding, slip face landslides, size changes, and other geomorphic features consistent with advancement (Fenton, 2006; Bourke et al., 2008). Similarly, fine-scale observations from the Mars Exploration Rovers (MER) showed evidence for saltation (Sullivan et al., 2008; Geissler et al., 2010; Golombek et al., 2010). A fundamental question has therefore been whether approximately meter scale and larger bedforms are active on Mars given such low threshold frequencies, or if a different climate is required, perhaps driven by the ~100 k.y. obliquity cycles. Until now, the answer has been ambiguous, with movement very recently identified from orbit in only three locations (Silvestro et al., 2010; Chojnacki et al., 2011; Hansen et al., 2011). Quantitatively gauging the extent and rate of sand motion over the entire planet requires the analysis of many high-resolution observations over a broad geographic extent, which was not possible in the earlier stages of the MRO mission because of the limited time span and number of images. Here we report on an analysis of multiple HiRISE images acquired over several Martian years that demonstrates that many regions contain moving bedforms.

METHODOLOGY

Since the beginning of operations at Mars, the HiRISE team has been targeting and analyzing images of bedforms to document changes. These targets were selected based on the presence of sharp-looking bedforms in previous images, followed by repeat observations over a sufficient time baseline for migration to potentially occur, and with similar lighting conditions such that changes could be tagged to true sand movement and not be misinterpreted because of photometric effects. As of this writing, HiRISE has acquired images over 2.3 Mars years, offering potentially two to three opportunities to image a site under similar viewing and seasonal conditions.

Map-projected images of ripples and dunes were overlaid and coregistered to common tie points that were assumed immobile, such as patterns on adjoining terrain and large rocks (see additional details in the GSA Data Repository[1]). One to five locations were measured that represented typical displacement in each area. For ripples, the distance between the margins of ripple crests and the nearest tie points was measured and then differenced between the two images (see the blink images in the Data Repository). To correlate migration to bedform size, distances between ripple crests, barchan dune width, and dome dune least principal axes were measured. Digital elevation models (DEMs) were not available for most of our studied locations; even if they were, ripple relief was below DEM resolution. However, numerous field investigations show that the ratio of crest-to-crest spacing to height for terrestrial sand and granule ripples is ~10:1, with ranges of 5:1–27:1 (Sharp, 1963; Werner et al., 1986; Zimbelman, 2010), the width of barchans relative to height is 7:1–15:1 (Hesp and Hastings, 1998; Gay, 1999), and dome dunes have width to height ratios of ~10:1 (Catto and Bacchuber, 2000). Therefore, measured bedform spacing and widths were converted to height by multiplying by 10, the one exception being the height of dunes in Nili Patera, for which a DEM was available.

[1]GSA Data Repository item 2012011, Figures DR1–DR3, Table DR1 (list of images), and blink images, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

MOVEMENT RELATED TO BEDFORM TYPE

We examined 57 image pairs, with the 2 images separated over temporal baselines of sufficient duration, generally 1–2 Martian years (1 Mars yr = 687 Earth days). Examples are shown in Figure 1 and in the Data Repository. Three classes of bedforms were examined: dunes, ripples, and transverse aeolian ridges (TARs). TARs are common Martian landforms that have morphologies intermediate between dunes and ripples (Fig. DR1d in the Data Repository), low migration rates, and are thought to contain coarse granules (Zimbelman et al., 2009). Of the 57 image sets examined, 27 contain TARs, none of which showed motion. This immobility agrees with the conclusion that such bedforms in a part of Meridiani Planum have remained static for the past 50–200 k.y. (Golombek et al., 2010). Smaller ripples are found on sand patches and dunes. Some of these show mobility and some do not. Sand patches commonly move en masse with the ripples; that is, the boundaries of the patch migrate at a rate similar to that of the ripples (Fig. DR1a; DR blink images 4 and 5). On mobile dunes (i.e., those showing lee or stoss face advancement), ripples on the dunes also migrated, in some cases so much so that the ripple pattern could not be tracked between the two images (Fig. DR1a; DR blink images 14–15 and 18–19). The complete catalog of images and resulting measurements is given in Table DR1.

LOCATIONS AND EXAMPLES OF MOVEMENT

The resulting map shows that sand is mobile throughout the north polar sand seas and exhibits variability at other latitudes (Fig. DR2). Examples of these changes are shown in Figure 1, Figure DR1, and the DR blink images. Prominent among these is ripple migration detected in Nili Patera, Kaiser Crater, Herschel Crater (Fig. DR1c), Matara Crater, Proctor Crater, and Meridiani Planum. Some of these changes are contrary to previous interpretations. For example, in MOC imagery, the dunes in Herschel Crater appear to have a grooved texture that was interpreted as cemented sand that was undergoing abrasion (Malin and Edgett, 2001). However, in HiRISE images, the texture is seen as complex sets of intersecting ripples that change with time (Fig. DR1c; DR blink images 10–17). Furthermore, many of the Herschel dunes show unambiguous stoss and lee advancement across the underlying terrain.

Bedforms showing no movement are located at a wide range of latitudes south of the polar sand seas, including parts of intracrater dunes in the southern highlands, such as Russell Crater, where seasonal gully activity occurs (Diniega et al., 2010). However, Kaiser, Matara, and Proctor Craters, where gully changes have also been observed, show unambiguous ripple migration. The static bedforms are found in both the classic high and low albedo regions. Ripples in Cerberus Fossae, a trough where topographic acceleration of wind flow could occur, show no change in position.

RATES OF MOVEMENT

Bedform displacement ranges from the limit of detection at 75 cm (3 pixels in a HiRISE image) to 4.5 m. All measured displacements are shown in Figure 2, plotted against the time interval in Earth days. Also shown are the results from the three recent topical studies, with two barchan dunes in Terra Meridiani (Chojnacki et al., 2011) having the greatest displacement, 10 and 20 m, as observed between MOC and CTX (Context Camera) images over a time interval of 1552 days. Migration rates from our study vary from 0.4 to 4.5 m yr^{-1}, except for one outlier for Nili Patera ripples at 9 m yr^{-1}, with the Meridiani dunes as measured by Chojnacki et al. (2011) at rates of 4–9 m yr^{-1}. Not surprisingly, all of our measured displacements are at or below MOC resolution and above that discernable with HiRISE (taken as 3 pixels).

On Earth, the migration rate of bedforms within individual fields is approximately inversely proportional to their height (Greeley and Iversen, 1985) (Fig. 3). Based on the apparently lower frequencies of threshold winds on Mars (Almeida et al., 2008), it was expected that Martian bedforms would also show such a relationship, but at correspondingly lower migration rates not observable from orbit. Plotting the migration rates against derived heights for the Martian sand bedforms and comparing to

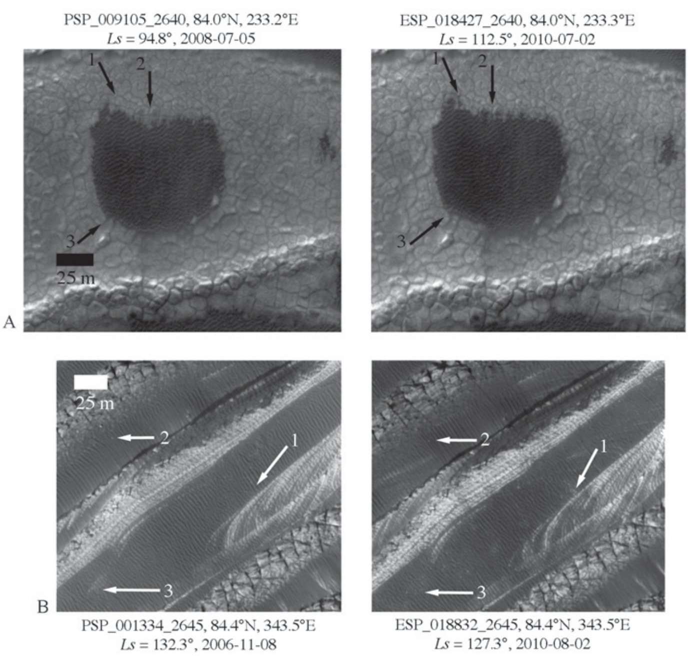

Figure 1. Bedform migration seen in HiRISE (High Resolution Imaging Science Experiment) images. A: Patch of rippled sand at margin of north polar layered deposits (726 days apart). B: Offsets of sand ripples in Chasma Boreale (1363 days apart).

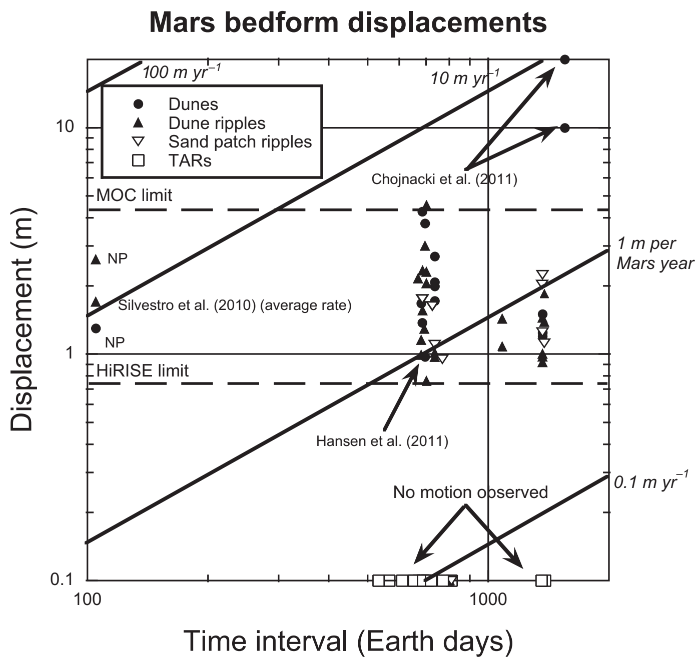

Figure 2. Displacement of Martian bedforms versus interval in Earth days. Diagonal lines are migration rates per Mars year. Where no motion was observed for Martian bedforms, they are plotted at the bottom of the graph. Data from three other references are identified, plus Nili Patera (NP) measurements made for this paper. TARs—transverse aeolian ridges; MOC—Mars Orbiter Camera; HiRISE—High Resolution Imaging Science Experiment.

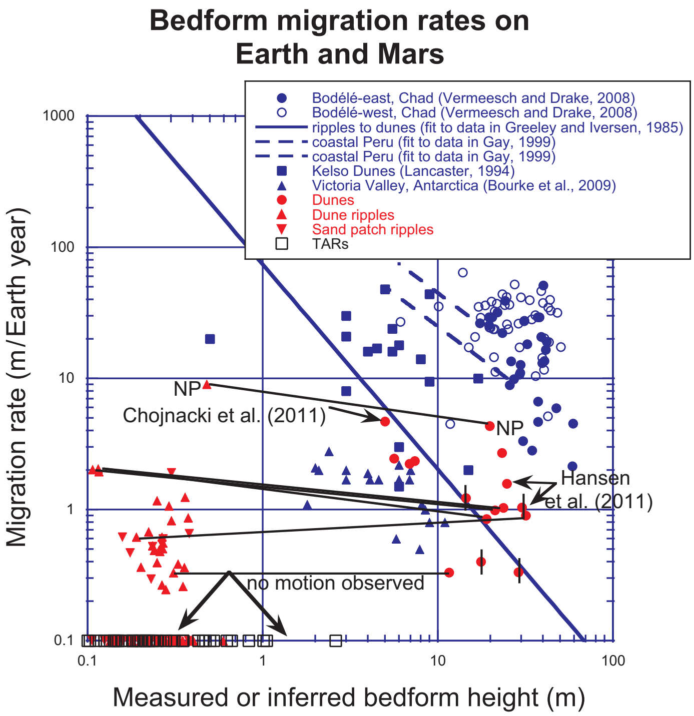

Figure 3. Bedform migration rates per terrestrial year versus height on Earth and Mars. Earth data are in blue and Mars data are in red, except transverse aeolian ridges (TARs), represented by black squares. Earth heights come from the literature, whereas Mars heights were derived from ripple and dune dimensions (see text). Lines connect ripples to their corresponding dunes. Vertical lines through Mars dune symbols indicate that ripples on dunes moved too much to track motion.

terrestrial data from the literature show several relationships (Fig. 3). The considerable scatter in the terrestrial data is attributable to variable conditions on Earth such as wind regime, precipitation, and presence of vegetation. Nevertheless, an inverse relationship between migration rate and height is apparent. Martian dunes overlap with migration rates found on Earth. In contrast, the Mars ripple migration rates are about three orders of magnitude less than typical Earth values for bedforms of the same size and are equivalent to those of the dunes.

Martian dunes with migration rates similar to some on Earth are unexpected, especially because some ripples migrate at rates comparable to those of the host dunes. If the Martian bedforms behaved like their terrestrial counterparts, and given the low frequency of threshold winds predicted by climate models, an inverse migration to height trend of similar slope, but offset downward of the terrestrial points, would be expected. One possibility is that many Martian dunes are indurated at depth, due to mineralogical cementation or, in high-latitude regions, ice cementation. If so, then the stoss and lee dune changes are actually reflective of the motion of a thin rippled skin over a harder interior, not that of the entire dune mass that would otherwise be expected to have a lower migration rate. The presence of ice in the subsurface only centimeters below the surface in polar regions is well supported by Gamma Ray Spectrometer data, seasonal thermal observations, and extensive theoretical studies (Mellon and Jakosky, 1993; Feldman et al., 2008). In addition, some polar dunes display what are interpreted as indurated features on their stoss slopes (Bourke, 2010).

COMPARISONS TO GLOBAL CIRCULATION MODELS

Comparing the movement map to predictions of the Ames Global Circulation Model (GCM) (Haberle et al., 2003) shows no correlation to the high wind frequency regions (Fig. DR3). This demonstrates that the models do not resolve small-scale topographic, katabatic (as occur in the north polar region; Ewing et al., 2010), and general boundary layer turbulence that may cause gusts above threshold (Fenton and Michaels, 2010). Even meso-scale models are compromised by limited surface data necessary for calibration. GCMs show consistency with wind directions derived from the orientation of surface wind streaks, bedform orientations where topographic effects are minimal, dune positions within craters, and dust storm source regions (Greeley et al., 1993; Hayward et al., 2009). Thus, they are likely correct in terms of large-scale wind patterns. Therefore, strong wind gusts not resolvable by GCMs are probably a major driver of sand motion. In polar regions not modeled by the GCM, katabatic winds may also greatly enhance local wind speeds (Ewing et al., 2010).

DISCUSSION

Based on the data discussed here, it is likely that the apparently immobile bedforms exhibiting characteristics of freshness, such as low albedo, sharp crests and brinks, or associations with gullies and avalanches, are actually mobile on time scales slightly longer than the 1–2 Mars years of this study. This hypothesis will be tested in future HiRISE images as the temporal baseline of observations increases. Below the resolution of HiRISE as seen by the MER rovers, the evidence for motion of fine sand is compelling, with indications of sand blowing out of Victoria Crater that erases rover tracks (Geissler et al., 2010), craters superposed on the ripples being filled with sand (Golombek et al., 2010), secondary ripples from winds funneled along the troughs, and one observation of small sand ripple migration (Sullivan et al., 2008).

However, other bedforms are likely immobile over much longer time scales because the frequencies or magnitudes of winds above threshold are relatively low, or they are coated with coarse granules, indurated, or dust covered. Minimal winds could allow geochemical processes promoting induration (Jakosky and Christensen, 1986; Sullivan et al., 2008) to take hold and dust thickness to increase without disruption from blowing sand. Such processes would be particularly effective for ripples coated with granules, such as those in Terra Meridiani studied by the MER *Opportunity* rover that seem to have very low migration rates (Golombek et al., 2010). If many other ripples and TARs on Mars are granule ripples, then the concentration of granules at the surface could promote a self-fossilizing effect where sand becomes more difficult to move with the granule lag. GCMs, even if not able to show the fine details of wind activity, as demonstrated here, provide predictions of Martian climate under different configurations of orbital elements and show that changes in the magnitude of various winds can be driven solely by the 50 k.y. Martian precessional cycle (Haberle et al., 2003). Therefore, where no sand migration is seen in HiRISE images today, such activity could very well have been more common on the scale of tens of thousands of years.

At obliquities greater than the present 25° to 50°, atmospheric density is predicted to increase due to release of CO_2 from polar cap sublimation and regolith desorption, resulting in pressures of 10–15 mbar compared to the current ~6 mbar (Kieffer and Zent, 1992; Phillips et al., 2011). Obliquity oscillates at a frequency of ~10^5 yr. In the past 5 m.y. it has ranged from 15° to 40°, with values of 25° to >45° reached during the past 5–20 m.y., and greater excursions, to 82°, possible in earlier epochs (Laskar et al., 2004). Therefore, even greater pressure increases are conceivable, although limited by the total inventory of CO_2. Because the threshold friction speed is approximately inversely proportional to the square root of atmospheric density, such pressure increases will reduce threshold friction speeds by 30%–60%. Therefore, if the movement of some Martian bedforms requires a pressure higher than that of today, significant motion may not have occurred for hundreds of thousands of years or more. Similar estimates for migration ages have been made for granule-coated ripples in Terra Meridiani (Golombek et al., 2010). Such conditions are probably needed to move other granule ripples and the larger TARs, and may be necessary to reset any sand dunes and ripples that become indurated or dust covered. Nevertheless, these results show that winds in the present low-density atmosphere of Mars are sufficient to move dunes and ripples in many areas of the planet. A major climatic change with a thicker atmosphere is not required.

ACKNOWLEDGMENTS

We thank Devon Burr, Lori Fenton, and an anonymous reviewer for very helpful reviews. Support to Bridges and several coauthors was through Mars Reconnaissance Orbiter/HiRISE (High Resolution Imaging Science Experiment) funding provided by the National Aeronautics and Space Administration.

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Manuscript received 18 April 2011
Revised manuscript received 3 August 2011
Manuscript accepted 15 August 2011

Printed in USA