Aeolian Research xxx (2013) xxx–xxx

Contents lists available at SciVerse ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Review Article

Bedform migration on Mars: Current results and future plans

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ARTICLE INFO

Article history:
Received 30 July 2012
Revised 19 February 2013
Accepted 19 February 2013
Available online xxxx

Keywords:
Mars
Dunes
Ripples
Bedforms
Change detection
Sand flux

ABSTRACT

With the advent of high resolution imaging, bedform motion can now be tracked on the Martian surface. HiRISE data, with a pixel scale as fine as 25 cm, shows displacements of sand patches, dunes, and ripples up to several meters per Earth year, demonstrating that significant landscape modification occurs in the current environment. This seems to consistently occur in the north polar erg, with variable activity at other latitudes. Volumetric dune and ripple changes indicate sand fluxes up to several cubic meters per meter per year, similar to that found in some dune fields on Earth. All "transverse aeolian ridges" are immobile. There is no relationship between bedform activity and coarse-scale global circulation models, indicating that finer scale topography and wind gusts, combined with the predicted low impact threshold on Mars, are the primary drivers. Several techniques have been developed to measure bedform changes and are largely dependent on dataset availability and the type of questions being pursued. Qualitative visual inspection can determine whether or not changes have occurred. Offsets registered to fixed tie points yield approximate migration rates of nearby crests and dune lee fronts. To compute volumetric sand flux requires precise orthorectification and registration using a digital elevation model base. Using this technique combined with sophisticated change detection software has the potential to detect changes as fine as 1/3 of a pixel (~8 cm) or less.

Contents

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http://dx.doi.org/10.1016/j.aeolia.2013.02.004

1. Introduction

Mars contains abundant dunes and ripples (collectively termed "bedforms"), attesting to processes associated with prodigious sand production and aeolian transport. The first process, sand genesis, occurred mostly in ancient eras when rock comminution associated with high energy fluvial, impact, volcanic, and other processes was more frequent than today. However, until very recently, the extent to which bedforms moved was not known at the scales of decimeters to meters. Several studies suggested very low migration rates at the scale of a few centimeters per millennium (Zimbelman, 2000; Claudin and Andreotti, 2006; Fenton, 2006; Parteli and Herrmann, 2007), with a past climate with different conditions (Breed et al., 1979) or wind regimes (Gardin et al., 2012) considered for greater rates. With the advent of the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO), it is found definitively that many ripples and dunes on Mars are moving, some with rates and fluxes comparable to those on Earth. These rates show that significant particle mobility and landscape modification occurs under present conditions, with a past climate possibly only needed to move coarse sand grains or remobilize bedforms that are indurated or dust covered.

There have been several comprehensive treatments on the attributes of Martian bedforms (Breed et al., 1979; Greeley et al., 1992; Malin and Edgett, 2001; Hayward et al., 2007). Our intent is not to reproduce those works, but rather to focus on the nature, causes, and measuring techniques associated with mobile ripples and dunes. As of this writing, we are in the midst of an influx of new data and ongoing analyses by many investigators, a pace that is unlikely to change in the near future. Nevertheless, given many recent findings of aeolian activity on Mars, an assessment of this field is needed. To give the most up-to-date perspective, additional data on the location and rates of bedform motion were compiled for this work. This paper begins with an overview of bedforms on the planet we know best, Earth. This is followed by a review of ripples and dunes on Mars, a discussion of major attributes and classification, and an overview of the implications for bedform mobility. A discussion of detection and assessment methods follows. This section serves not only to document measurement procedures, but to also provide a tutorial for any investigator wishing to reproduce published results or make new measurements themselves. We then review the major results of past and current studies and compare Mars bedforms to those on Earth. We conclude with a discussion that summarizes the results, considers implications for past Martian climates, and speculates on future research directions, techniques, and technological advances.

2. Background

2.1. Aeolian bedforms on Earth

Bedforms on Earth are commonly organized into a hierarchical system consisting of ripples, dunes, and draas (Wilson, 1972). Ripples range from "normal ripples" that form on the surfaces of sand beds and dunes to "megaripples" of significant size. Heights range from a few millimeters to several meters for megaripples, and indices (height/spacing) of 0.05–0.25 (Sharp, 1963; Werner et al., 1986; Ashley, 1990; Yizhaq et al., 2009; Milana, 2009; Zimbelman, 2010). Ripples are composed dominantly of fine to medium sand, with coarser and denser grains at and in the lee of crests. Normal ripples form from impact splash from saltating grains in a process called "reptation" (Anderson, 1987; Andreotti, 2004). Coarser-grained "granule ripples" consist of particles up to several centimeters in size, with wavelengths of decimeters to meters (Fryberger et al., 1992; Lancaster, 1995; Milana, 2009; de Silva et al., 2012). Their method of formation is poorly understood.

Dunes begin as small sand patches located in stable accumulation zones and can grow into kilometer-scale landforms (Bagnold, 1941; Lancaster, 1995). They can cause significant modification of the landscape through burial and associated sand abrasion. Their shapes are determined by wind regime and sand supply. Transverse and barchan dunes form from unidirectional or bimodal winds when the divergence angle (the angle between the two winds) is less than 90°, with barchans occurring under conditions of more limited sand supply. Linear dunes typically form under bidirectional wind regimes when the divergence angle is greater than 100° (Rubin and Ikeda, 1990; Parteli et al., 2009; Reffet et al., 2010). More complicated star dunes with three or more slip faces are produced when strong winds blow from several directions, with higher frequencies of wind reorientation promoting growth and decreasing arm dimensions (Zhang et al., 2012).

Draas are assemblages of complex dunes with spacings >500 m (McKee, 1979) and, if considered as individual bedforms, are the largest on Earth. They consist of large dunes over which secondary dunes of the same (compound) or different (complex) morphology are superposed (Breed and Grow, 1979). Their formation has been attributed to the interactions between flows and sediment transport over large primary dunes (Rubin and McCulloch, 1980; Lancaster, 1985) or to major variations in climate and wind regimes (Kocurek et al., 1991).

2.2. Aeolian bedforms on Mars

Martian aeolian bedforms can be broadly divided into three categories based on size and albedo: dunes, ripples, and transverse aeolian ridges (TARs).

2.2.1. Dunes

Sand dunes are common on the Martian surface and were discovered in Mariner 9 images of the Hellespontus region and subsequently documented over diverse regions of the planet (McCauley et al., 1972; Cutts and Smith, 1973). Later global inventories based on data from the Viking Orbiters (Ward et al., 1985), Mars Global Surveyor's (MGS) Mars Orbital Camera (MOC), and Mars Odyssey's Thermal Emission Imaging System (THEMIS) (Hayward et al., 2007) showed scattered dune fields inside craters at all latitudes and an enormous north polar sand sea covering 680,000 km^2, rivaling the largest ergs on Earth (Breed et al., 1979; Tsoar et al., 1979; Hayward, 2011). Martian sand dunes were found with heights as great as ~300 m (Fenton et al., 2003; Bourke et al., 2006), with thicknesses of crater-trapped sand deposits in the southern highlands reaching more than 100 m (Thomas, 1982).

Despite differences in composition and planetary environment, Martian and terrestrial dunes have similar morphologies, indicating analogous formation processes. Excluding some examples of eroded dunes located in high southern latitudes (Fenton and Hayward, 2010), the same classification scheme used for terrestrial dunes (McKee, 1979) is considered valid for Mars. Barchan, barchanoid, linear, and star dunes are all found, along with sand patches without recognizable slip faces (Hayward et al., 2007). The main morphologic difference between duneforms on the two planets is represented by the distribution of these types. Most sand seas on Earth consist of linear dunes whereas transverse morphologies dominate on Mars, suggesting that Martian near-surface winds have a strong unidirectional component at coarse scales (Lee and Thomas, 1995). Dune ripples, brink and crest profiles, and bedform interference patterns are indicative of complex wind patterns at fine scales. For example, star dunes in Proctor Crater (Fenton et al., 2003) and in several other locations (Hayward et al., 2007; Silvestro et al., 2012) indicate formative winds from multiple directions. Complex patterns of dunes and dune ripples in the north polar erg have been documented (Ewing et al., 2010). Such complexity is attributable to topography, seasonal and diurnal changes, and longer term variability in the wind regime. The spacing (or wavelength) of Martian dunes seems larger than on Earth, an observation attributable to the greater saturation drag length in the low density Mars atmosphere (Claudin and Andreotti, 2006).

2.2.2. Ripples and TARs

Sand and granule ripples have been documented by surface missions (Greeley et al., 1999, 2002; Sullivan et al., 2005, 2008). HiRISE has shown that ripples, down to at least two orders, are common on sand dunes (Bridges et al., 2007). The wavelength of Mars dune ripples are up to a few meters, larger than typical values on Earth and more akin to terrestrial megaripples. The Mars Science Laboratory (MSL) will drive through a dune field for the first time that, based on HiRISE data, shows considerable mobility (Silvestro et al., 2013). A closer inspection of the large ripples superposing the dunes will provide a better understanding of the exact nature of these features.

TARs, with wavelengths comparable to terrestrial granule ripples (Bourke et al., 2003), have been observed by MOC (Malin et al., 1992; Thomas et al., 1999; Edgett and Malin, 2000) and HiRISE (Zimbelman, 2010). Global studies show that bright TARs are generally older than dark dunes and lack any clear evidence of recent activity (Balme et al., 2008; Bridges et al., 2012a). This seems confirmed by evidence of cratered and eroded TARs reported from several areas of Mars (Reiss et al., 2004; Golombek et al., 2010; Kerber and Head, 2011). Analyses of HiRISE data show that TARs with heights $\geqslant 1$ m with symmetrical topographic profiles are most similar to reversing dunes, whereas TARs with heights $\leqslant 0.5$ m have profiles more like granule ripples (Zimbelman, 2010). The large coarse-grained ripples trenched by the Mars Exploration Rovers (MERs; Spirit and Opportunity) may be considered small-scale TARs. If the analogy scales to larger sizes, then the armor of coarse (0.3–2 mm) fragments (Squyres et al., 2004; Sullivan et al., 2005, 2008) that prevents the ripples from being easily activated under the current wind regime may, by extension, be present on TARs and likewise explain their immobility. In addition, the ripples studied by Spirit were coated with dust aggregates (Sullivan et al., 2008), perhaps because of their immobility, a model which would explain why the TARs are light-toned.

2.3. Martian sand properties

Unlike on Earth where sand composition is dominated by resistant quartz eroded from continental crust, sand on Mars is mainly composed of basalt (Christensen et al., 2004; Morris et al., 2004; Squyres et al., 2004; Soderblom, 2004; Tirsch et al., 2011), reflecting the dominant rock type and low chemical degradation rates on the planet. In addition, orbital spectroscopic data indicate that the north polar sand sea is locally rich in gypsum (Langevin et al., 2005), Terra Meridiani contains coarse hematite grains (Christensen et al., 2001; Squyres et al., 2004; Weitz et al., 2006), and sand-sized dust aggregates have been hypothesized to coat some terrains (Bridges et al., 2010). Early thermal inertia measurements from the Infrared Thermal Mapper on the Viking Orbiters indicated that the basaltic grains that make up most Martian sands were 0.2–2 mm in diameter (Christensen, 1983), with those in Hellespontus crater dune fields estimated to have an average effective particle size of 500 ± 100 μm (Edgett and Christensen, 1991). More recent work from the MGS Thermal Emission Spectrometer indicates sizes of 50–600 μm, with the exact range dependent on location (Fergason et al., 2006; Chojnacki et al., 2011). Wind tunnel tests and modeling at Martian conditions show that the optimal grain size for saltation, and thereby the easiest to form into dunes and sand ripples, is 115 μm (Greeley and Iversen, 1985). Direct microscopic imaging from Mars surface missions shows a dominance of sand grains <100 μm in size in the interior of dark ripples (El Dorado ripple field) and within lighter-toned ripples in Gusev Crater (Sullivan et al., 2008), and 50–125 μm grains in ripples at Eagle Crater in Terra Meridiani (Sullivan et al., 2005). Many of the dark-toned ripples examined by the MERs are armored by coarse granules, with those at Spirit composed of basalt and those at Opportunity dominated by hematite (Soderblom, 2004). This is in contrast to ripples on the surfaces of many dunes and sand sheets, which are presumably composed of finer sand (although, as on Earth, likely having slightly denser, larger grains near and in the lee of crests), but which have not been investigated in situ (Sullivan et al., 2008). At the Phoenix landing site, dark sand grains, presumably emplaced via saltation, are somewhat smaller than those measured from MER data, ranging from about 20–100 μm (Goetz et al., 2010).

2.4. Implications for mobility

2.4.1. Motivation for study

The mobility of Martian bedforms is more than an academic question, as it has profound implications for understanding landscape modification and erosion rates. There are three avenues to investigate the problem. The first is theoretical and experimental predictions of sand movement in Mars' low gravity and low density atmosphere. Two speeds are relevant: The fluid (u_t^*) and impact threshold friction speeds. The first is the friction speed needed to initiate saltation and the second that to sustain it. On Earth, the values are close, with the impact threshold about 80% the fluid threshold (Bagnold, 1941). Investigations have consistently shown that Martian fluid threshold friction speeds are about about an order of magnitude greater than on Earth (Iversen et al., 1976; Greeley and Iversen, 1985). Only recently has theoretical work shown that the impact threshold speed on Mars is about $0.1\times$ the fluid threshold (Claudin and Andreotti, 2006; Almeida et al., 2008; Kok, 2010), in other words, similar to fluid and impact threshold speeds on Earth.

The second avenue derives from global- and meso-scale models and surface meteorological measurements from landers that predict the frequency at which threshold winds should occur. Although this "threshold frequency" (f_t) varies geographically on both planets, values are estimated at $\sim10^{-7}$ on Mars (Almeida et al., 2008), considerably lower than ~0.01–0.2 for typical desert environments on Earth (assuming a free stream threshold speed of $10\ \mathrm{m\,s^{-1}}$; Fryberger, 1979; Bridges et al., 2004; Lancaster, 2004). In other words, it is much harder to initiate sand motion on Mars than on Earth. This is despite the fact that dust, which has even higher threshold friction speeds than sand (Greeley and Iversen, 1985), is frequently suspended. It is likely that saltating sand acts as a trigger for dust movement, as the flux of dust lofted by saltating sand is proportional to $(u^*/u_t^*)^3$ (White, 1979; Newman et al., 2002) or $(u^*/u_t^*)^4$ (Westphal et al., 1987; Haberle et al., 2003), such that even winds slightly above sand threshold can cause large dust fluxes with minimal sand fluxes. In addition, vortices induced by surface–atmosphere thermal instabilities can also saltate sand, but not form bedforms, and provide enhanced lift to raise dust, producing dust devils (Greeley et al., 2004).

Actual imaging investigations of the surface is the third and most important avenue. However, a meaningful record of sand movement requires high spatial resolution, a sufficient time baseline over which to see changes, and enough geographic sampling to build up meaningful statistics. Until very recently, investigations were challenged by one or more of these factors, leaving open the question of the magnitude of current sand activity on Mars. Some observations prior to HiRISE pointed toward only limited mobility (Zimbelman, 2000; Malin and Edgett, 2001; Fenton, 2006), consistent with evidence for indurated dunes (Malin and Edgett, 2001), and minor changes seen at the Viking Landing sites spanning 6 Earth years (Moore, 1987), including infrequent gusts above predicted threshold (Arvidson et al., 1983; Moore, 1985; Almeida et al., 2008). On the other hand, MOC showed evidence for dune brink rounding, slip face landslides, and shrinkage and disappearance of polar dome dunes (Fenton, 2006; Bourke et al., 2008). The MERs, which, unlike the Viking Landers, visited a diversity of terrains, showed strong evidence for saltation (Sullivan et al., 2008; Geissler et al., 2008, 2010). So at the landing site scale, evidence of sand movement was documented at some locations, and at the MOC scale, indications of bedform migration, although not direct confirmation, was seen in some areas of the planet but not in others.

As we will discuss below, HiRISE results show that many bedforms move at appreciable rates, but with displacements right below that which could be detected by MOC. A question is "in the absence of visual data, what bedform migration rates are predicted?" The answer depends on one's assumptions on how saltation should behave in the Martian environment. Several pre-HiRISE papers, while not discounting all sand movement, predicted that, based on the low fluid threshold frequencies (Almeida et al., 2008), dunes on Mars should move much more slowly than those on Earth (Zimbelman, 2000; Fenton, 2006; Parteli and Herrmann, 2007), and considered that aeolian saltation and erosion were greater under past climatic regimes (Breed et al., 1979; Armstrong and Leovy, 2005). However, the recent predictions of low impact threshold speeds on Mars indicates that saltation can be sustained on Mars despite low fluid threshold frequencies (assuming these low impact thresholds and using threshold frequencies like those on Earth (0.03), Claudin and Andreotti (2006) nevertheless predicted dune formation times 5 orders of magnitude slower than on Earth). It may be that the extensive bedform movement documented by HiRISE that will be discussed forthwith is vindication for such models. In other words, were the physics of saltation like that on Earth, then much less migration would be observed. Although more completely addressing this issue may require additional data, the high level of sand movement in many areas shown thus far indicates that Mars is a very active aeolian planet.

2.4.2. Wind conditions

If bedforms are moving, then the wind must be of sufficient strength over a long enough duration to mobilize sand. Endmember cases are that wind is at speeds near saltation threshold over sustained periods, or that infrequent gusts occur at speeds significantly above threshold. In reality, a combination of the two is likely, as wind speed and direction vary on diurnal and seasonal time scales. Martian global- and regional-scale climate models have relied on basic atmospheric properties, topographic data, and albedo, and links to three surface meteorological stations (Guo et al., 2009; Nelli et al., 2010). The recent findings of moving bedforms provide fundamental information with which to estimate wind parameters near the surface, thereby anchoring the models to ground truth. With the higher resolution and shorter temporal observation baselines available with HiRISE compared to earlier data (see Section 4), spatial scales of decimeters to meters and temporal scales of days are possible.

2.4.3. Sand flux

Sand flux is the volume or mass (M) of sand moved over a unit length (L) per time (θ) (i.e., $L^3L^{-1}\theta^{-1} \equiv L^2\theta^{-1}$ or $ML^{-1}\theta^{-1}$). Within a dune field, flux is heterogeneous, varying with position on a dune and in the interdune regions. For example, bulk and interdune sand fluxes are about 1/3 those measured at nearby dune crests (Ould Ahmedou et al., 2007). On Earth, dune crest fluxes can be as great as $\sim1000\ \mathrm{m^3\,m^{-1}\,yr^{-1}}$ (Vermeesch and Drake, 2008). If bedforms are mobile, there is sand flux and, if topographic data are available, this can be estimated. With wind being the predominant geomorphic agent on Mars today, such estimates provide first order approximations of the overall transport rate of non-suspended mobile particles.

2.4.4. Landscape modification

The Martian landscape has been extensively modified by aeolian processes. This includes dust that is variously lofted, suspended, and deposited on the surface due to short-term and seasonal winds. Most relevant to this paper is that the action of saltating sand is readily apparent. Dune distribution and orientations delineate sediment transport pathways and long term migration (Fenton et al., 2003; Bourke et al., 2004; Fenton, 2006; Hayward et al., 2007, 2009; Silvestro et al., 2010a; Chojnacki et al., 2011), with many craters and other depressions serving as long term sinks or at least areas in which accumulation exceeds removal. Large yardangs (Malin and Edgett, 2001) and field-scale ventifacts (Laity and Bridges, 2009) demonstrate significant sand abrasion. The question of bedform mobility on Mars therefore ties directly into the extent to which these associated major geomorphic processes are occurring today, and the rates at which they modify the landscape.

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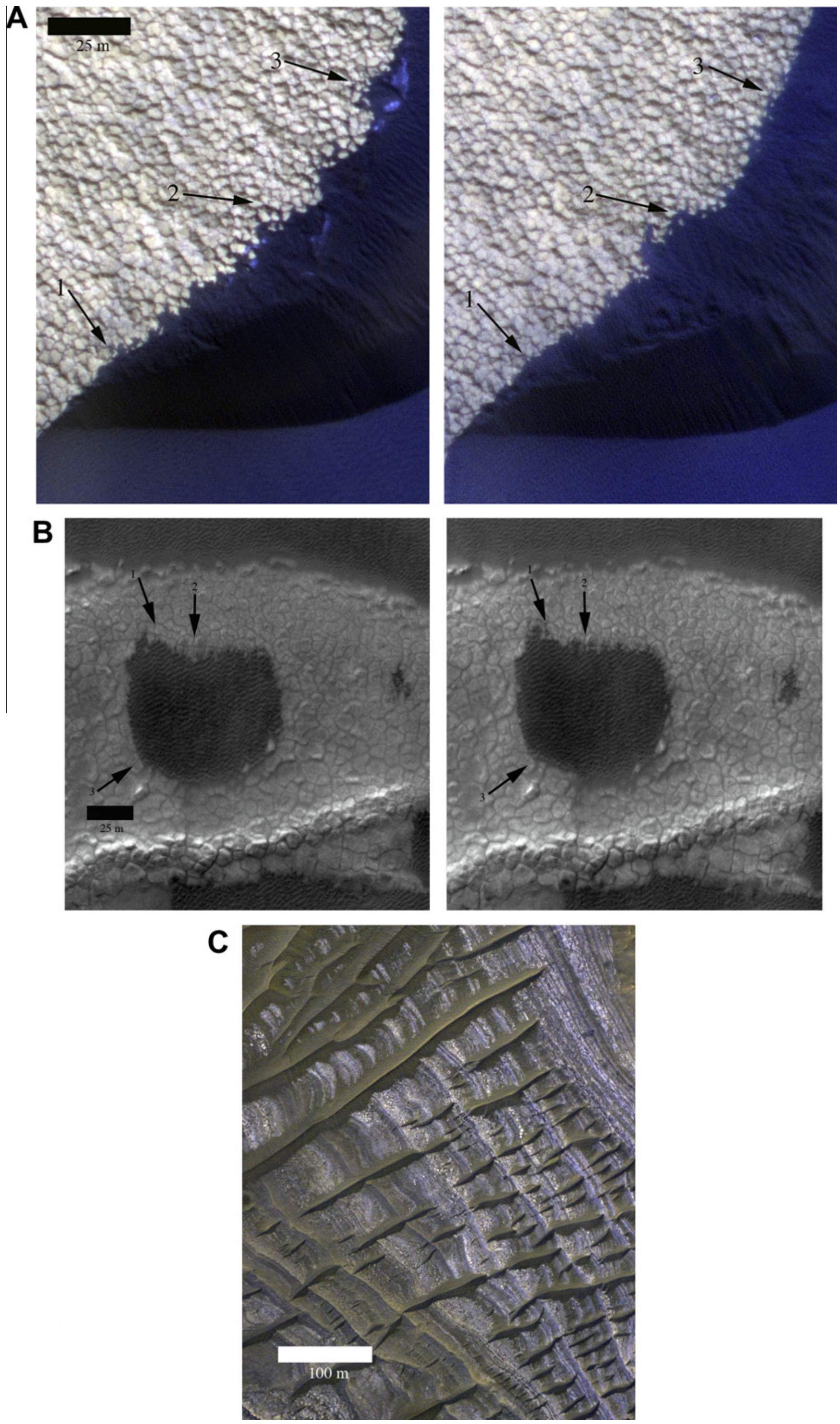

Fig. 1. Mobile and static sand seen in HiRISE images. (A) The lee slope contact of a barchan dune in Tenuis Cavus near the North Polar Layered Deposits (NPLD). From HiRISE images PSP_008968_2650 (left) and ESP_017895_2650 (right) (696 Earth days apart). Numbered arrows point to fixed features. (B) A patch of rippled sand at the margin of the NPLD (PSP_009105_2640, ESP_18247_2640, 726 days apart). (C) Example of Transverse Aeolian Ridges (TARs) near Juventae Chasma which, like all TARs, show no migration (PSP_004990_1755).

2.4.5. Climate

The Martian climate has changed over time. Evidence for significant volumes of flowing and standing bodies of water in the Noachian and Hesperian eras (∼4.1–3 Ga) points to past conditions when the atmosphere was probably thicker and the temperature maybe warmer (Bibring et al., 2006; Di Achille and Hynek, 2010; Grotzinger et al., 2011). However, bedforms presently on the surface are affected by more recent climatic fluctuations under dry conditions. Mars is subjected to large changes in obliquity, precession, and eccentricity, parameters that affect solar insolation as a function of latitude and season (Laskar et al., 2004). Variations in precession and eccentricity can change the magnitude of near-surface winds (Haberle et al., 2003). Increases in obliquity potentially releases CO_2 trapped in the southern cap and regolith, increasing

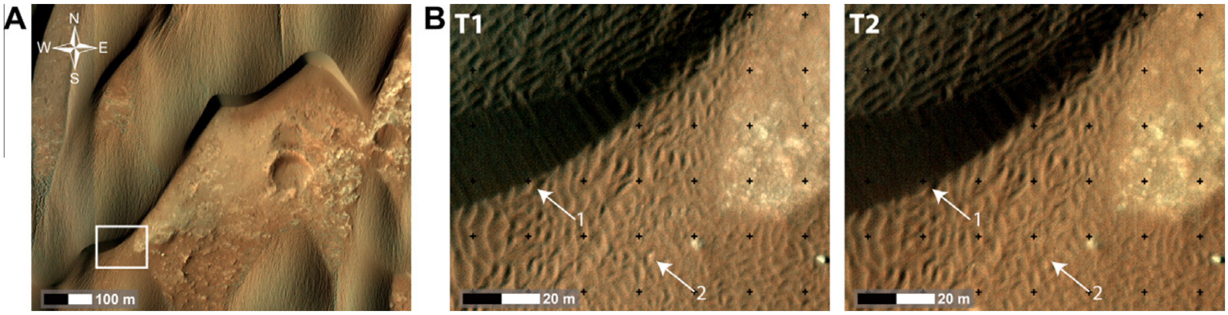

Fig. 2. Time series HiRISE images of a barchan dune field within Herschel Crater on Mars. The dunes are moving from north (at top) to south, as evidenced by the orientation of the dune slip faces and barchan shapes. Textures on the dune surfaces are ripples. Changes in the position of ripples and the dune slip face can be seen between March 7, 2007 (HiRISE image PSP_002860_1650, left and middle images) and December 1, 2010 (ESP_020384_1650, right image), an interval equivalent to about two Martian years. Note the dune's lee side advancement with respect to the reference grid (arrow 1) and the albedo variation due to the change of the ripple pattern (arrow 2).

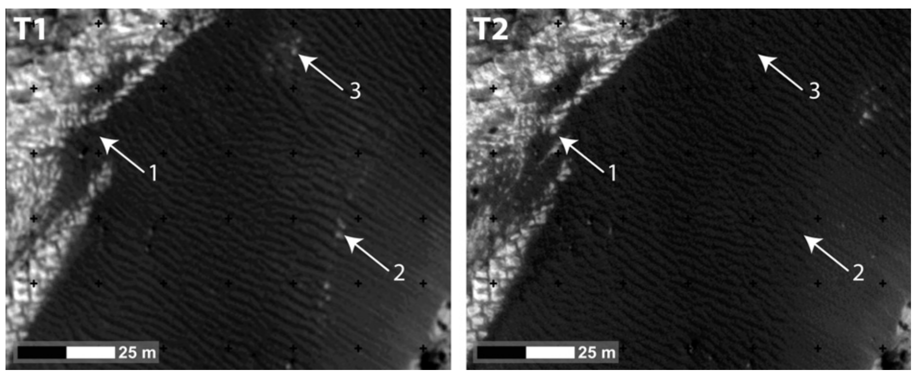

Fig. 3. Offsets of sand ripples in Chasma Boreale (HiRISE images PSP_001334_2645, ESP_018832_2645, 1363 days apart). Numbered arrows are common tie points in the two images where ripple position and pattern changes have taken place.

atmospheric pressure up to 10–15 mbar compared to the present ~6 mbar (Kieffer and Zent, 1992; Philipps et al., 2011) and thereby lowering threshold friction speeds by 30–60% (Bridges et al., 2012a). Considering these changing conditions, it is reasonable to consider whether bedform motion, and associated geomorphic processes such as sand abrasion, are cyclical (Armstrong and Leovy, 2005). A related question is the magnitude of current processes. If minor, then the peaks of cyclical events are an appealing mechanism for moving bedforms and abrading rocks and landforms. If significant sand motion is occurring today, then sand activity occurs over a much greater fraction of Martian orbital cycles than in the first case, with peaks potentially corresponding to periods of particularly vigorous activity that may re-activate currently immobile bedforms. New data are showing the viability of this second model, offering insight into the effects of Martian climate.

2.5. Bedform studies with HiRISE

Searches for Martian dune motion prior to HiRISE were mostly unsuccessful (see review by Bourke et al., 2008). Evidence for static bedforms were based on spacecraft observations spanning more than 3 decades, including comparisons between Mariner and Viking and Viking to MGS–MOC, and repeated MOC observations (Edgett and Malin, 2000; Zimbelman, 2000; Malin and Edgett, 2001; Edgett, 2002; Fenton et al., 2003; Schatz et al., 2006; Bourke et al., 2008). However, the presence of shifting wind streaks, avalanching slip faces (Malin and Edgett, 2001; Fenton, 2006), the shrinkage and disappearance of north polar dome dunes (Bourke et al., 2008), and small ripple migration seen by Spirit (Sullivan et al., 2008) showed that the Martian sands were mobile in at least some locations.

With the advent of data from HiRISE at decimeters- to meters-scale (McEwen et al., 2007), features with sizes approaching those seen by landers and rovers can be identified, mapped, and tracked virtually anywhere on the Martian surface. HiRISE has been acquiring data in its primary science orbit since late 2006. With a pixel scale as fine as 25 cm/pixel, significant results have emerged. The images of bedforms show spectacular detail (Figs. 1–3). Almost all Martian dunes are superposed by 2nd order and in some cases 3rd order ripple sets (Bridges et al., 2007), with the ripples larger than typical dune ripples on Earth. Even more importantly, HiRISE has now shown that bedforms migrate, with significant movement initially identified in Nili Patera (Silvestro et al., 2010b), Terra Meridiani (Chojnacki et al., 2011; Silvestro et al., 2011; Geissler et al., 2012a) and the north polar erg (Hansen et al., 2011), and subsequently in dozens of regions over the whole planet (Bridges et al., 2012a). Migration is seen for meters-scale ripples, both within sand patches and on dune surfaces, and in a few cases actual movement of large dune slip faces. Combined, these results show that many sand ripples and dunes on Mars exhibit movement of up to a few meters per year, demonstrating that Martian bedforms migrate under current conditions in diverse areas of the planet (note, unless otherwise noted, "per year" refers to an Earth year, which is 53% the length of a Mars year).

3. Methods

3.1. Detection

The detection and analysis of mobile bedforms requires data optimized for image quality, timing, and lighting and viewing geometry. HiRISE is the best system for studying Martian bedforms

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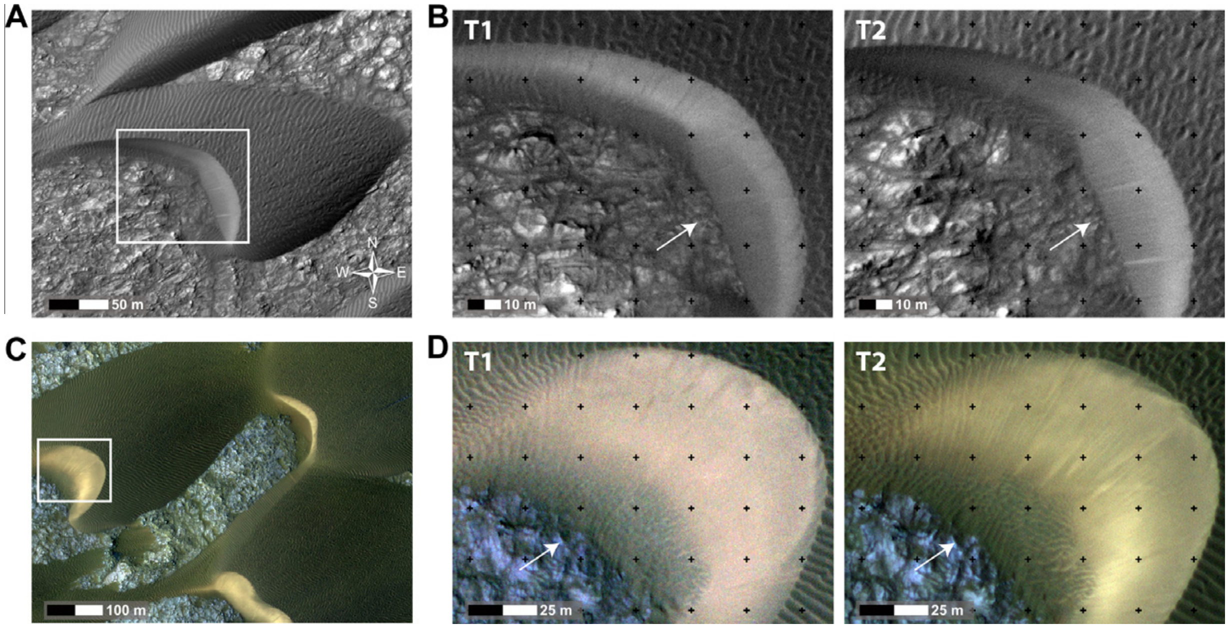

Fig. 4. Top row: Changes in the Nili Patera dune field over 963 days between images PSP_005684_1890 (T1) and ESP_018039_1890 (T2). (A) A dune lee front as seen in T2. White box shows location in b. (B) Close-up of dune lee front displacement between T1 and T2. Arrow in image set points to area where dune changes are seen relative to fixed bedrock texture. Bottom row: Changes in the Nili Patera dune field over 1526 days between images PSP_004339_1890 (T1) and ESP_023920_1890 (T2). (C) A dune lee front as seen in T2. White box shows location in d. (D) Close-up of dune lee front displacement between T1 and T2. Arrow in image set points to area where dune changes are seen relative to fixed bedrock texture See Fig. 5 for Nili ripple changes over a shorter time scale of 105 days.

remotely due to its superior resolution (pixel scales down to 25 cm, so able to resolve features <1 m in size) and high signal-to-noise (commonly approaching or even greater than 200:1) (McEwen et al., 2007). To best utilize HiRISE's capabilities, images at full resolution acquired under good illumination are desired. Optimal lighting in mid-latitudes is available year-round, but the changing conditions in polar regions constrains observations to summer, after the surface has defrosted and before atmospheric condensates in the polar hoods partially or completely obscure the surface. In addition, seasonally hazy conditions are common in topographic lows such as the Hellas Basin and Vallis Marineris, and local, regional, and global dust storms can temporarily degrade viewing conditions. All of these factors constrain when the first image of a change detection set is acquired.

The second image, that is, the one for which changes relative to the first will be assessed, is planned to minimize differences in illumination and viewing geometry. Changes in these parameters can alter the appearance of a scene, spoofing bedform migration when, in fact, none has occurred. The first constraint is easily met by acquiring the new image at approximately the same season, with ±5° of L_s being a good rule of thumb (L_s is the areocentric longitude of Mars relative to the Sun, with $L_s = 0$ corresponding to the northern hemisphere spring equinox). The viewing geometry constraint is more difficult to achieve because targets can only be imaged from a limited number of orbital tracks whose positions do not exactly repeat from one year to the next. Most non-stereo images and generally one image of a stereo pair are acquired with small rolls of the MRO spacecraft, constrained as less than 9° in either direction. Therefore, although potential differences of 18° are possible, most change detection sets have roll angle differences of less than 9°, with nearly half (46%) of these within 2°.

Beginning in 2008, targets were selected for repeated imaging based on coverage obtained at a similar season (L_s), one to three Martian years earlier (so, since 2006 and going to 2013). Repeat targets were chosen where bedforms were observed, especially those with nearby fixed features such as bedrock textures and rocks that could serve as tie points. Supplementing these annual change assessments were areas on Mars for which more rapid bedform migration was observed. The most notable are the dune and dune ripples of Nili Patera, where significant changes on time scales of just 3 months are documented (Figs. 4 and 5) (Silvestro et al., 2010b; Bridges et al., 2012b). Other areas of Mars also show rapid migration and are currently being investigated.

3.2. Landforms

Distinct geomorphic landforms that represent bulk sand body motion are most desired for remote measurement. These can be divided among the following:

(1) *Sand patches*: By definition, these lack periodic structures that define bedforms. Change measurements therefore rely on determining boundaries relative to adjacent terrain.
(2) *Ripples*: In planview ripples are characterized by adjacent light–dark bands that represent surfaces that are illuminated and shadowed, respectively. Secondary and even tertiary ripple sets are located within and oriented approximately perpendicular to higher order sets and can produce an "accordion" appearance (Bridges et al., 2007, 2010). Abutting ripples produce triple "Y-junctions" (Silvestro et al., 2010b) and dense intersections can exhibit a "honeycomb" pattern (Bridges et al., 2010).
(3) *Dunes*: Larger than ripples and most sand patches, dunes have potentially a greater number of points that can be used to define their motion. For simplicity, it is assumed that their shape and volume are maintained, with sand flux proportional to dune height (Ould Ahmedou et al., 2007). Such a model ignores variations in sand supply and wind regime, but can be considered approximately true in most cases. Therefore, the measurement of any part of the dune, such as the stoss or lee boundary, crest, or brink, should correspond to the bulk motion. Although the brink is a distinctive

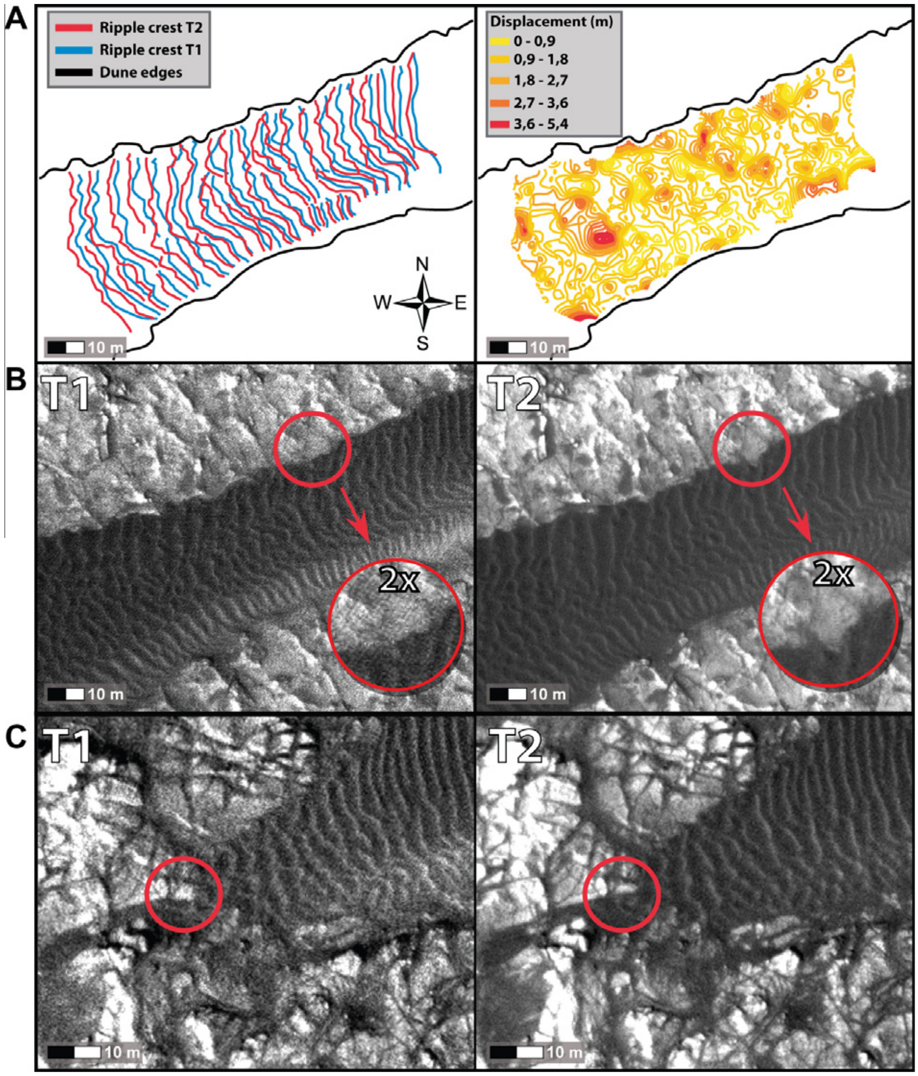

Fig. 5. Changes in the Nili Patera dune field over 105 days, between images PSP_004339_1890 and PSP_005684_1890. (A) Ripple migration using the manual correlation techniques of Silvestro et al. (2010b). (B and C) Albedo variations due to sand removal at the edge of the dunes (A and B, modified from Silvestro et al., 2010b). Average ripple displacement in Nili Patera during this period was 2.5 m, or 8.7 m per Earth year. See Fig. 4 for Nili dune changes over longer time interval of 963 days.

feature, it is a poor landform to use for assessing dune motion because its high elevation results in parallax between time series images and rarely are stereo-derived topographic models available for both. The crest, being the highest part of the dune and upwind from the brink, is difficult to determine in images and, again, topography is rarely available.

3.3. Qualitative assessment methods

Two methods can be used for qualitatively assessing whether bedforms move. One is to simply look at two images and use best judgment. In some cases, very large changes are apparent. A preferable method is to overlay the images, using rocks, bedform textures, and other fixed features as tie points. Because viewing geometry results in geometric distortion as a function of elevation, the tie points must be near the bedforms of interest. Alternatively, ISIS (using "coreg"), ENVI, and ArcGIS can be used to warp an image such that the spacing and orientation of tie points match those in the companion image. In either case, changes can be seen by blinking between the images, subtracting one image from the other, or by making an anaglyph and noting areas of color fringing that correspond to displacement.

3.4. Quantitative assessment methods

Quantitative assessment requires radiometrically-calibrated image pairs processed through the HiRISE pipeline (Eliason et al., 2007). These images are map-projected using the Mars global shape model derived from Mars Orbiter Laser Altimeter data that accounts for regional slope and topography. Ideally, the best way to identify changes in the dune and ripple pattern and address the issue of different viewing geometries, is to orthorectify the images over a digital elevation model (DEM) built from a stereo pair. To make these products, each image in the pair is processed. First, the 10 individual image strips from the separate CCDs in the HiRISE red channel are assessed for jitter greater than 1–2 pixels by estimating the offsets of fixed features in the CCD overlap regions (Mattson et al., 2009). A jitter correction, if needed, is applied to the strips, which are then stitched together. The DEMs are made from standard software, such as SOCET SET (®BAE Systems). Once a DEM is produced, the original images can be orthorectified (geometrically corrected for viewing angle differences) using programs such as SOCET SET or Co-registration of Optically Sensed Images and Correlation (COSI-Corr) (Leprince et al., 2007). With 0.2 pixel matching between stereo pairs, vertical precision of 10s of centimeters is possible in the DEMs (Cook et al., 1996; Kirk et al., 2003, 2008), with post spacing at 1 m (McEwen et al., 2007). In most cases where a higher resolution DEM is unavailable, residual errors leave the images misregistered by several pixels. Geometric correction can be improved in these cases using empirical methods of image co-registration, for example the program "coreg" in the ISIS software system provided by the US Geological Survey (Anderson et al., 2004), as described above.

3.4.1. Measurement objects and methodologies

Depending on the region of interest, one or more objects can be measured, with the specific object type and methodology dependent on the aeolian landform. In the case of sand patches, the simplest method is to compute the displacement of a defined edge. Patches may be elongated along the azimuth of the principal wind regime above threshold, such that measuring the boundaries at the major axis intersections provides an approximate migration measurement. To best determine the contribution of all wind components, the centroid can be found by measuring the patch perimeter and computing the center of figure (a standard feature of many image processing programs, including Photoshop). The migration of the centroid therefore represents the average displacement of the sand patch.

For ripples, ripple pairs or trains can be used to track motion between images, but care must be given to individually tagging each ripple based on some unique characteristic. If the ripples cannot be distinguished between two images, then a migration over an apparent distance x could potentially be $x\,(1 \pm \lambda)$, where λ is the ripple wavelength (Silvestro et al., 2010b), such that derived displacements and rates can be considered minimum values. Another technique is to use junctions between and among ripples, although there are complexities, as ripples can move relative to the junctions. Such textures may be easier to identify between images compared to parallel ripples, but the parallel ripples have the benefit of being better correlated to a predominant wind regime, such that displacement can be more easily tied to overall sand migration and flux.

With dunes, boundaries are the easiest surfaces to measure, and points near the center line on the lee or stoss end can be used to infer the net motion transverse to the dune bisector. Over short time scales motion can be highly heterogeneous. For example, local landslides on lee slopes can bias inferences on overall dune motion to high values unless other boundary areas are accounted for. A robust technique to compute net displacement is to measure the lee or stoss boundary in two images, compute the area subtended by the dune advance, and divide this area by the boundary length (Hansen et al., 2011; Bridges et al., 2012a). Isolated dune motion can also be computed by determining the offset in the centroid position, as with sand patches.

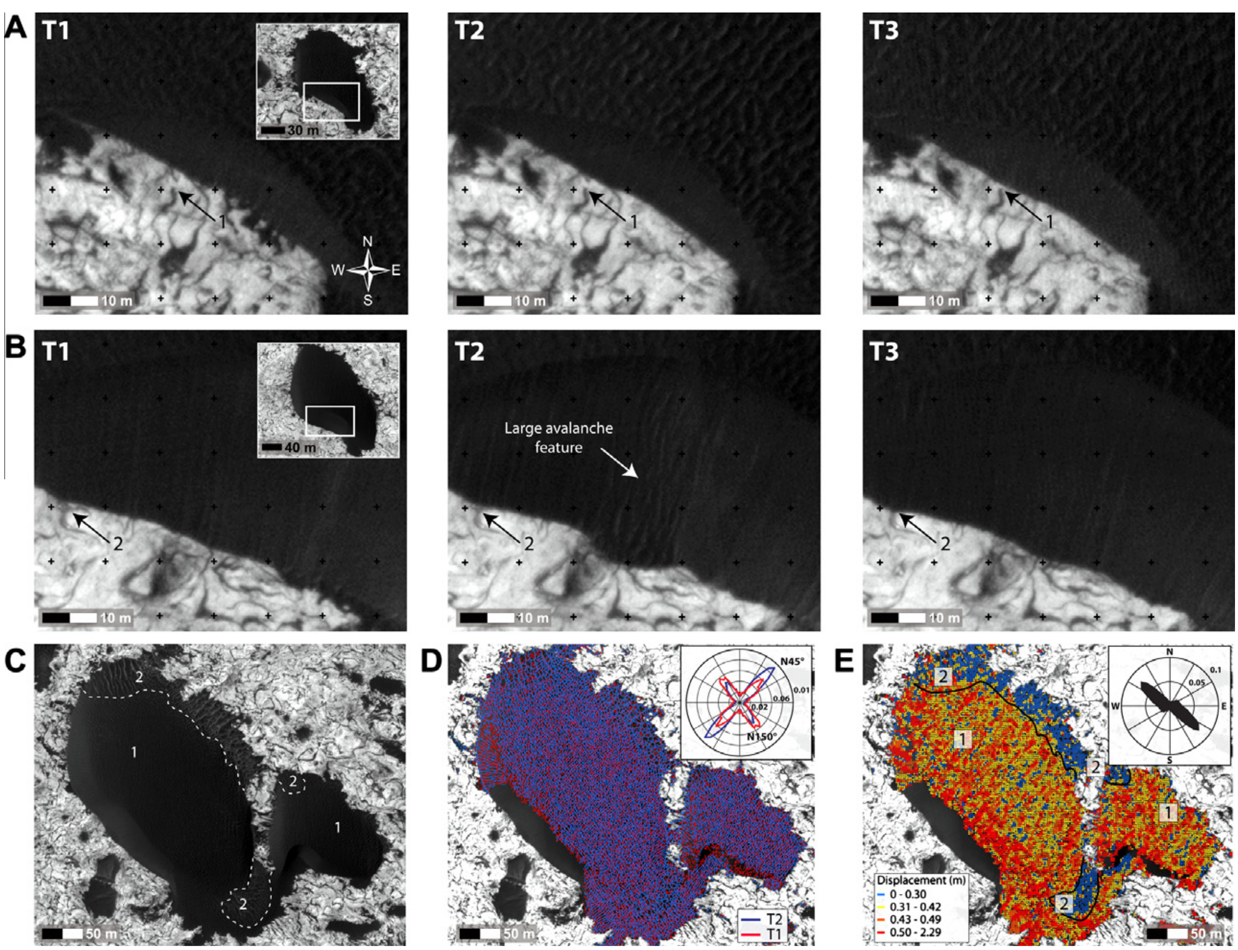

Fig. 6. Dune movement in Terra Meridiani between PSP_007018_1830 and ESP_016459_1830 (735 days, T1–T2) and ESP_026230_1830 (1640 days, T1–T3). (A and B) Changes on the lee of two dunes. Inset in the T1 frame shows the general location. (C–E) Results of T1–T2 displacement using the automatic techniques of Silvestro et al. (2011). Two main ripple populations are distinguished. Both populations show two orthogonal trends with different distributions in the two images. The minimum ripple displacements are also automatically computed (E).

Please cite this article in press as: Bridges, N., et al. Bedform migration on Mars: Current results and future plans. Aeolian Research (2013), http://dx.doi.org/10.1016/j.aeolia.2013.02.004

A new result shows that ripples located on dunes exhibit displacements that are proportional to local dune height (Bridges et al., 2012b). This relationship is expected for dunes at steady state, with their entire volumes composed of mobile sand (Ould Ahmedou et al., 2007) and the expected increase in wind speed with height on a dune (Andreotti et al., 2006; Claudin and Andreotti, 2006). If the ripple height can be estimated, then the ratio of ripple to local dune height multiplied by ripple displacement gives the dune motion due to reptation. Therefore, a measurement of dune ripple displacement can be used to get an approximate bound on overall dune migration. This is particularly effective for short time scales over which ripple motion is obvious but for which dune displacement is at the limit of resolution.

3.4.2. Measurements relative to fixed objects

Looking for aeolian changes in images that are not co-registered, much less orthorectified, is challenging. However, with similar lighting geometry, movement relative to fixed objects on the ground (boulders or fractures, for example) can be determined. Once identified, the displacement is quantified by computing the difference between the two measured positions.

3.4.3. Measurements relative to inertial space

With orthorectification using a DEM, parallax errors are removed and objects on the ground can serve as geographically-defined control points to align the image pair. Mapped ripple crests on the coregistered images can be used to measure displacement with manual (Silvestro et al., 2010b; Bridges et al., 2012a; Geissler et al., 2012a) or automatic (Silvestro et al., 2011; Bridges et al., 2012b) techniques (Figs. 5 and 6). However, geometric distortions that arise from the difference in viewing geometry cannot be corrected for ripples by orthorectification because the resolution of the HiRISE DEMs cannot resolve their height. Therefore, in areas for which fixed benchmarks are lacking, such as in the interior of dunes, displacements are most accurately measured using change detection pairs with minimal parallax angles between them, as has been done in the Nili Patera studies (Silvestro et al., 2010b; Bridges et al., 2012a).

The same methodology can be used for measuring whole dune displacement (Silvestro et al., 2011). To avoid errors caused by geometric distortions that arise from different viewing geometry from non-orthorectified images, the lee or stoss dune margins are examined. The best way to determine motion of other dune components, such as the brink and crest, is to eliminate parallax distortions by producing a DEM for each image in the change detection set. Given the considerable effort needed to make DEMs, such studies are only now getting started (Ayoub et al., 2012).

3.4.4. Measurements from sub-pixel registration and change detection

Sub-pixel change detection requires accurate co-registration of images acquired over the change detection interval, with proper account for stereoscopic effects and geometric distortions due to the imaging system, as well as an appropriate correlation technique. This has been implemented in the software package COSI-Corr (Leprince et al., 2007). The COSI-Corr methodology allows for automatic and precise ortho-rectification, co-registration, and sub-pixel correlation of push broom satellite and aerial images. Orthorectified images are resampled to a common grid, that is, each pixel is projected onto a specific geographic location. Relative displacement between the image pairs is found from the phase difference in their Fourier transform along column (vertical) and row (horizontal) axes. Because of radiometric calibration limitations due to natural atmospheric haze and instrument performance, the absolute radiometry values are not known precisely, but with this approach they are irrelevant. Rather the distribution of data number (DN) values along the column and sample directions is what is correlated to displacement. COSI-Corr has been successfully used to measure diverse tectonic and geomorphic processes, including co-seismic deformation, ice flow, landslide and sand dune migration on Earth (Avouac et al., 2006; Leprince et al., 2007;Vermeesch and Drake, 2008; Necsoiu et al., 2009) and has recently been applied to Mars (Bridges et al., 2012b; Ayoub et al., 2012).

4. Results of Mars bedform migration studies

4.1. Bedform migration across Mars

Although new HiRISE data are continually being acquired, published work (Bridges et al., 2012a) and additional results incorporated for this paper show that bedform migration is common, but not universal, across the entire planet. Of 88 image pairs examined, 41 (47%) exhibit no change, 39 (44%) show bedform migration, and 8 (9%) are inconclusive (Fig. 7 and SOM Table 1). A few overarching observations are that: (1) Where motion occurs, the ripples and dunes are dark, with crisp textures, (2) Virtually all images of dune fields and ripple patches in the north polar erg show migrating bedforms, (3) Bright bedforms, including all those classified as TARs, are immobile. The first observation is the most qualitative of the three, as "crisp textures" has not been quantified

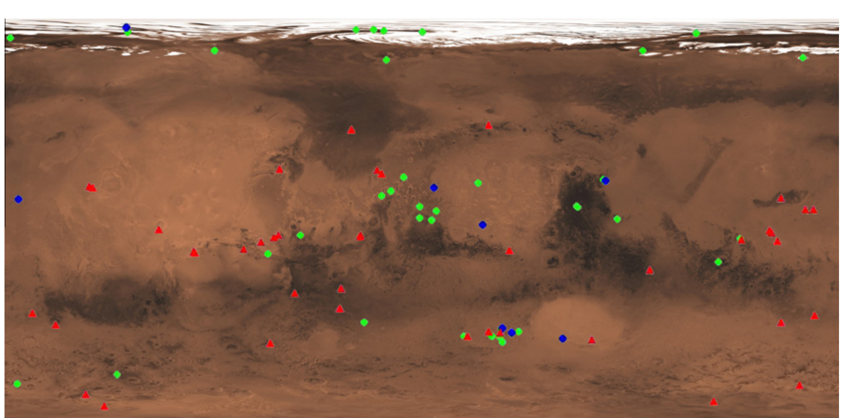

Fig. 7. Map of bedform changes on Mars. Each symbol shows where images were analyzed for bedform migration. Red: No motion detected (41 image pairs); Blue: Evidence for motion (such as avalanches or possible movement at the pixel scale) but no definitive migration; or uncertain (8); Green: Definitive migration of ripples or dunes (39). For a list of all data, see SOM Table 1.

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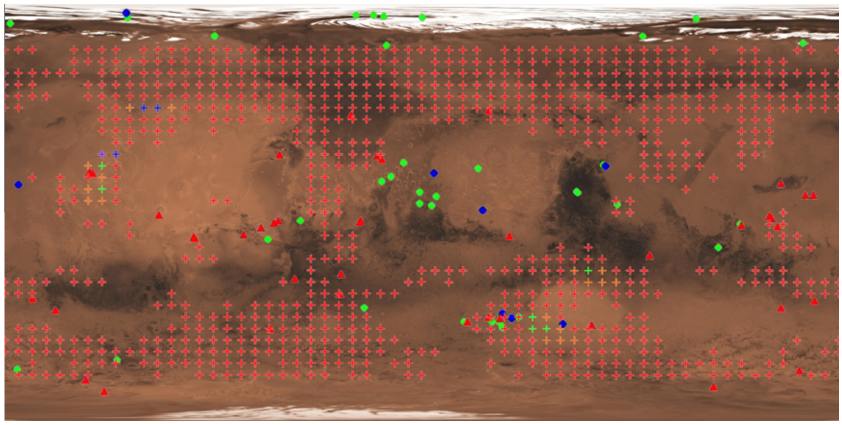

Fig. 8. Change map with the Ames GCM results (Haberle et al., 2003; downloaded from http://pubs.usgs.gov/of/2010/1170/) overlain as red crosses. The model computes surface stresses 8 times per each degree of L_s, for a total of 2880 vectors per 6° longitude × 5° latitude cell over the latitude range of 70°S to 70°N. From these data, we computed the fraction of occurrences per cell over a Mars year at which surface stresses are >0.025 Pa, commonly considered as the threshold value on Mars. Output values are shown as crosses: Purple: Frequencies of wind shear stresses greater than 0.025 Pa is >0.4; blue: 0.3–0.4; green: 0.2–0.3; orange: 0.1–0.2; red: 0.0003–0.1; no crosses indicate that winds do not get above threshold at the level of GCM modeling. For 90% of the cells, threshold is never reached, whereas 8% and 1% of cells have threshold frequencies of 0.0003–0.01 and 0.01–0.1, respectively. The average frequency value, including those of zero, is 6×10^{-4}. Note the poor correlation to the bedform migration results, indicating that the GCM fails to model gusts and other effects that must be driving sand motion.

and there are some fresh appearing bedforms for which motion has not yet been detected. Many bright bedforms, and certain TARs (Zimbelman, 2010), are likely dunes that have become dust covered or indurated through a gradual process in which the competition between mechanisms which promote these actions win out over winds which would otherwise help maintain the low cohesion of sand grains through continual saltation (Sullivan et al., 2008). Therefore, the geographic distribution of active versus immobile bedforms can be considered a map of where sand is concentrated and winds of sufficient magnitude and frequency above threshold occur.

Although bedforms commonly reside in depressions such as basins, craters, and canyons (Hayward et al., 2007), current data do not indicate an obvious local elevation difference between static and mobile varieties and the role of topography is ambiguous (however, recent work has shown that on a global scale, lower elevation dunes exhibit more activity that at higher elevations (Geissler et al., 2012b)). On the one hand, all dune fields in the north polar erg show bedforms with mobility. This sand sea resides within the north polar basin (Fishbaugh and Head, 2005) and katabatic winds from the high elevation polar cap are a major driver of saltation (Ewing et al., 2010). On the other hand, dunes in Cerberus Fossae, where funneling of winds are expected, do not show mobility. The lack of meso-scale wind models for most areas of the planets, and statistics relating bedform position to local and regional elevation and slope, prevent a more detailed assessment at the present time.

The location of mobile bedforms shows no correlation to the frequency of high speed winds as predicted by the Ames General Circulation Model (Bridges et al., 2012a) (Fig. 8). This is likely due to two factors. The first is that GCMs are inherently low in spatial and temporal resolution, and therefore insensitive to localized gusts (Fenton and Michaels, 2010). The second is that these gusts are only needed to initiate saltation, with sand transport maintained by the much lower impact threshold speeds on Mars (see above).

4.2. Migration rate

The slowest possible migration rate is, of course, zero. It is therefore more appropriate to consider the smallest value that can be detected with Mars orbital imagers. Using traditional techniques, the minimum measurable displacement is on the order of 3 pixels. For HiRISE and MOC at highest resolution, this translates to ~75 cm and 4.5 m, respectively. For the 6 (so far) and 8 Earth year spans of these investigations, rates of ~10 and 60 cm/year, respectively, are theoretically detectable. However, most images from MOC were binned to at least 2 × 2 pixels, have lower signal-to-noise than HiRISE, and had limited temporal coverage of the same locations, such that no migration rates were detected, except in cases of comparison to later Context Imager images in Terra Meridiani (Chojnacki et al., 2011). All data, except for the Meridiani example, plot between the resolution obtainable with MOC and HiRISE (Fig. 9), indicating that MOC was just at the cusp of bedform migration detection. This is consistent with findings from MOC indicative of dune motion, although not showing it directly, such as lee slope avalanches, brink rounding, and dome dune changes (Malin and Edgett, 2001; Fenton, 2006; Bourke et al., 2008).

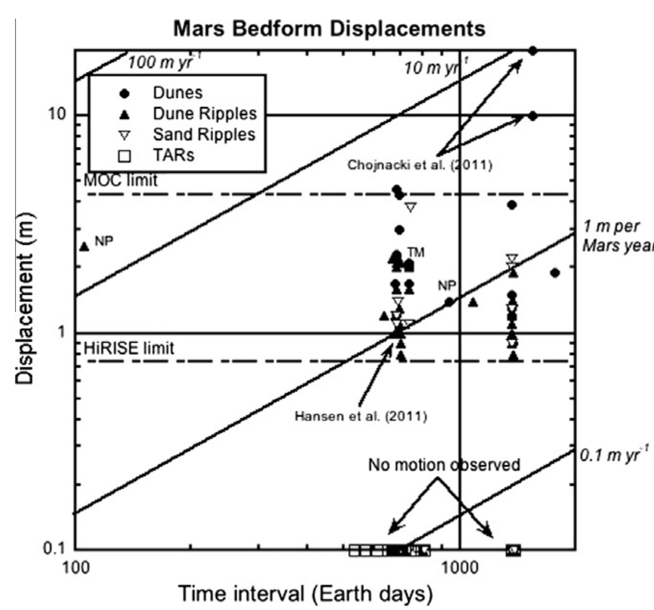

Fig. 9. Mars bedform displacement vs. time. "NP" refers to average values for Nili Patera in Bridges et al. (2012b) and TM for Terra Meridian from Silvestro et al. (2011). Bedforms with no displacement are shown at bottom.

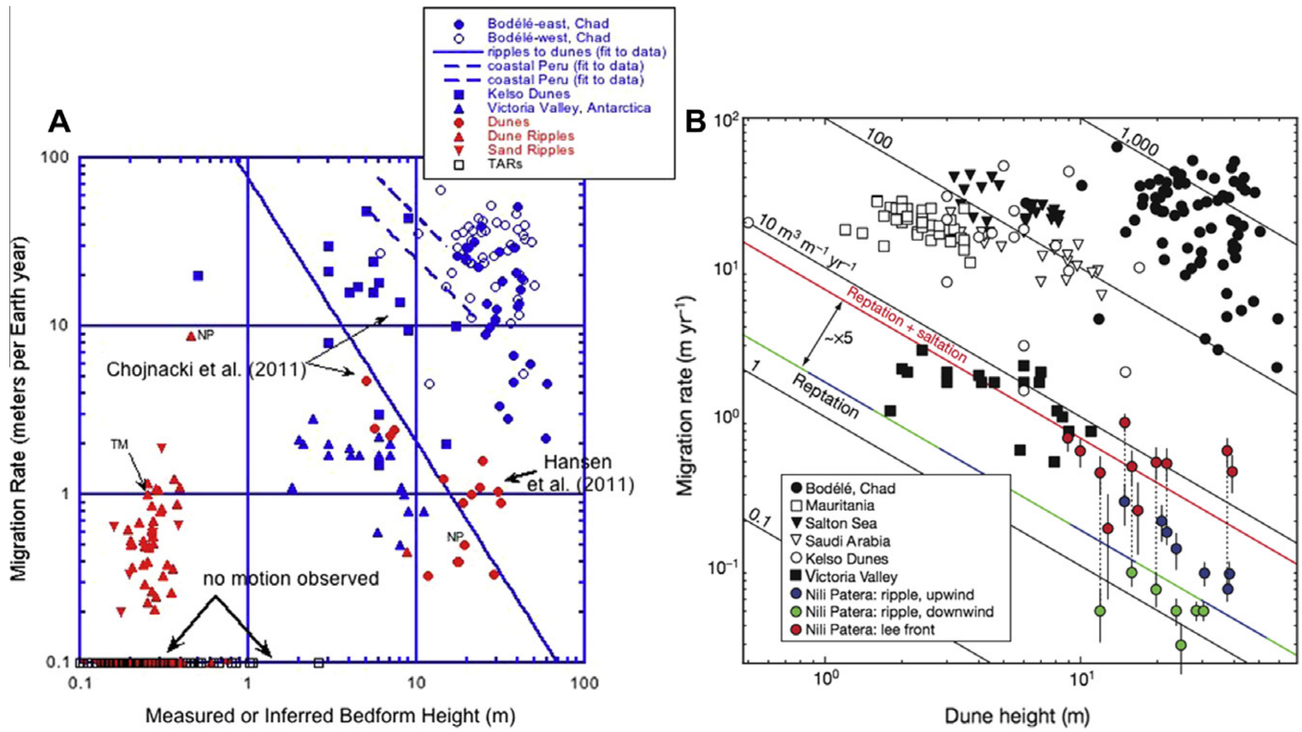

Fig. 10. Bedform migration rates per terrestrial year versus height on Earth and Mars. (A) Earth data are in blue and Mars data are in red, except transverse aeolian ridges (TARs), represented by black squares. NP and TM values are average values for Nili Patera (Bridges et al., 2012b) and Terra Meridiani (Silvestro et al., 2011). Earth heights come from the literature, whereas Mars heights were derived from ripple and dune dimensions (Bridges et al., 2012a), except NP dunes, which come from stereo-derived topography. (B) Comparison of 14 Nili Patera dune migration rates compared to dunes on Earth. Black diagonal lines are isopleths of sand flux. Red and blue/green diagonal lines are mean sand fluxes derived from the lee-front advance and ripple migration measurements, respectively. Vertical error bars show 1 standard deviation confidence intervals for the dune migration rates. The factor of five between the two fluxes suggests that the saltation flux is about four times the reptation flux (from Bridges et al., 2012b; acknowledgement to Nature Publishing Group). References: Bodélé (Vermeesch and Drake, 2008); ripples to dunes (Greeley and Iversen, 1985); Peru (Gay, 1999); Kelso (Lancaster, 1994); Victoria Valley (Bourke et al., 2009); Mauritania (Ould Ahmedou et al., 2007); Salton Sea (Long and Sharp, 1964); Saudi Arabia (Fryberger et al., 1984).

Martian bedform migration rates range from 0.2 to 12 m per Earth year (Fig. 10). Given the large amount of data, only Nili Patera has undergone a detailed set of studies in which ripple and dune migration rates in various locations (Silvestro et al., 2010b), or throughout the dune field using orthorectified images (Bridges et al., 2012b), have been measured. The other bedforms were investigated using simpler techniques, without orthorectification (which requires a DEM), such that the most apparent motion, subject to parallax-induced uncertainties, was estimated. Comparing estimates of ripple migration rates using simple techniques (Bridges et al., 2012a) to the detailed Nili analyses (Bridges et al., 2012b) gives similar average values ($\sim$9 m yr^{-1}). This provides confidence that the range of values reported in published studies are approximately correct, with many dunes and ripples on Mars moving at rates of decimeters to several meters per year.

Over all of Mars, there is a rough negative correlation between dune migration rate and height (Fig. 10a), and within a single dune field (in this case Nili Patera), a tighter relationship (Fig. 10b). This is an expected trend given how dunes behave on Earth (Greeley and Iversen, 1985). As with terrestrial dunes, variability is attributable to differences in factors such as wind regime, sand cohesion, and local topography. For example, in Nili Patera, dunes in the upwind portion of the field have higher migration rates than those downwind (Bridges et al., 2012b). At our present state of analysis, with only three Mars years or less worth of data from HiRISE, the range of displacements is limited, constrained by where overlapping images are located, and subject to possible seasonal variations. The statistics of small values therefore makes assessing where motion is "fast" versus "slow" over the long term uncertain. Considering data at hand, however, the highest ripple and dune migration rates occur in Terra Meridiani (Chojnacki et al., 2011) and Nili Patera (Silvestro et al., 2010b; Bridges et al., 2012a,b), respectively.

In Nili Patera, the migration rate of superposed ripples is proportional to elevation on the dune surface (Bridges et al., 2012b). Given the standard assumptions that dunes maintain their shape and volume as they migrate, such a relationship is most consistent with the entire dune volume composed of mobile sand (the alternative, a rippled skin over an indurated core is theoretically possible, but would be short lived and therefore unlikely). Whether such relationships are apparent in other dune fields must await future study.

4.3. Sand flux

Sand flux can be estimated by combining bedform migration rate and topography. This requires precise orthorectification using terrain models and sub-pixel image registration (see above). So far, flux has only been measured at Nili Patera, with an average value of 2.3 m^3 m^{-1} yr^{-1} in the dune field, implying basalt abrasion rates of 1–50 μm yr^{-1} (Bridges et al., 2012b). This shows that significant landscape modification can occur under current conditions where there is sufficient sand and wind gusts.

4.4. Comparisons with Earth

Interplanetary comparisons on geologic processes are affected by selection bias. In the case of bedform mobility, terrestrial data are limited to what has been reported in the literature, which generally focuses on the movement of fairly active dune fields. For Mars, statistics are biased by the limits of image resolution and temporal baselines (Fig. 9), and affected by variable geographic sampling. Over time as more images are acquired, the limitations induced by temporal baselines and geographic sampling become less of an issue. Detailed terrestrial studies comparing dune migration rates to wind data are very limited (Fryberger, 1979) and for Mars are non-existent, save for comparing locations of movement to threshold frequencies predicted by GCMs, which show no correlation (Bridges et al., 2012a). So, the ideal case of comparing movement and threshold frequencies on one planet to another is not yet possible.

We are therefore left with data on bedform migration rate and size on the two planets. Based on the above discussion, we can consider these upper bounds, with lower rates either not extensively reported (Earth) or seen (Mars). From this perspective, we note that the "the world's (Earth's) fastest barchans," those in Bodélé, Chad (Vermeesch and Drake, 2008), move at rates 1–3 orders of magnitude faster than the comparably sized dunes of Nili Patera (Fig. 10), meaning that the derived terrestrial sand fluxes are 10–1000× greater. Similarly, the dunes of Nili Patera have comparable sand fluxes to those in Victoria Valley, Antarctica, yet ~1000× their volume, implying that dune formation time scales are about 1000× longer (pre-HiRISE estimates by Claudin and Andreotti (2006) put the value at 100,000× longer). The derived abrasion rates based on these fluxes are 1–50 $\mu m\ yr^{-1}$ (Bridges et al., 2012b), a result that agrees well with field-based abrasion rates in Victoria Valley of 30–50 $\mu m\ yr^{-1}$ (Malin, 1986).

The comparison of fluxes derived from dune ripple vs. dune lee front advance provides an estimate of the volumetric movement of sand from reptation (short hops) versus reptation + saltation (short hops + long hops), respectively (Bridges et al., 2012b). On Mars, this measurement has only been done in Nili Patera, where it is found that the saltation flux is about 4× that from reptation. This compares to a ratio of 1.5–9× computed for a range of shear velocities under terrestrial conditions (Andreotti, 2004). Therefore, the flux contributing to ripple and dune movement in Nili, and likely other places on Mars where saltation is active, is similar to that on Earth.

5. Discussion

5.1. Summary of current sand movement on Mars

If the reader is to take away one message from this and other recent papers on the topic, it is that sand movement can be a very active process on Mars, with rates of bedform migration and sand fluxes comparable to that found in many places on Earth. The key dataset to reach this conclusion has been the high resolution provided by HiRISE and the temporal baseline of many months to years to quantify bedform displacement. The results presented herein are but a snapshot in time; if HiRISE continues to operate in the coming years, the increasing temporal baseline, more observations to compile statistics, and associated analog field, experimental, and theoretical investigations will surely provide a more complete picture. At present, however, we are confident in several general conclusions regarding sand movement on Mars:

(1) *Bedform Migration is common, not rare:* It is our perspective that were it not for the Earth-like impact thresholds on Mars indicated by recent modeling (Kok, 2010), that HiRISE would not have found bedform changes to the extent and magnitude observed. With well planned observations and the techniques outlined above, at the HiRISE scale it is easy to identify bedform migration, whereas at lower resolutions it is hard or impossible. Bedform migration is a common process on Mars, with many areas having rates and sand fluxes like that found on Earth.

(2) *Clues to movement commonly point to activity:* Dunes exhibiting circumstantial evidence for activity, such as sharp brinks, crisp outlines, slip face landslides, and dark tone (a non-terrestrial property, given the basaltic nature of most Martian sand) are attributes that can be assessed using HiRISE, as well as MOC and lower resolution imagers. Although a detailed study comparing these characteristics to where HiRISE sees movement has not been done, qualitatively, the relationship commonly holds up. For example, where MOC showed these characteristics, such as dunes in the craters Kaiser, Proctor, and Rabe (Edgett and Malin, 2000; Malin and Edgett, 2001; Fenton, 2006), and the north polar erg (Malin and Edgett, 2001), migration is clearly seen by HiRISE. This gives confidence that predictions on where bedform migration is occurring can be made from single images, with time series required for verification and deriving rates. Nevertheless, some dark dunes on Mars show no activity (see #4 below), although this may change with future monitoring.

(3) *Bedform migration is pervasive in the north polar erg:* The one geographic region where ripple and dune motion is seen in every HiRISE change detection image pair (except for one uncertain case) is in the north polar erg. This is in contrast to other regions of the planet, where both static and mobile bedforms are documented. There are probably several reasons for this:

- First, because of katabatic winds from the high elevation, cold north polar cap, the fluid, and certainly the impact, threshold speed is likely exceeded much more frequently than in most other areas of Mars (unfortunately, the Ames and other GCMs do not extend to these latitudes and modeling of wind shear stresses in the erg has not yet been done).
- Second, dune migration pathways in the erg have been traced to the basal unit beneath the north polar layered deposits (Edgett et al., 2003; Fishbaugh and Head, 2005; Calvin et al., 2009; Massé et al., 2012), itself likely an ancient sand sea subsequently covered by ice. This indicates fresh sand that has not had sufficient time to become indurated, instead being continuously mobilized and transported by the winds.
- Third, being in the polar region, the dunes are covered with carbon dioxide frost in the winter. It has been proposed that springtime defrosting processes act to mobilize and loosen sand for subsequent wind transport (Hansen et al., 2011). Specifically: (1) basal sublimation beneath the CO_2 slab ice acts to entrain dune particles, most particularly at the brink, (2) frozen CO_2 ice chunks cascade down dune slip faces, promoting sand avalanches, and (3) sublimating dry ice lowers sand cohesion. However, this last point (3) is still controversial, with recent work showing that polar dune alcove production is due primarily to aeolian processes and independent of CO_2 sublimation (Horgan and Bell, 2012).
- A more minor factor may be the presence of gypsum that, based on infrared spectral signatures, is a component of the erg sand (Langevin et al., 2005; Massé et al., 2012). With a density of 2300 $kg\ m^{-3}$ compared to typical basalt at 3000 $kg\ m^{-3}$, gypsum should have a lower threshold friction speed.

(4) *Mobility of bedforms at other latitudes is variable:* Outside of the north polar erg, there are no obvious correlations of bedform mobility to latitude, geographic region or regional albedo. GCM-predictions of threshold frequency also fail to show any links. From MOC, it was known that many loca-

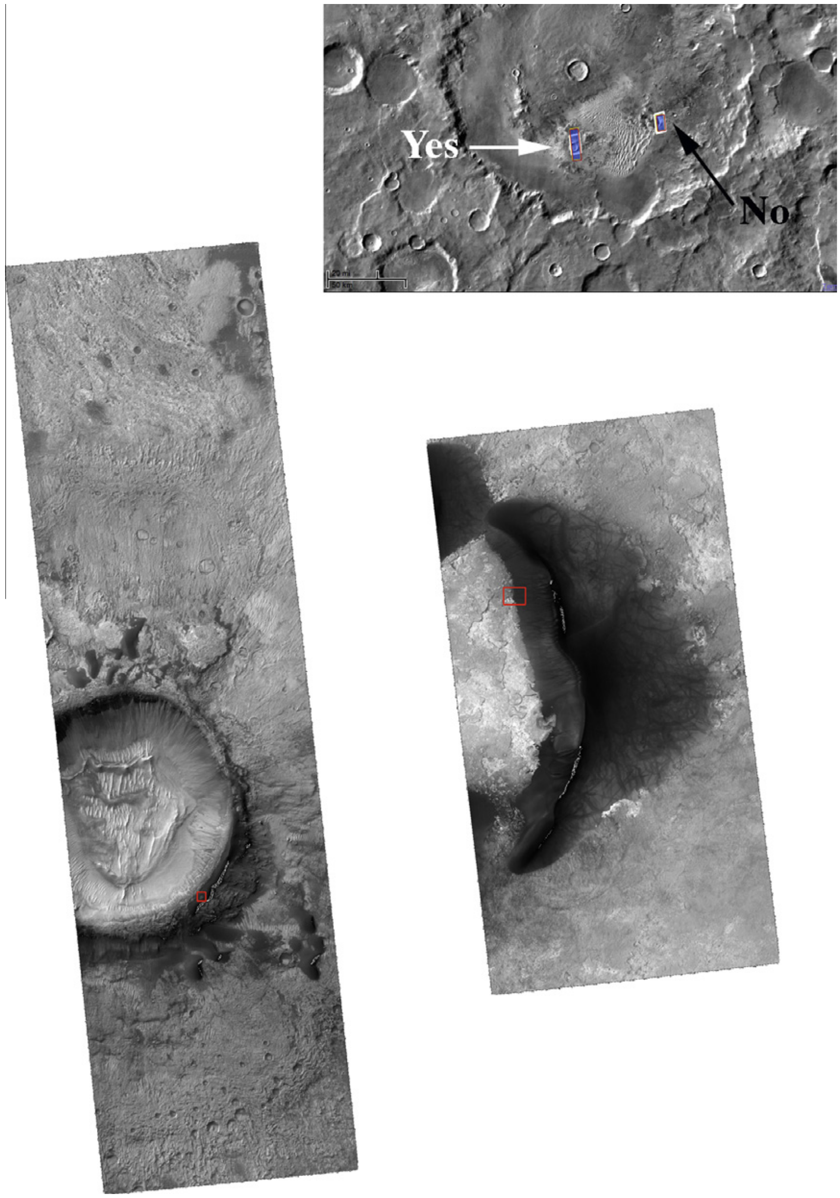

Fig. 11. Two HiRISE images 56 km apart within Kaiser Crater that show positive and negative evidence for bedform migration. The location of the two HiRISE targets and an indication of whether bedform motions is seen is shown here. Close-ups where the red boxes are located is shown in Fig. 12. Note the prominent dust devil tracks in the right image, suggesting that dust has accumulated on inactive dunes.

tions on Mars exhibit ripples and TARs overlain by dark dunes, indicating differences in mobility (Edgett and Malin, 2000). As is the case for dune fields on Earth (except that the dunes are light toned), HiRISE shows that even dark dunes with similar morphologies located a few 10s of kilometers apart can exhibit mobile and immobile states at the HiRISE scale (Figs. 11 and 12). These non-correlations can be attributed to local variations in (i) threshold frequency, (ii) bedform properties, and (iii) insufficient monitoring to decipher variable rates. In detail:

(i) The low impact threshold wind speeds on Mars (Kok, 2010), which can be invoked to explain much of the bedform movement observed, do not obviate the fact that fluid threshold speeds, that is the minimum necessary to start the process, are much rarer than on Earth in most areas of the planet. Local winds are strongly influenced by topography. Funneling through notches, acceleration over highs, sheltering from obstacles, and other configurations can all contribute to variable wind speeds. For example, in Nili Patera there is a clear decrease in dune ripple displacement, and by inference wind speed, downwind within the dune field, which can be attributed to sheltering from upwind dunes (Bridges et al., 2012b). Based on the significant displacements and sand flux in this area, the regional f_t is probably greater than in most other places on Mars, such that even wind speeds that are somewhat below average still imply mobility. However, elsewhere, the regional threshold frequency may be lower, such that only bedforms geographically positioned to receive winds whose speeds are increased by topographic effects will exhibit movement on short time scales.

(ii) Variations in grain size and induration can increase the threshold friction speed. As shown by in situ observations at the MER sites, many ripples are coated with coarse-grained sand and granules that were probably emplaced by saltation-induced creep (Arvidson et al., 2006; Greeley et al., 2004; Soderblom, 2004; Sullivan et al., 2005, 2008),

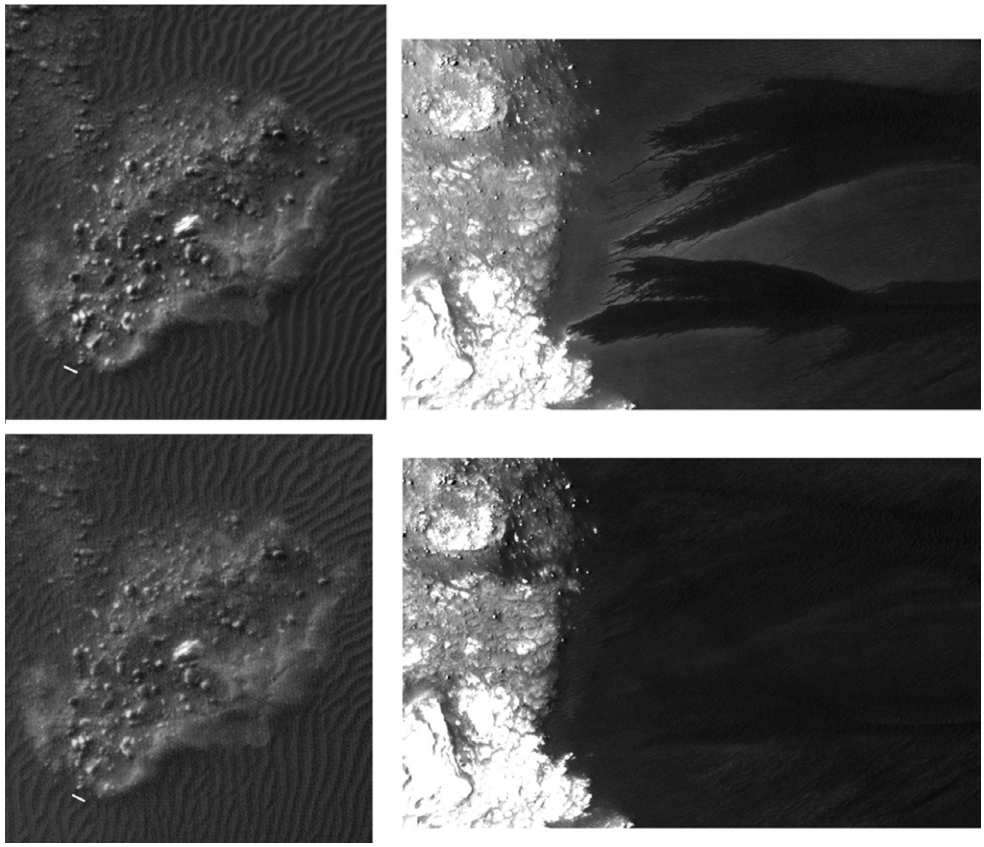

Fig. 12. Close-ups of positive and negative indications of bedform migration in Kaiser Crater. The location of these targets is shown in Fig. 11. The left footprint is for PSP_007110_1325 (2/1/08, top)/ESP_015918_1325 (12/18/06, bottom). The right footprint is for ESP_013584_1330 (6/19/09, top)/ESP_02221_1330 (4/23/11, bottom) where, although superficial changes in slope streaks are obvious, no bedform motion is discerned. As shown in Fig. 11, this area has prominent dust devil tracks, suggesting that the dunes have accumulated dust and are therefore inactive.

such that higher wind speeds than those needed to move the majority fraction of fine sand are needed for significant mobility. Many bedforms on Mars appear indurated and dust covered and must require very high speed winds to reactivate them. Older bedforms with coarse grains or that are indurated can be geographically distributed similarly to fresh sand, leading to local mixing of immobile and mobile bedforms. For example, in Fig. 12, the apparently immobile dunes and ripples, although relatively dark, also contain dust devil tracks, indicating a dust coating that may be both a result of and promote induration.

(iii) With a maximum of only three Mars years of observations from HiRISE, whether some bedforms in a region with nearby activity are truly immobile or just slower, cannot be reliably assessed. For example, the dark bedforms in Figs. 11 and 12 that appear immobile may show activity upon the analysis of future images.

5.2. Role of past climate

Bedforms that are immobile at the HiRISE scale because of anchoring by coarse granules or induration are unlikely to exhibit much or any movement under current Martian conditions. However, as discussed previously, climate changes on Mars can change the magnitude of surface winds and lower friction speeds by as much as 60%. Therefore, whereas the frequency of threshold winds needed to move coarse grains (whether by direct saltation or enhanced saltation-induced creep) or break through the crust of indurated bedforms is low or nil today, it was likely greater in the past. On the flipside, decreases in obliquity will result in higher threshold friction speeds and lower threshold frequencies. Therefore, the map of bedform movement on Mars is a proxy for longer-term movement as well. Bedforms that are immobile today are likely mobile in higher obliquity periods whereas currently mobile bedforms probably had even greater rates at high obliquity and more limited mobility under low obliquity.

5.3. Future research direction and techniques

Despite the attempts at a thorough review of Martian bedform migration herein, our understanding of this topic remains immature. We discuss here three areas of focus for which progress can be made by future investigators:

5.3.1. Continued acquisition and analysis of HiRISE Images

HiRISE data cover 1.7% of the Martian surface, with change detection images a small fraction of this. Statistics are biased to where images have been targeted. As more data are acquired and analyzed, we should be able to better relate the presence and rates of migration to geography, local topography, elevation, and other parameters. Similarly, migration rate data are constrained to the temporal baselines, currently limited to 3 Mars years, but with most image sets having time separations of a year or two. Lacking are multiple baselines for many areas, such that seasonal and year-to-year variations can be tracked, as has been done on Earth (Vermeesch and Leprince, 2012). Such data can address a number of questions, including: (1) whether migration rates and sand fluxes are sensitive to seasonal variations in atmospheric pressure.

Threshold friction speed is proportional to the square root of fluid density, such that the seasonal pressure variations of ~25% (Hess et al., 1980) should change friction speeds by ±50% about the mean. Because flux is proportional to the cubed power of excess shear velocity (the velocity above threshold) (Greeley and Iversen, 1985), this could lead to variations in sand flux of ~3× greater in northern winter/southern summer (when the southern cap sublimates) and ~90% less right before the northern fall/southern spring equinox; (2) do large-scale events such as global dust storms, which may affect near-surface turbulence, result in greater sand transport? Near-surface linear winds in storms can increase dramatically and get above threshold (Moore, 1985). Depending on duration, these may be able to move significant amounts of sand, or at the very least disrupt stable or indurated sandy surfaces, thereby lowering their cohesion and threshold speed.

5.3.2. Implementation of sub-pixel change detection in new areas

Sub-pixel change detection has been applied to only one area of Mars, Nili Patera (Bridges et al., 2012b; Ayoub et al., 2012). This is because the COSI-Corr technique, when combined with large HiRISE images, takes considerable time and effort to implement. This will change in the coming years, with plans to considerably improve ease of use and processing time, with the release of a HiRISE COSI-Corr package to the planetary community planned by 2014. Foci of investigation should be areas where: (1) bedform migration cannot be discerned visually, and (2) displacements are qualitatively apparent, but quantification is essential for addressing dune evolution and sediment transport.

For the former, COSI-Corr can detect displacements down to 8 cm or smaller compared to the HiRISE unbinned pixel scale of 25–32 cm, but in the Nili study all changes were supra-pixel (Bridges et al., 2012b). Studying areas for which changes are below the inherent HiRISE resolution will significantly increase the change detection resolution over that possible with earlier studies. For example, in the first planet-wide study of bedform migration on Mars based on HiRISE visual changes (Bridges et al., 2012a), there were several dune fields for which no displacements were detected. In addition, no migration of the enigmatic TARs was apparent. It may be that some Martian dunefields and TARs could have migration rates on the scale of centimeters per year as opposed to decimeters to meters. With COSI-Corr's ability to measure changes down to at least 8 cm, and with the approaching 4th Mars year of HiRISE observations, net migration rates as low as 2 cm per year are potentially detectable, with even finer discriminations in the future as the temporal baseline increases.

Regarding the 2nd focus, there are numerous areas where changes have been identified visually in HiRISE images (Silvestro et al., 2010b, 2011; Hansen et al., 2011; Bridges et al., 2012a). For example, the north polar erg is large and has several potential targets. The erg is intriguing because dune migration has been definitively identified in almost all areas examined. Seasonal frost condensation and sublimation might be linked to the erosion of the dunes (Hansen et al., 2011). Ripple patterns on dunes in Olympia Undae are complex. Pattern mapping in one area indicates an older ripple set formed by radial winds from the pole and a younger generation from circumpolar easterly to northeasterly winds that may have resulted from the development and channeling of flow through the Olympia Cavi reentrant (Ewing et al., 2010). Of the many intracrater dunes on Mars, obvious candidates for study are Herschel, Kaiser, Russell, Richardson, and Gale. All show evidence for movement (Bridges et al., 2012a; Silvestro et al., 2013) and each is worthy of a focused study for unique reasons. Herschel has complex ripple patterns that change dramatically over one Mars year, and slip faces which show significant advancement (Bridges et al., 2012a). Analogous to what seems to occur in the north polar erg (Hansen et al., 2011), but in this case within the southern seasonal cap, dunes in Kaiser, Russell, and Richardson craters all exhibit gullies and mobile sand that are probably linked to CO_2 frost accumulation (Diniega et al., 2010). Finally, nailing down the precise migration rate and sand fluxes in Gale Crater (Silvestro et al., 2013) could have important implications for interpreting results from MSL, which landed in Gale in August, 2012. In all of these, and other areas, the following can be derived:

(a) Mean, standard deviation, and direction of bedform displacements
(b) For dune ripples, amount of displacement as a function of elevation on dune surfaces
(c) Dune migration rate (length per time), derived from ripple displacement as a function of height on the dune or directly from lee front advance (if dunes have moved that far)
(d) Sand flux (volume per length per time) derived from migration rate and an estimate of bedform height

Each of these quantities will yield fundamental information about the aeolian geology and wind regime of the area, and Mars in general and help answer the following questions:

(a) What areas of Mars, of those sampled, show the greatest bedform displacements and sand fluxes? Is this tied to latitude (and possibly the presence of seasonal volatiles), geomorphic setting (e.g., polar vs. intracrater dunes), predicted GCM winds, or other factors?
(b) To what extent do bedforms which have not been observed to move based on traditional measurement techniques, actually move? If all are found to exhibit motion, this implies that many additional areas of Mars not examined in initial studies (Bridges et al., 2012a) actually contain active bedforms.
(c) Does ripple displacement correlate with dune height in areas besides Nili Patera (Bridges et al., 2012b)? If so, this indicates that these other dunes are also at steady state and migrate as integrated volumes of sand.
(d) How much sand is moved on Mars, and what does this tell us about the aeolian regime and rates of landscape modification on the planet? If it is found that sand fluxes are as great as determined in the study of Nili Patera, which are similar to those for Antarctic dunes (Bridges et al., 2012b), then it is likely that many areas of Mars are being abraded at comparable rates to those on Earth, perhaps explaining the vast fields of yardangs and exhumed mantles on the planet.

5.4. Technological advances

Technological advances in image processing and instrumentation promise to further increase our understanding of Martian bedform migration. For using COSI-Corr with HiRISE, decreases in processing time and improvement in the ease of use should expand both the number of sites investigated and users. Another potential improvement could be the use of 14-bit images to increase the radiometric precision over the 8-bit data that is the standard mode. This would lower quantization noise on dark sand dunes, allowing the discrimination of more subtle albedo differences. The Nili Patera analysis showed that change detection resolution was ~1/3 pixel (~8 cm) (Bridges et al., 2012b), the limit imposed by inherent CCD misalignment and jitter during image acquisition of the change detection sets and images used to make the DEM. However, there may be more stable images that can be used such that the theoretical limit of COSI-Corr, ~1/10 pixel (~3 cm) (Leprince et al., 2007), can be reached.

With MSL now exploring Gale Crater, and the presence of migrating dunes there as seen by HiRISE along the planned traverse route (Silvestro et al., 2013), a new opportunity will be presented to combine surface meteorological measurements with high resolution change monitoring. Two previous landed missions, Viking Landers 1 and 2 had anemometers, but HiRISE did not exist over their duration (1976–1982). The Pathfidner and Phoenix landers had a wind sock and a tell-tale, respectively, from which winds could be inferred. However, only Phoenix was active during HiRISE, had a limited mission duration (May–August 2008) and no nearby bedforms. MSL contains the Rover Environmental Monitoring Station that measures wind speed and direction, pressure, relative humidity, air and ground temperatures, and ultraviolet radiation (Gomez-Elvira et al., 2011). Potentially the wind speeds can be correlated to dune and ripple changes in Gale seen with HiRISE.

Farther in the future, instruments and missions beyond HiRISE and MRO can further increase insight into aeolian bedform migration on Mars. Higher resolution imagers and more stable platforms would significantly increase the detail seen on dunes and ripples, allowing more precise change measurements. A powerful synergy would be to augment such a package with a high resolution interferometer that measures the Doppler shift of CO_2, thereby providing an estimate of surface wind speeds (Amzajerdian et al., 2012). Combining wind speed data with surface changes would link wind parameters such as friction speed, gustiness, and flow patterns to bedform migration rate and sand flux, thereby providing a full picture of surface-atmosphere interactions.

The last few years have seen considerable advancement in techniques for measuring bedform displacements on Mars, with many profound, and some surprising, results. Our understanding is still evolving just with the data in hand. The next decade and beyond promises even further penetrating insight and discovery.

6. Conclusions

Mars contains a diversity of aeolian bedforms, many with characteristics like those found on Earth. Prior to MRO, studies were largely focused on the distribution, morphology, and sediment pathways of dunes. With the higher resolution provided by HiRISE, detailed measurements of ripple and dune migration, and derivation of sand flux and abrasion rates, are possible. Measurement objects include sand patches, ripple crests, and dune crests and boundaries. A range of change detection techniques can be employed, bounded by quick, yet simple methods on one end to lengthy, complex studies on the other. Sub-pixel registration and correlation can quantitatively measure displacements over an entire scene down to scales of 1/3 of a pixel or less (so $\sim\leqslant 8$ cm). Martian dunes and ripples migrate over diverse areas of the planet, with the north polar erg the most prevalent geographic region for displacement. As of yet, no geographic, latitudinal, local topographic, or albedo correlations, nor any linkage to results from global circulation models, have come from the analyzed data. Rather, migration may be tied to very local conditions where a sufficient frequency of gusts initiates saltation, which is then sustained by the low impact thresholds on Mars. Migration rates range from the limit of resolution to 12 m per Earth year. Sand fluxes have only been derived in one location on Mars, the Nili Patera dune field, at $\sim 2.3\ m^3\ m^{-1}\ yr^{-1}$. These values, and estimated rock abrasion rates of 1–50 $\mu m\ yr^{-1}$, are equivalent to those estimated in Victoria Valley, Antarctica. Mars therefore seems a planet for which sand bedforms are moving in many places. Past climates with faster wind speeds or lower threshold values in a higher density atmosphere are only necessary to explain migration of granule-coated or reactivation of indurated bedforms. Future techniques, instruments, and missions promise to further increase our understanding of dune and ripple movement on Mars.

Acknowledgments

Detailed reviews by Mary Bourke, Matthew Chojnacki, and an anonymous reviewer substantially improved the manuscript and are gratefully acknowledged. Bradley Thomson computed the threshold frequencies from the Ames GCM, as shown in Fig. 8. Support to NTB for this research was provided the Mars Reconnaissance Orbiter Project (HiRISE co-investigator) and NASA's Mars Data Analysis Program (NNH11ZDA001N). S. Silvestro is supported by a grant from the NASA's Mars Data Analysis Program (NNH09ZDA001N).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.aeolia.2013.02.004.

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