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An integrated model for dune morphology and sand fluxes on Mars

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ABSTRACT

The transport and deposition of sand is the most prevalent agent of landscape modification on Mars today, with fluxes comparable to some sand dunes on Earth. Until now, the relationship between sand flux and dune field morphology has been poorly constrained. By tracking dune movement over ∼10 km-long dune fields in Herschel Crater and Nili Patera, representative of many dune fields on Mars, we find a downwind flux decrease that correlates with a sequence of changing morphology from barchans to barchanoids and seifs (longitudinal dunes) to isolated dome dunes and ending with sand sheets. We show empirical consistency with atmospheric Internal Boundary Layer (IBL) theory which can describe these broad flux and morphology changes in Martian dune fields. Deviations from IBL flux predictions are from wind streamline compressions up slopes, leading to a speedup effect. By establishing a dune field morphology type example and correlating it with measured and predicted flux changes, we provide an integrated morphology and flux model that can be applied to other areas of Mars and be used to infer paleo-environmental conditions from preserved sandstone.

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1. Introduction

1.1. Martian aeolian environments

The Mariner 9 orbiter returned the first data indicating the presence of aeolian bedforms on Mars (Sagan et al., 1972). Sand dunes are now known to cover all major latitude zones (Hayward et al., 2007) and are common in craters, basins, the north polar region, and in the lee of topographic obstacles such as crater rims. With the exception of vegetated (e.g. parabolic) dunes, all of Earth's dune forms are represented on Mars: barchan, barchanoid, transverse, seif (or longitudinal), star, reversing, and dome. Mars' dunes are mobile and are not relicts of past Martian climates (Silvestro et al., 2010; Bridges et al., 2012). In contrast to Earth, the aeolian processes responsible for dunes and other bedforms on Mars are unhindered by most other geomorphic agents, especially water. Indeed, on Mars the movement of sand and dust is the dominant process of geomorphic change in the current climate. The inferences gained from understanding regional and global sand transport pathways and erosional regimes provide constraints on current and past Martian climate (e.g. Grotzinger et al., 2005) and landscape evolution, in particular interpreting aeolian stratigraphy (Grotzinger et al., 2013; Milliken et al., 2014) and reconstructing paleoclimates, as has been done in terrestrial aeolian systems (Hunter, 1977; Clemmensen and Abrahamsen, 1983; Eastwood et al., 2012).

Given the need to understand modern dune patterns and sand flux variations, and to interpret paleoenvironments evidenced in sandstone stratigraphy, we establish links between modern sand fluxes, dune morphology sequences, dune height, and flux predictions from Global Circulation Models (GCMs). By combining the results of surface roughness changes and the GCM, we show consistency between measured and predicted fluxes for three sites. Two aeolian regions on Mars within the 300 km-diameter Herschel Crater (centered at 14°S, 130.1°E) and one region within the Nili Patera caldera (8.8°N, 67.3°E) serve as these case studies (Fig. 1), in which we used HiRISE (the High Resolution Imaging Science Experiment (McEwen et al., 2007)) images to measure dune height (from stereo digital elevation models), dune slip face advancement (Fig. S1), dune morphology (Fig. 2), ripple migration (Fig. 3), and dune volumetric crest flux across temporally-spaced images (see Text S1 in the Supporting Information).

The western and eastern Herschel Crater and the Nili Patera dune fields show similar dune morphological trends downwind in

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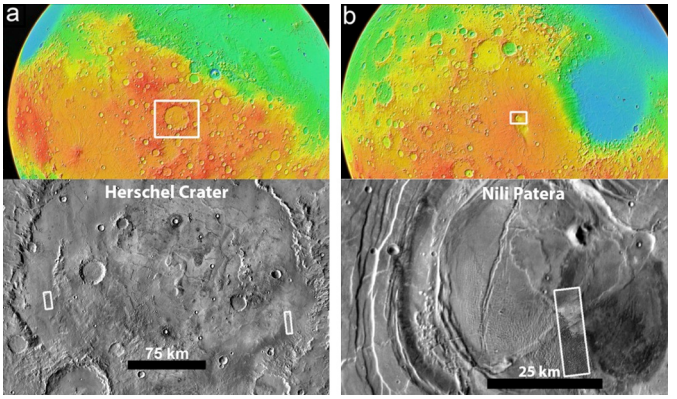

Fig. 1. An overview of the locations (white boxes, top) of (a) Herschel Crater and (b) Nili Patera. Western and eastern Herschel dune fields are boxed in the lower blow-up of Herschel (a), corresponding to available HiRISE coverage. Global views are MOLA colored topography from GoogleMars where warm colors indicate higher elevations than cooler colors. Regional images are HiRISE embedded in daytime THEMIS mosaics from JMARS (Christensen et al., 2009). North is up. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

which the dune morphologies transition from classical barchans to sand sheets (Fig. 2) and have been described by Cardinale et al. (2012, 2016). We identify this morphological trend as an illustrative type-example of dune field (Fig. 2). Importantly, their upwind margins are sharply defined and they all sit on bedrock as opposed to a sandy substrate.

Geomorphologically, some dunes exhibit asymmetry. Asymmetric barchans in western Herschel alternate between the west and east horns being longer whereas in eastern Herschel the west horns are more consistently longer. Dunes in Nili Patera, in contrast, are highly symmetric with relatively few dunes exhibiting horn asymmetry. Whereas our case study sites are constrained by the HiRISE footprints (necessary for temporal comparison of small scale features), broader Context Camera (CTX; (Malin et al., 2007)) images reveal the dune fields extending for many kilometers with the same broad morphological evolutionary sequence. Within this broader view provided by CTX, the long axes of barchans rotate a few degrees, suggesting a regionally varying resultant sand transport azimuth; this is substantiated by Cardinale et al.'s (2016) measurement of slip face directions.

1.2. Internal boundary layer theory applied to aeolian systems

Atmospheric and field studies on Earth show that flat-plate internal boundary layer (IBL) theory applied to the inland White Sands dune field accurately predicts the measured sand fluxes downwind and that this flux decrease corresponds to a spatially evolving dune morphology (Jerolmack et al., 2012; Anderson and Chemacki, 2014); this has also been applied to coastal aeolian systems (Rasmussen, 1989). Dunes acting as roughness elements to the oncoming wind reduce the wind's shear stress downwind, either from the initial upwind roughness transition (Jerolmack et al., 2012) or from the field-wide roughness (Pelletier, 2015). Either way, the heterogeneous dune roughness controls IBL flow, shear stress, and therefore sediment flux at White Sands (Pelletier, 2015).

An IBL forms when an increase in surface roughness, such as the wind transitioning from blowing over bedrock to dunes, acts as a momentum sink and greatly increases turbulence (Anderson and Chemacki, 2014). At least one manifestation of this turbulence is in the form of Kelvin–Helmholtz instability rollers which form behind upwind dunes and impinge upon downwind dunes (Anderson and Chemacki, 2014). Due to turbulence and drag, momentum retardation diffuses upward and advects downwind such that the IBL thickens downwind (McLean and Smith, 1986). The region within

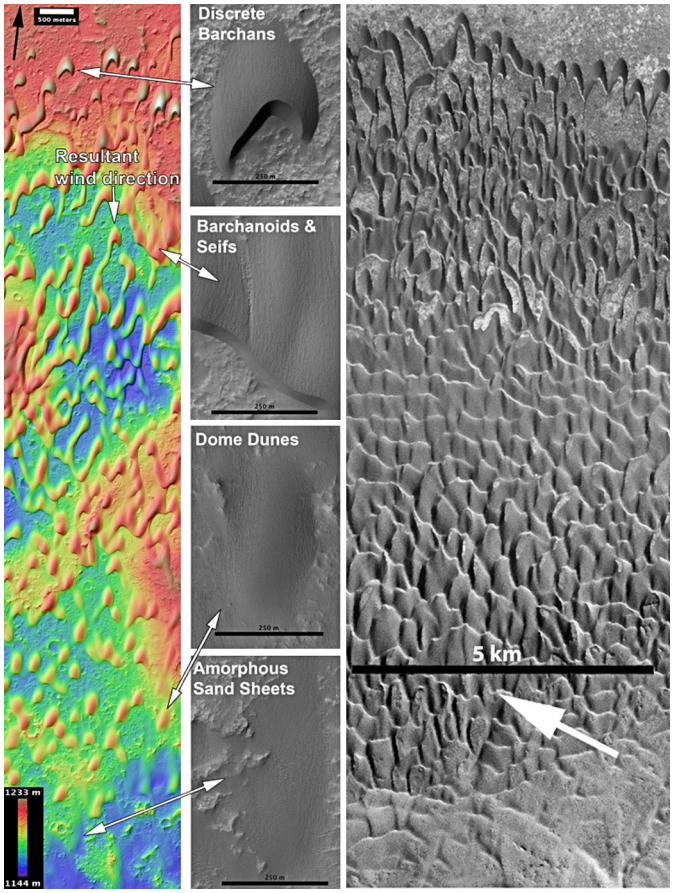

Fig. 2. The western Herschel Crater dune field (far left, height-colorized HiRISE DEM) and Nili Patera dune field (far right, CTX image) are type examples of a changing morphology downwind from barchan, to barchanoid and seif, to dome dunes, to sand sheets, each with successively lower heights and sand fluxes (north is indicated in each with a single-ended arrow; they have been rotated so that "downwind" is down). The term "downwind" is with regards to the apparent resultant transport direction evidenced by dune orientation. Less frequent but obliquely-blowing winds (up to angles $>90°$) likely produce asymmetrical dune elongation (Courrech du Pont et al., 2014), but obliquity effects are averaged over the several years between observations. The effect of obliquity on our IBL model may be to merely add a noise component. This morphology change is consistent with a decrease in downwind sand flux from the formation of an IBL, as observed at the White Sands dune field on Earth (Jerolmack et al., 2012). Note that the DEM is absolute elevation above Mars' datum. DEM credit: NASA/University of Arizona/USGS; HiRISE subscenes from PSP_002860_1650; CTX image B21_017762_1891_XN_09N292W, Credit: NASA/MSSS. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the IBL is thus where the speed and shear stress are significantly different from upwind conditions (Garratt, 1990). The downwind thickening of the IBL occurs within the Atmospheric (or Planetary) Boundary Layer (ABL), which is a well-mixed turbulent layer of atmosphere between the Sun-heated ground and the stably stratified free atmosphere above. ABLs can be several km thick, and depending on the heat capacity of a planet's atmosphere may collapse (e.g. Savijarvi and Maattanen, 2010) to nearly zero height above the ground at night, as is often the case on Mars and is in accordance with our GCM.

Inspired by a similar geomorphological sequence observed at White Sands (Kocurek et al., 2010; Jerolmack et al., 2012) as in our Martian case study sites, we test the hypothesis that IBL theory can likewise describe the measured flux changes. Cardinale et al. (2016) hypothesized IBL-controlled sand fluxes for Herschel Crater dunes but did not test the hypothesis. Our work is the first time IBL theory has been quantitatively applied to Martian dune fields

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