HIGH SAND FLUXES AND ABRASION RATES ON MARS DETERMINED FROM HIRISE IMAGES

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Introduction

The volumetric transport rate of sand, or flux, is a fundamental parameter that controls the rate of landscape modification. This process is responsible for the movement of ripples and dunes, as well as the abrasion of rocks and landforms. Measuring sand flux on Mars was previously not possible because of the lack of high spatial and temporal resolution images, and appropriate techniques, for making displacement and accurate topographic measurements. These limitations have now been overcome because, 1) It is found that many dunes and ripples on Mars are mobile in High Resolution Imaging Science Experiment (HiRISE) images [1-4], and 2) the application of precise image registration and correlation methods permits the quantification of movement to sub-pixel precision that, when combined with topographic data, can be used to derive the sand flux.

Sand transport occurs via two modes, saltation and reptation [5,6]. Saltation occurs in long hops initiated from aerodynamic shear and subsequent propagation as grains are rebounded or ejected downstream. Reptation operates via shorter hops resulting from the "splash" ejection induced by the collision of upwind saltating grains. Reptation contributes to the migration of ripples whereas both processes result in the net movement of dunes. Therefore, by knowing the rate of movement of these bedforms and their volume, the reptation and saltation flux can be estimated.

Here, we measure the migration rate of sand ripples and dune lee fronts at Nili Patera, Mars. From these data, we derive the reptation and total (reptation + saltation) fluxes, respectively. The dunes have unexpectedly high sand fluxes that are like those in Victoria Valley, Antarctica, implying that rates of landscape modification on Mars and Earth are similar.

Methods

Recent advances in image registration and correlation techniques permit the quantitative measurement of changes down to the sub-pixel level. This has been implemented in the Co-registration of Optically Sensed Images and Correlation (COSI-Corr) tool suite, which provides quantitative surface dynamics measurements via automatic and precise ortho-rectification, co-registration, and sub-pixel correlation of images [7]. Structural and geomorphic changes as diverse as fault offset and sand dune migration, respectively, have been measured using Earth satellite data [8,9]. Under a Mars Data Analysis Program effort, we have used COSI-Corr on HiRISE images, with the goal of quantifying bedform changes on Mars at scales ranging from ~1/10 pixel (~3 cm) to several pixels (a few meters). As a first use of the application, we chose the Nili Patera dune field, where unambiguous ripple motion has been identified [1,4].

Four images were used in our analysis (Table 1). ESP_017762_1890 (subsequently designated *S*1) and ESP_018039_1890 (*S*2) were processed to make a stereo-derived digital elevation model (DEM). PSP_004339_1890 (*T*1) and PSP_005684_1890 (*T*2) were draped onto the DEM to make an orthorectified model. With a bedrock base containing fine-scale textures, the mean mis-registration was 4 cm E-W and 8 cm N-S, which is effectively the lower limit of bedform displacement that can be measured. In processing orthorectified images *T*1 and *T*2 through COSI-Corr, the displacement of ripples across the entire dune field in the overlap region was computed. In addition, using the registered image *S*1 and comparing to *T*2, the displacement of dune lee fronts was measured.

Table 1: HiRISE Images Used For Analysis

Image ID	L_S(°)	Date Acquired	ΔDays
PSP_004339_1890	268	6/30/07	0
PSP_005684_1890	330	10/13/07	105
ESP_017762_1890	89	5/11/10	1046
ESP_018039_1890	99	6/2/10	1068

At 1 m post spacing, the DEM cannot resolve individual ripples, but estimates of ripple height were made by: 1) Measuring 5 ripple trains consisting of 9-13 ripples each and assuming height-spacing ratios like those on Earth and for larger Martian megaripples of ~1:10 [10,11]. This gives a mean crest height of 46±9 cm. 2) In seven areas the shape of ripples was clearly delineated where in contact against the bedrock. Using the local slope of the dune and the profiles of the ripple projections onto the bedrock, an estimate of the ripple height of 35±3 cm was obtained. Combined, we estimate the mean height (crest to trough) of Nili dune ripples at 20±6 cm.

Results

The two results from the data analysis are: 1) Ripple displacement increases with elevation on the dune stoss slopes. This linear relationship is consistent with the behavior of steady state migrating dunes in which mass is conserved while shape and volume are maintained [12], and increasing wind shear stress with dune elevation [13,14] 2) Except for localized slumps [1,4], dune lee fronts do not move in the 105 day *T*1-*T*2 interval, but show measurable advance between *S*1 and *T*2.

Interpretation

The ripple and dune migration rates are related, as they both reflect sand transport, and can be used to estimate sand flux. The reptation sand flux is estimated by multiplying the ripples' migration rate (d_r) by their average height (h_r). Assuming the reptation sand flux equals that of the whole dune, the dune migration rate is $d_r h_r/(h_D t)$ where h_D is local dune elevation and t is time (105 Earth days). This can be computed over the entire dune study area, giving a histogram of dune migration rates that peaks at an average value of ~0.1 m/yr (Earth year). This distribution is consistent with the dune speeds derived from linear fits to the selected ripple profiles that range from 0.03±0.01 to 0.27±0.08 m/yr. Baselining the dune migration rates derived from lee front advancement to a year shows that the lee-derived rates are approximately 5 times larger than the ripple-derived rates. The higher values characterize the contribution of the saltation sand flux that is not considered in the correlation of ripples-to-dunes-derived fluxes.

Multiplying the dune migration rates by their maximum heights (h_{Dmax}) gives sand fluxes at the dune crests ($Q_0 = d_D h_{Dmax}/t$, where d_D is dune displacement) [9]. The calculated mean fluxes assuming reptation only and reptation+saltation are 2 and 10 m^3/m/yr, respectively. This is comparable to sand fluxes for dunes in Victoria Valley, Antarctica based on their crest heights and migration rates [15]. Terrestrial studies show that bulk and interdune sand fluxes are about 1/3 that of the crest flux [12], such that typical fluxes in Nili should be ~3 m^3/m/yr.

Discussion

How can such large sand fluxes occur on Mars, given the low frequency of winds above threshold? The answer probably lies in fundamental differences in how saltation and reptation physics operate on Mars compared to Earth. On Earth, the impact threshold is about 80% the fluid threshold [16]. However, because of the higher and longer saltation trajectories on Mars [17], grains are accelerated to a greater fraction of the wind speed than on Earth, resulting in impact threshold wind and particle speeds that are only about 10% the fluid threshold, equivalent in magnitude to that on Earth [18]. Therefore, once saltation is initiated by low frequency gusts, moderate wind speeds can maintain significant fluxes of sand.

These fluxes can be used to estimate the abrasion of rocks on the surface. The abrasion susceptibility, S_a, is the ratio of the mass of sand expended to that of rock eroded. For basalt grains impacting basaltic rocks under fluid threshold Martian conditions, $S_a = 2\times10^{-4}$ [19]. However, S_a is proportional to the kinetic energy of grains, such that at impact threshold the susceptibility should be ~2×10^{-6}. Taking the average flux above of 3 m^3/m/yr and distributing over an area vertically bounded by the typical 0.1 m mean saltation height on Mars [18], the abrasion rate would be 60 µm yr^{-1}, similar to field measurements of basalt abrasion rates in Victoria Valley of ~30-50 µm yr^{-1} [20]. This shows that both fluxes and computed abrasion rates in Nili Patera are similar to an active aeolian environment on Earth.

These results demonstrate that large volumes of sand move on Mars in the present environment. This helps explain why Mars dunes, although migrating at rates smaller than many terrestrial dunes [4], have fresh appearances consistent with active saltation. The high abrasion rates imply significant rates of landscape erosion in areas containing sand and wind gusts. Such material removal may be the primary mechanism for the exhumation process that has removed mantled materials over much of the planet [21].

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