Icarus 230 (2014) 81–95

Contents lists available at ScienceDirect

Icarus

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

Constraints on Mars' recent equatorial wind regimes from layered deposits and comparison with general circulation model results

E. Sefton-Nash [a,*], N.A. Teanby [b], C. Newman [c], R.A. Clancy [b], M.I. Richardson [c]

[a] Department of Earth and Space Sciences, University of California Los Angeles, 595 Charles Young Drive East, Los Angeles, CA 90095, USA
[b] School of Earth Sciences, University of Bristol, Queen's Road, Bristol BS8 1RJ, UK
[c] Ashima Research, 600 S. Lake Ave., Suite 104, Pasadena, CA 91106, USA

A R T I C L E I N F O

Article history:
Received 30 March 2013
Revised 6 November 2013
Accepted 11 November 2013
Available online 20 November 2013

Keywords:
Aeolian processes
Atmospheres, dynamics
Geological processes
Mars, climate
Mars, surface

A B S T R A C T

Aeolian modification has been a fundamental surface process on Mars throughout the Amazonian. Orientations of aeolian features such as bedforms and yardangs are controlled by the prevailing wind regime during the feature's formation. Therefore, observation of recently formed bedform orientations provides a way to probe Mars' recent wind regime and constrain/test general circulation models (GCMs). We collect statistical distributions of transverse bedform and yardang azimuths at nine sites on Mars, and compare measured feature orientations to those predicted by using vector wind field output from the MarsWRF GCM.

We focus on layered deposits because their erodible nature makes them applicable to determination of Mars' modern wind regime. Our methods of mapping from the long-term wind field to predicted feature orientations include consideration of wind stress thresholds for sand movement to occur, sand flux equations, and the direction of maximum gross bedform-normal transport. We find that all methods examined typically agree with each other to within $\sim 15^{\circ}$, though there are some exceptions using high order wind stress weightings with multi-directional annual wind fields. Generally, use of higher wind stress thresholds produces improved matches to bedform orientations.

Comparison of multiple yardang orientations to annually variable wind fields is accomplished by inspection of directional maxima in modelled wind vector frequency distributions. Yardangs match well to model predictions and sub-populations in close proximity to each other are shown to match individual directional maxima in GCM output for a single site, implying that topographic effects may produce very localised unidirectional wind fields unresolved by the GCM.

1. Introduction

Aeolian features on Mars' surface are transient on a range of timescales. Relatively short-lived features such as wind streaks and active dunes are representative of present-day surface wind regimes, while less transient features such as yardangs and transverse aeolian ridges are a product of the time-integrated, changing wind regimes over longer timescales. In this study we compare orientation distributions of bedforms and yardangs to examine agreement between their inferred formative wind fields.

Aeolian feature orientations, morphology, and (in the case of active bedforms) movement may be used to infer aspects of the wind environment in which they formed. While some information may be extracted without employing atmospheric models at all (e.g., Ewing et al., 2010), additional insight can often be gained by comparing with model results, whether they are global (~degree scale) general circulation models (GCMs) or high-resolution (~km scale) mesoscale models. Equivalently, comparison between observed aeolian features and predicted surface wind fields can be used to validate the capability of a present day atmospheric model (if the bedforms are known to be currently active) or even to assess a paleo-climate simulation. A simple comparison of dune faces with model-predicted present-day prevailing/dominant winds (e.g., Fenton et al., 2005; Hobbs et al., 2010) provides a basic means of assessing whether dunes are currently active or may have formed in a past wind environment. However, because aeolian features are produced according to the time-integrated effect of the full wind field in a non-linear manner, more complex approaches have also been used that combine model output with dune formation theory to map winds to aeolian features, and predict, e.g., the movement and orientation of sand dunes. For Mars, modelled wind fields have been used in this way at global scales (e.g., Hayward et al., 2009) and also for some mesoscale (~km resolution) regions (e.g., Fenton et al., 2012; Newman et al., 2012). Previous comparisons of aeolian feature orientations with those predicted from Mars GCMs

* Corresponding author.
E-mail address: e.sefton-nash@uclmail.net (E. Sefton-Nash).

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.11.014

(Haberle et al., 1993; Greeley et al., 1993; Gardin et al., 2012) have shown that there is often not agreement between modelled present-day wind vectors and those inferred from the orientations of aeolian features, at least when rather straightforward mappings between winds and aeolian features are assumed (e.g., when yardang orientations are compared to the seasonally-averaged wind directions predicted by a GCM). Climate forcing by the combination of orbital eccentricity cycles and precession of Mars spin axis (Ward, 1979a) has been shown by Fenton and Richardson (2001) not to cause sufficient change to surface wind fields to account for the observed disagreement, for obliquity <45°. More significant changes to the surface wind field have been noted for obliquities exceeding 45° (Newman et al., 2005). It has also been suggested that changes to local topography, climate or polar wander may also have occurred (Fenton and Richardson, 2001). However, several other factors may also contribute to the disparity, including (but not limited to): (i) low GCM resolution compared to local topographic variation (meaning that the model cannot properly capture the feature-forming wind field); (ii) uncertainty in properties that can influence erosive or depositional behaviour and therefore feature orientation (such as sediment availability, grain size distributions, and fine-scale surface roughness), or (iii) choice of numerical technique employed to map GCM surface wind vectors to predicted feature orientation (see Section 3.2). Hayward et al. (2009) found a better match between modelled wind directions and slip face orientations using a mesoscale model than with a GCM, demonstrating the likely importance of (i) – i.e., increased atmospheric model resolution which we intend to pursue in future work (see Sections 5 and 6). The uncertainties listed in (ii) are certainly likely to be important too, but require data that are unavailable at this time. In this work, we therefore focus on (iii) i.e., the methods by which we map from model wind stresses to predicted feature orientations. The selection of appropriate numerical relationships to use here is impeded by gaps in our understanding of sediment transport, formation of bedforms, and rock erosion, both for Mars and in general.

Surface wind dynamics and erosion rates on Mars differ greatly from those on Earth, but relationships developed through field observation, laboratory experiments, and modelling form the basis for much of our understanding of aeolian processes on Mars (e.g., Bagnold, 1941; Greeley et al., 1982; Bitter, 1963a,b; Merrison et al., 2008; Rubin and Hunter, 1987). More recently, in situ and orbital observations have yielded erosion and sediment transport rates in selected locations (Sullivan et al., 2005; Bourke et al., 2008; Golombek et al., 2010; Fenton, 2006; Silvestro et al., 2010, 2011, 2013; Bridges et al., 2012a,b).

Whereas some aspects of Mars' erosional environment are well-constrained, others are largely unknown (e.g., sediment availability, grain-size distributions and material strength). In an attempt to better understand the remaining disparities between predicted and observed aeolian features, we test a range of numerical mappings between wind vectors output by the MarsWRF GCM (Richardson et al., 2007; Toigo et al., 2012) and predicted bedform orientations (see (iii) above). These are described in detail in Section 3.2; here we merely note that the formation mechanisms for bedforms (depositional features) and yardangs (erosional features) are very different. Bedforms and yardangs will therefore reflect different aspects of the wind regime and thus different weightings, or numerical mappings, of the GCM outputs.

Bedforms are initially built from scratch via the accumulation of sand, while yardangs are produced by the removal of rock material from around the sides of an existing feature as the wind is deflected around it. As an example, we would expect a unidirectional wind field to produce transverse dunes (or barchan where sand supply is limited) with crests oriented normal to the wind direction, but we would expect the same wind field to produce yardangs oriented parallel to the wind direction, i.e., at 90° to the dunes. For more complex wind regimes, however, theory suggests that dunes will form with an orientation that maximises gross bedform-normal transport (GBNT) of sediment (Rubin and Hunter, 1987) (see Sections 2.2 and 3.2), while yardang orientations may perhaps be more controlled by the dominant sediment carrying wind direction (see Section 2.3). Thus a 90° offset between bedform and yardang orientations need not generally occur.

In this study we use the term 'bedforms' to refer to features that may include transverse dunes and transverse aeolian ridges (TARs), that may or may not be active under present-day wind regimes (Balme et al., 2008; Zimbelman, 2010) (also see Section 2.2). It is unclear whether TARs originate as small dunes (formed by saltation) or large ripples (formed by creep), but in either case their transverse and sedimentary nature suggests that their orientation should be controlled by GBNT, and upper limits on their age may be constrained by the crater retention age of their host surface.

We compare our predictions to the observed populations of bedforms and yardangs at nine sites (Figs. 1 and 2) selected for their highly wind-eroded nature. Sites are constrained to locations of fine layered deposits (FLDs), which occur predominantly at low latitudes, have highly eroded sedimentary surfaces, young crater retention ages and are typically elevated above the surrounding terrain (Catling et al., 2006; Okubo et al., 2008; Sefton-Nash et al., 2012; Warner et al., 2011) making them more susceptible to erosion by oncoming winds due to topographic forcing.

In order to place upper limits on the age of the least transient wind-eroded features, we also derive model crater retention age fits to established isochrons for young surfaces with populations of small diameter craters (Hartmann, 2005). This study benefits from the use of high resolution (25–60 cm pixel^{-1}) images acquired by the High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007, 2010) instrument on Mars Reconnaissance Orbiter (MRO), which resolves small diameter craters and fine detail on eroded surfaces.

2. Study sites

2.1. Fine layered deposits

FLDs, also referred to as interior layered deposits (ILDs) if in chaotic terrains, are easily eroded deposits characterised by their high albedo, visible layering at a variety of scales and low crater densities (Lucchitta et al., 1992; Catling et al., 2006; Okubo, 2010; Ansan et al., 2011; Flahaut et al., 2010; Fueten et al., 2010; Sefton-Nash et al., 2012). Regardless of their formative mechanism, their most recent history has been dominated by aeolian modification (e.g., Fig. 3B). FLDs have been identified in chaotic terrain, crater interiors, among spur-and-gully wall units, and inter-crater terrain (Malin and Edgett, 2000; Chojnacki and Hynek, 2008), but are generally confined to the martian tropics and subtropics. FLDs are commonly elevated above the surrounding terrain which, combined with their generally friable nature, likely makes their surfaces accurate recorders of recent wind directions.

2.2. Identifiable aeolian features I: bedforms

Aeolian bedform type is largely determined by the wind regime and the availability of mobile material. Martian dunes (Fig. 3E and F) are mostly transverse and crescentic (barchans). Rare dune types include longitudinal (Breed et al., 1979; Lee and Thomas, 1995; Hayward et al., 2007) and star (Edgett and Blumberg, 1994) dunes, which indicate predominantly unidirectional (McKee, 1979) and multi-directional wind regimes, respectively.