PLANET-WIDE SAND MOVEMENT ON MARS AS DOCUMENTED BY THE HIRISE CAMERA

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Introduction

Dunes, ripples, and sand sheets are abundant and widespread on Mars, with concentrations in the North Polar Erg and within craters and other depressions that trap sediment [1]. The abundance of aeolian bedforms attests to ancient rock breakdown mechanisms capable of producing large volumes of sand-sized particles and winds of sufficient strength and frequency to move and collect it into extensive deposits. Because of Mars' thin atmosphere, the threshold friction speed ($u*_t$) for movement of fine sand from linear wind shear is about 7-8 times greater than on Earth (using derivation of [2]). Based on lander measurements and global circulation models, the frequency of winds meeting or exceeding this value (f_t) is 10^{-3}-10^{-4} [3,4] in comparison to typical Earth deserts that have values of 0.01-0.02. This was considered consistent with 4 decades of orbital observations indicating no bedform movement at scales down to a few meters [5-8]. A fundamental question had therefore been whether bedforms can currently migrate on Mars given such high $u*_t$ and low f_t or movement requires a different climate, thereby constraining migration to a past epoch. The High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO), with a pixel scale down to 25 cm, high signal-to-noise, and with an orbital lifetime of over 2.2 Mars years (as of this writing), is the ideal instrument to address this question.

Hints of bedform migration or ambiguous results on the role of deflation vs. migration has come from earlier Mars Orbiter Camera (MOC), MER, and initial HiRISE data [5,7-11]. Prior to this report, published results using HiRISE showed no unequivocal migration except for Nili Patera, where ripples moved ~1.7 meters in less than 4 terrestrial months [12]. Although significant, this is but one location and not necessarily representative of conditions elsewhere on Mars.

Methods

Bedform monitoring has been a primary task from the beginning of HiRISE's active science phase in November, 2006. Two criteria are used: 1) Repeat imaging over a sufficient time baseline for migration to occur, and 2) acquisition of the same targets under similar lighting conditions such that changes can be tagged to true sand movement and not be subject to photometric effects. This means that change detection images are best acquired in different years and in the same season, which we generally constrain to within 10° of L_s.

Change detection images were overlaid and co-registered to common immobile tie points such as boulders or polygonal patterns on adjoining terrain. Movement was assessed by blinking between images. To minimize the effect of parallax, images with similar roll angles were used, if available. With HiRISE's pixel scale of 25 cm in unbinned map-projected images, changes on the order of a meter or smaller could be discerned. Change was quantified by noting offsets in the position of dune or sand patch contacts against underlying terrain or in the position of sand ripple crests relative to nearby tie points. For dunes, stoss and lee slope positions were documented in some cases, but only rarely could the crest line be confidently judged to move relative to nearby immobile features. Future analysis with digital elevation models should permit crest line migration studies.

Results

We have examined 57 repeat targets that contain dunes or ripples. Of these, 34 show no evidence for bedform planform changes or sand ripple migration. The remaining 23 show verifiable changes, of which 20 exhibit definitive movement of sand, with 3 showing features such as lee slope avalanches indicative of migration (Fig. 1). A map of where movement does and does not occur, including results from references 10 and 12, shows that sand is mobile at the meter and larger scales in virtually all of the North Polar Erg and indicates variability over the rest of the planet (Fig. 2). Prominent movement in non-polar areas include ripple migration in Nili Patera [12], Kaiser Crater, Herschel Crater, Rabe Crater, Matara Crater, and changes in sand patch distribution in Pasteur Crater and Meridiani Planum [10]. Sites where no change was detected are all located south of the North Polar Erg. At present this includes intracrater dunes in the southern highlands such as Proctor, Russell, Richardson and Newton Craters, and Cerberus Fossae. Seasonal gully activity has been documented in Proctor, Russell, Richardson, and Matara Craters [13], but sand motion is only found (so far) in the latter. All movement occurs in low albedo regions whereas immobile bedforms are found in both high and low albedo areas. Displacement rates range from decimeters to a few meters per Mars year.

Discussion

Given that some, but not all, bedforms move, we

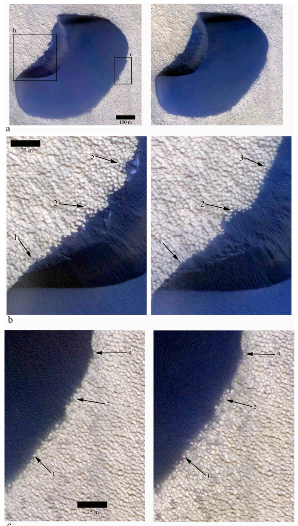

Figure 1: Changes in dune lee and stoss contacts on a barchan dune in the North Polar Erg. Left side: HiRISE image PSP_008968_2650, L_s = 90°, acquired on 6/25/08; right side: ESP_017895_2650, L_s = 94°, May 21, 2010. Numbers show common tie points between images.

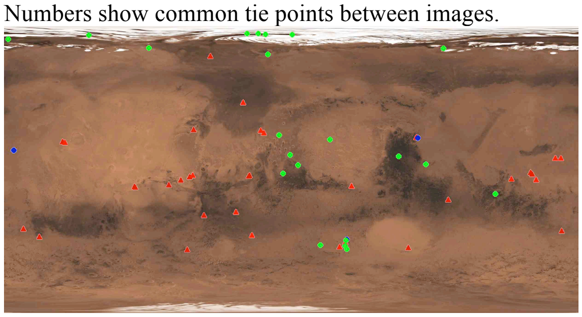

Fig. 2: Map showing detectable aeolian bedform major changes (green circles), minor changes (blue circles), and non-changes (red triangles) over temporal baselines of 1-2 Mars years seen in HiRISE images.

explore whether this is consistent with our understanding of saltation in the current Martian environment. Multiple measurements of ripples and dunes at a range of scales on Earth show that migration rate (r) is inversely proportional to height (h) with a power law relationship of $r = (x/h)^y$, with the terrestrial data fitting to x = 15.8 and y = 1.56 [Figure 5.29 in reference 14]. On average, dunes have spacings or lengths ~10 times their height [15,16]. Assuming such an aspect ratio for all measured bedforms and defining camera resolution as 3 pixels, MOC (max=~3 m/pixel for 2x2 binning needed for sufficient SNR on dark sand) and HiRISE (~0.3 m/pixel) can distinguish ripples of heights of 1 m and 0.1 m, respectively. Based on the lifetime of these imaging system (4.1 and more than 2.2 [so far] Mars years, respectively], migration rates of 2 m/year, and 40 cm/year can be detected, respectively. Taking f_t on Mars as 0.01 times the typical value on Earth and assuming that it is proportional to the migration rate implies that bedforms on Mars should migrate at average rates fitted to x = ~0.8. This implies that MOC should have seen just hints of activity and HiRISE should be able to see motion of bedforms 0.1 – 1 m in height. This is in agreement with our data.

Whether bedforms in which no migration is observed are truly immobile or migrate at rates below the spatial or temporal resolution of HiRISE cannot be determined. Based on the superposition relationships of large, granule-dominated, ripples relative to young craters, it seems that such bedforms have remained static for the last 50-200 ka [17] and it is unlikely that HiRISE will see their motion in the future. Below the resolution of HiRISE, however, the evidence for motion of fine sand is compelling, with rover tracks being erased [18], craters superposed on the ripples being filled with sand [17], and secondary ripples from winds funneled along the troughs [19]. Nevertheless, the lack of motion for dunes and sand ripples at the HiRISE scale either means that f_t is too low for the recognition of motion over 1-2 Mars years or bedforms are indurated or dust covered. Considering the latter case, a low f_t should allow significant induration and dust cover without disruption from blowing sand. Global Circulation Models show that changes in the magnitude of various winds can be driven strictly by the 50 ka Martian precessional cycle [20]. Therefore, where no sand migration is seen in HiRISE images, activity could very well have been more common on the scale of 10s of ka. The longer time scale obliquity and eccentricity cycles (10^5-10^6 years) upon which the higher frequency precessional cycle is superimposed can result in changes in atmospheric pressure with an associated decrease in threshold friction speed [21]. Such changes are probably needed to move granule ripples and to "reset" any sand dunes and ripples that become indurated or covered. Nevertheless, the present results show that winds in Mars' present low density atmosphere are sufficient to move dunes and ripples in many areas of the planet. A major climatic change with a thicker atmosphere is not required.

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