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1 Constraints on Mars' recent equatorial wind regimes
2 from light-toned layered deposits and comparison with
3 general circulation model results

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10 **Abstract**

11 Aeolian modification has been the dominant surface process on Mars
12 throughout the Amazonian. Orientations of aeolian features such as dunes
13 and yardangs are controlled by the prevailing wind regime during the fea-
14 ture's formation. Therefore, observation of recently formed bedform orienta-
15 tions provides a way to probe Mars' recent wind regime and constrain/test
16 general circulation models (GCMs). We collect statistical distributions of
17 transverse dune and yardang azimuths at nine sites on Mars, and compare
18 measured feature orientations to those predicted by using vector wind field
19 output from the MarsWRF GCM. We focus on interior layered deposits be-
20 cause their young surface age (0.1-10Ma) and erodible nature makes them
21 applicable to determination of Mars' modern wind regime. Our methods of
22 mapping from the long-term wind field to predicted feature orientations in-
23 clude consideration of wind stress thresholds for sand movement to occur,
24 sand flux equations, and the direction of maximum gross bedform-normal
25 transport. We find that all methods examined typically agree with each
26 other to within $\sim 15^\circ$, though there are some exceptions using high order
27 wind stress weightings with multi-directional annual wind fields. Generally,
28 use of higher wind stress thresholds produces improved matches to dune ori-
29 entations.

30 Comparison of multiple yardang orientations to annually variable wind
31 fields is accomplished by inspection of directional maxima in modeled wind
32 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 localized unidirectional wind fields unresolved by the GCM.

Keywords: Mars, aeolian, GCM, palaeoclimate, dunes, yardangs, GBNT

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, ventifacts and fretting are a product of the time-integrated, changing wind regimes over longer timescales. In this study we compare orientation distributions of dunes and yardangs to examine agreement between their inferred formative wind fields.

Aeolian feature orientations may be used to validate the capability of global circulation models (GCMs) to predict surface wind fields. Previous comparisons of aeolian feature orientations with those predicted from Mars GCMs (Haberle et al., 1993; Greeley et al., 1993; Gardin et al., 2012) have shown that there is often not agreement between modelled wind vectors and those inferred from the orientations of aeolian features, at least when rather straightforward mappings 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, 1979b) 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 $<45^\circ$, though 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 regarding the physical properties of the surface that are key to aeolian processes (such as sediment availability, grain size distributions, and fine-scale surface roughness), or (iii) choice of

68 numerical mapping between GCM surface wind vectors and predicted fea-
 69 ture orientation (which is impeded by gaps in our understanding of sediment
 70 transport, dune formation, and rock erosion, both for Mars and in general).
 71 We explore in particular the impact of (iii) in this work.

72 While surface wind dynamics and erosion rates on Mars differ greatly
 73 from those on Earth, relationships developed through field observation, lab-
 74 oratory experiments, and modeling form the basis for much of our under-
 75 standing of aeolian processes on Mars (e.g. Bagnold (1941); Greeley et al.
 76 (1982); Bitter (1963a,b); Merrison et al. (2008); Rubin and Hunter (1987)).
 77 While some aspects of Mars' erosional environment are well-constrained, oth-
 78 ers are largely unknown (see (ii) and (iii) above). In an attempt to better
 79 understand the remaining disparities between predicted and observed aeolian
 80 features, we test a range of numerical mappings between wind vectors output
 81 by the MarsWRF GCM (Richardson et al., 2007; Toigo et al., 2012) and pre-
 82 dicted bedform orientations (see (iii) above). These are described in detail
 83 in Section 3.2; here we merely note that the formation mechanisms for dunes
 84 (depositional features) and yardangs (erosional features) are very different,
 85 and thus we cannot use the same mapping to predict the orientations of both
 86 sets of features. As an example, while we would expect a unidirectional wind
 87 field to produce transverse linear dunes (or Barchan where sand supply is
 88 limited) with crests oriented normal to the wind direction, we would expect
 89 the same wind field to produce yardangs oriented parallel to the wind di-
 90 rection - i.e., at 90° to the dunes. This is because the dunes are built from
 91 scratch via the accumulation of sand, while the yardangs are produced by the
 92 removal of rock material from around the sides of an existing feature as the
 93 wind is deflected around it. For more complex wind regimes, however, the-
 94 ory suggests that dunes will form with an orientation that maximizes gross
 95 bedform-normal transport (GBNT) of surface material (Rubin and Hunter,
 96 1987) (see Sections 2.2 and 3.2), while yardang orientations may perhaps be
 97 more controlled by the dominant wind direction (see Section 2.3). Thus a 90°
 98 offset between dune and yardang orientations need not generally occur. We
 99 compare our predictions to the observed populations of dunes and yardangs
 100 at nine sites (Figures 1 and 2) selected for their highly wind-eroded nature.
 101 Sites are constrained to locations of interior layered deposits (ILDs), which
 102 are relatively young highly eroded surfaces that are typically elevated above
 103 the surrounding terrain (Catling et al., 2006; Okubo et al., 2008; Sefton-Nash
 104 et al., 2012; Warner et al., 2011) and therefore more susceptible to erosion
 105 by oncoming winds due to topographic forcing.

Figure 1: Location of sites selected for this study. Reference map is MOLA 32ppd topography (Zuber et al., 1992).

106 In order to place upper limits on the age of the least transient wind-eroded
 107 features, we also derive model crater retention age fits to established isochrons
 108 for young surfaces with populations of small diameter craters (Hartmann,
 109 2005). This study benefits from the use of high resolution ($25\text{-}60\text{ cm pixel}^{-1}$)
 110 images acquired by the HiRISE instrument on Mars Reconnaissance Orbiter
 111 (MRO) (McEwen et al., 2010), which allow fine detail on eroded surfaces and
 112 small diameter craters to be resolved.

113 2. Study sites

114 2.1. Interior layered deposits

115 Interior layered deposits (ILDs) are relatively young (Amazonian), easily
 116 eroded deposits, characterized by their high albedo, visible layering at a
 117 variety of scales and low crater densities (Catling et al., 2006; Okubo, 2010;
 118 Ansan et al., 2011; Flahaut et al., 2010; Fueten et al., 2010; Sefton-Nash
 119 et al., 2012). Regardless of their formative mechanism, their most recent
 120 history has been dominated by aeolian modification (e.g. Figure 3B). ILDs
 121 have been identified in chaotic terrain, crater bulges and inter-crater terrain
 122 (Malin and Edgett, 2000), but are generally confined to the martian tropics
 123 and subtropics. Because ILDs formed relatively late in Mars' history they

124 are elevated above surrounding terrain which, combined with their generally
125 friable nature, likely makes their surfaces accurate recorders of recent wind
126 directions.

127 *2.2. Identifiable aeolian features I: dunes*

128 Aeolian bedform type is largely determined by the wind regime and the
129 availability of mobile material. Martian dunes (Figure 3E,F) are mostly
130 transverse and crescentic (barchans), as opposed to rare linear longitudinal
131 dunes (Breed et al., 1979; Lee and Thomas, 1995), indicating a predom-
132 inantly unidirectional wind regime (McKee, 1979). Where more complex
133 wind regimes exist, the gross bedform-normal transport (GBNT) hypothesis
134 proposes that dunes will form with a bedform crest orientation such that the
135 total ('gross') sediment transport normal to the crest is maximized, where
136 total refers to transport from both sides of the crest. The use of gross rather
137 than net transport reflects the idea that e.g. an E-W oriented crest will grow
138 higher if equal amounts of sediment accumulates there from the north as
139 from the south, despite the net transport in that case being zero. There is
140 growing evidence that this approach works well on Earth for both aeolian
141 and sub-aqueous bedforms (e.g., Lancaster (1991); Anthonsen et al. (1996);
142 Lancaster et al. (2010); Reffet et al. (2008); Rubin et al. (2008); Wu et al.
143 (2009)), though disagreement has been noted in some situations or regions
144 (e.g., Lancaster (1991); Clarke et al. (2008); Derickson et al. (2008)).

145 Estimates of aeolian transport rates on Mars are complicated by a lack of
146 ground truth measurements. Due to Mars' thin atmosphere, wind velocities
147 required to initiate saltation are thought to be much higher on Mars than on
148 Earth (Greeley and Iversen, 1985), with measured and modeled surface wind
149 speeds on Mars appearing to rarely exceed the estimated saltation threshold
150 (Moore, 1985; Bridges et al., 2012). However, the occurrence of major dust
151 storms every few years (with the majority of dust injection presumed to
152 occur via saltation of sand-sized particles) suggests a far more active aeolian
153 environment. In addition, while the majority of large martian dunes appear
154 to be relatively stable and inactive, recent analysis of high resolution images
155 shows substantial dune formation and migration in isolated areas (Edgett
156 and Malin, 2000; Bridges et al., 2007, 2012; Silvestro et al., 2013). The
157 apparent shortfall in modeled winds may be due to their having come from
158 GCMs, which run at a few degrees resolution and thus cannot resolve strong,
159 localized wind gusts that have the greatest influence on transport and erosion
160 (Bridges et al., 2012). Hysteresis effects (Kok, 2010) – i.e., the ability to

Figure 2: Context of sites selected for this study. Rendered HiRISE stamps indicate our study areas. Background context basemap is from THEMIS daytime IR imagery.

Figure 3: Examples of yardangs and bedforms as seen in HiRISE images listed in Table 2. A) Yardangs in Aeolis. B) Elongate yardangs on layered terrain in east Gale crater C) Teardrop-shaped yardang, allowing dominant wind direction to be inferred. D) Symmetric yardang only allowing inference of wind direction with 180° ambiguity. E) Transverse dune field in Candor Chasma. F) Measurement of dune crest trend, normal to inferred wind trend.

maintain saltation at much lower wind stresses (which must only exceed the impact threshold) once the higher fluid threshold has been exceeded – may also greatly impact these estimates. For active dunes, the length of time taken for a dune to migrate its own length is described as the turnover time (Andreotti et al., 2002), and provides an estimate of the time period over which the dune was formed. Recent modeling of transport properties under Mars surface conditions suggested dune migration rates of a few centimetres per thousand years (Claudin and Andreotti, 2006), in approximate agreement with dune turnover times of 10,000 to 100,000 years estimated by Gardin et al. (2012), which are on the order of timescales of climatic forcing over obliquity cycles. However, observations at Rabe Crater (44 S°) of dune migration of 1–2 cm per Mars year (Fenton, 2006) and dune advancement rates of 0.4–1 m year⁻¹ in the tropics (Silvestro et al., 2011, 2013) indicate that more rapid bedform migration occurs in some areas under present day conditions.

This suggests very rapid turnover times of order 50–100 years for a typical 50m wavelength dune. Therefore, dunes may represent wind regimes of about 100 years duration based on observations, although significant uncertainty exists. The martian surface likely holds a combination of slowly migrating (or even ‘fossil’) dunes that formed during past climate epochs and rapidly migrating dunes that are very active in the present day wind regime.

2.3. Identifiable aeolian features II: yardangs

Yardangs are remnant, wind-eroded, aerodynamic ridges (Figure 3A–D), which form parallel to the wind direction as the result of strong unidirectional wind regimes which cause abrasion and deflation into channels, which are then widened or streamlined (Ward, 1979a). Martian yardangs are larger and more elongate than their terrestrial counterparts (Bridges et al., 2007; de Silva et al., 2010). Yardangs are formed over longer timescales than dunes and are predominantly found on terrains with effectively young model crater retention ages, where erosive resurfacing produces low crater densities, such as ILDs. The surface exposure age gives an upper limit for the yardang formation timescale. Yardang long axis orientation is therefore indicative of recent, but not necessarily modern, wind regimes (Ward, 1979a).

2.4. Surface dating

In order to constrain the maximum age for aeolian features we date ILD surfaces at each site via crater counting using the HiRISE images shown in

Figure 2 and listed in Table 2. We found only six of the ten sites to harbour a sufficient crater population to enable dating: Aeolis, Candor Chasma, Danielson Crater, Gale Crater (east), Gordii Dorsum (south) and Iani Chaos. ILD surfaces within HiRISE image footprints for sites at Arabia Terra, Gale crater (west) and Gordii Dorsum (north) showed fewer than 10 identifiable craters, which we deemed inadequate for reliable crater statistics. Traditionally, error is constrained using the statistical variation between crater populations in separate areas on the same geologic unit (e.g. Warner et al., 2011). However, the small geographic area and young age of ILDs leads to generally low crater counts for this study. For statistical robustness we therefore treat counts for each site as one population. Error bars in Figure 4 represent a factor of two either side of the measured crater density, as suggested by Hartmann (1999). Isochrons represent model crater retention ages based on Hartmann (2005), which represents a refinement and synthesis of crater-dating techniques. Importantly for this study, this includes a correction applied to account for the loss of small ($D \lesssim 20$ m) bolides in Mars' atmosphere (Popova et al., 2003). Uncertainties are greatest if only small ($D \lesssim 100$ m) craters are used (Hartmann, 2005) and we therefore interpret our crater statistics to give order of magnitude resurfacing age estimates, rather than constrained model ages.

Loss of small craters due to deflation, abrasion and deposition is more likely than for larger craters, which have greater topographic expression. Deviation of our crater statistics from model age isochrons may be an indicator of this process, because the sites we chose by definition must exhibit extensive aeolian modification. Craters $\gtrsim 50$ m diameter in Candor Chasma (Figure 4) may represent this aeolian fractionation of the local crater population by erosive capability. However, we do not count large diameter craters in any other regions and this may simply be an artefact of the relatively small size of study areas.

We find most model ages for ILDs to span 0.1-10 Ma. Note that here 'model age' refers to the age since the surface was exposed to the atmosphere, rather than the age of the deposit. However, the absence of larger craters may artificially lower model ages. For comparison, Warner et al. (2011) calculate model ages for a group of ILDs in Iani Chaos, including the deposit we dated, as $24.8^{+3.2}_{-3.3}$ Ma. It is unclear whether the decline in frequency of small diameter craters that we observe at most sites (Figure 4) is due to a larger atmospheric ablation loss than predicted by Popova et al. (2003), preferential aeolian resurfacing of small craters, or an artefact of image resolution, i.e.

Figure 4: Comparison of crater populations at each of the six sites with isochrons from Hartmann (2005), which applies a correction for ablation of small diameter bolides in Mars’ atmosphere. Error bars represent a factor of two, as suggested by Hartmann (1999). See Table 1 for crater counting statistics and age estimates.

Site	No. craters	Area (km ²)	Est. exposure age (Ma)
Aeolis	103	4.5	1–10
Candor Chasma	81	4.3	1–10
Danielson Crater	25	12.2	0.1–10
Gale Crater (East)	117	66.4	0.1–10
Gordii Dorsum (South)	12	9.4	<10
Iani Chaos	118	26.0	0.1–4

Table 1: Crater count statistics and age estimates for each of the six sites with sufficient crater populations. Crater counts at Arabia Terra, Gale Crater (west and south), and Gordii Dorsum (north) are not reported as they showed fewer than 10 countable craters. See Figure 4 for comparison of crater populations with isochrons from Hartmann (2005), which were used to derive the model crater retention ages.

234 where craters with diameters close to the resolving limit of HiRISE are more
 235 difficult to positively identify. In any case, the young model ages suggest
 236 aeolian features observed in these deposits will have been formed by recent
 237 wind regimes.

238 3. Method

239 3.1. Measurement of feature orientation

240 For our nine sites in seven areas (Figure 1) where heavily wind-eroded
 241 ILDs are present, we chose appropriate HiRISE footprints (Figure 2) such
 242 that enough area was covered to produce adequate statistics of dune/yardang
 243 fields. Details of feature counts, site locations and HiRISE product IDs are
 244 shown in Table 2.

245 Yardang orientation was determined by calculating the azimuth of a vec-
 246 tor defined by the two endpoints of their long axis. In some sites yardangs
 247 showed a distinctive teardrop shape (e.g. Figures 3C and 5), allowing infer-
 248 ence of a unique wind direction. In other sites, yardangs with more elongate
 249 and parallel topography allowed only inference of a 180° ambiguous trend
 250 line (e.g. Figure 3D).

251 Dune populations at each site were found only to be transverse, with
 252 the exception of Gordii Dorsum (north) and Arabia Terra where no dunes
 253 were present within the image footprint (Table 2). Dune orientation was
 254 determined by measurement of the trend line parallel to the mean azimuth
 255 of each dune crest (Figure 3F). Dune slip-face normals (which, assuming a
 256 unimodal wind, approximate wind direction) were perpendicular to this. For
 257 transverse dunes wind direction remains 180° ambiguous without detailed
 258 inspection of dune morphology, which was beyond the scope of this study.

259 3.2. Mapping from GCM winds to predicted aeolian feature orientations

260 A $2^\circ \times 2^\circ$ horizontal resolution run of the MarsWRF GCM (Richardson
 261 et al., 2007; Toigo et al., 2012) was sampled at the nine locations listed in
 262 Table 2 for each minute of a Mars year, giving a total of 963360 wind vec-
 263 tors at each site, spread uniformly throughout the year. For each point we
 264 extracted zonal (u) and meridional (v) wind velocities, the friction velocity,
 265 u_* , and the atmospheric density, ρ . u and v were interpolated to an altitude
 266 of 1.5m using similarity theory (the lowest model altitude was 10m). Wind
 267 speeds at 1.5m were deemed representative of those that control transport
 268 via saltation. To account for a range of theories regarding the relationship

Figure 5: Example measurements of feature orientation (upper) and crater counting (lower) in Candor Chasma.

Site	Lat.	Lon.	HiRISE product	Dunes	Yardangs
Aeolis	-6.40	149.30	PSP_001448_1735	228	65
Arabia Terra	8.61	21.15	PSP_001545_1885	0	32
			PSP_003655_1885		
			PSP_006846_1885		
Candor Chasma	-6.40	283.20	PSP_003474_1735	129	131
Danielson Crater	7.90	353.20	PSP_002878_1880	324	44
Gale Crater (East)	-5.30	138.30	PSP_001897_1745	76	93
Gale Crater (West)	-5.00	137.40	ESP_012195_1750	69	55
			ESP_017364_1745		
Gordii Dorsum (North)	10.90	211.70	PSP_006839_1910	0	96
Gordii Dorsum (South)	10.10	211.50	TRA_000865_1905	125	62
Iani Chaos	-0.90	341.50	PSP_008100_1790	590	72

Table 2: HiRISE image products inspected and number of yardangs and dunes identified at each site.

between wind vectors and the resultant erosion and transport, we derive predicted bedform orientation from GCM output. We use two different numerical mapping approaches specific to dunes and yardangs, both of which require construction of wind stress, σ , given by:

$$\sigma = \rho u_*^2 \quad (1)$$

For a wind with unit direction vector $\hat{\mathbf{x}}$, the particle transport flux $\boldsymbol{\tau}$ is defined by:

$$\begin{aligned} \boldsymbol{\tau} &\propto \rho u_*^2 (u_* - u_{*t}) \hat{\mathbf{x}} & \text{if } u_* > u_{*t} \\ \boldsymbol{\tau} &= 0 & \text{otherwise} \end{aligned} \quad (2)$$

where ρ is the air density, u_* is the friction velocity, and u_{*t} is the saltation threshold friction velocity - i.e. the minimum value required to keep grains in saltation. To account for large annual variations in surface pressure on Mars we define a constant saltation threshold stress σ_t and use this to determine u_{*t} via $u_{*t} = \sqrt{\sigma_t / \rho}$.

3.2.1. Approach for dunes

Our approach for dunes is based on the observation that transverse dune crests developed by a temporally dynamic wind field tend not to align normal

283 or parallel to the direction of sediment transport, but to trend such that the
 284 maximum gross bedform-normal transport (GBNT) is achieved (Rubin and
 285 Hunter, 1987). We use a modified version of Rubin and Hunter (1987)'s
 286 original approach, using the Fryberger flux in Equation (2) to determine the
 287 transport and incorporating a saltation threshold as before. As a function of
 288 hypothetical dune crest orientation, θ' , again defined clockwise from north,
 289 our modified GBNT, $T(\theta')$, is given by:

$$T(\theta') = \sum_{i=1}^n \rho_i u_{*i}^2 (u_{*i} - u_{*t}) \left| \frac{u_i \cos \theta' - v_i \sin \theta'}{\sqrt{u_i^2 + v_i^2}} \right| \quad \forall i \text{ where: } u_{*i} > u_{*t} \quad (3)$$

290 where the first term is the Fryberger transport flux and the second term is
 291 the absolute value of the transport flux direction vector projected into the
 292 bedform-normal direction. The optimum dune crest orientation θ is then
 293 given by maximizing $T(\theta')$. We solve this using a simple grid search in the
 294 range $0^\circ \leq \theta' < 180^\circ$ such that T is maximized for each site (Figure 6).
 295 To explore sensitivity to saltation threshold, we calculate predicted dune
 296 crest line orientations θ for: zero stress threshold $\sigma_t = 0 \text{ Nm}^{-2}$; a moderate
 297 stress threshold $\sigma_t = 0.008 \text{ Nm}^{-2}$ and a higher threshold $\sigma_t = 0.016 \text{ Nm}^{-2}$.
 298 For comparison, 0.008 Nm^{-2} corresponds to $u_{*t} \approx 0.7 \text{ ms}^{-1}$ for an average
 299 martian surface air density.

300 For sites where the GBNT function showed significant secondary maxima
 301 (observed only at Iani Chaos), we also show the expected dune crest orien-
 302 tation for wind stress thresholds of $\sigma_t = 0.008 \text{ Nm}^{-2}$ and $\sigma_t = 0.016 \text{ Nm}^{-2}$
 303 for the secondary GBNT peak.

304 3.2.2. Approach for Yardangs

305 We count MarsWRF surface wind vectors unweighted, weighted by wind
 306 stress and weighted by particle transport flux in angular bins to illustrate the
 307 distribution of transport in annual wind fields that may contribute to yardang
 308 formation (Figure 7). We determine the the directions of primary and sec-
 309 ondary maxima in these distributions to indicate the most likely yardang-
 310 forming weathering direction (Figure 9). In addition to weighting by Fry-
 311 berger flux, we also investigate the impact of assuming that rock abrasion
 312 rates, which are responsible for producing yardangs, vary as u_*^5 rather than
 313 as u_*^3 . In that case particle transport flux τ has the relationship:

$$\tau \propto \rho u_*^4 (u_* - u_{*t}) \hat{\mathbf{x}} \quad (4)$$

Figure 6: Gross bedform-normal transport (Rubin and Hunter, 1987) calculated by solving equation 3 over the 180° angular range of possible bedform trend line orientations.

314 This was suggested by the results of Anderson (1986), and can be thought
 315 of conceptually as the transported particle flux varying as u_*^3 , with the erosion
 316 produced by particles impacting the rock face varying as u_*^2 (related to the
 317 kinetic energy of the particles). We refer to particle transport flux calculated
 318 in this manner as ‘yardang flux’.

319 4. Results

320 The orientations of transverse dune trend lines and yardang long axes
 321 were measured at each site (e.g. Figure 5). Azimuth distributions for each
 322 feature are plotted on Rose diagrams normalized to percentage of the total
 323 population for that feature (Figures 8 and 9). The mean direction of yardangs
 324 (blue) and dunes (red) should be approximately normal to each other if both
 325 populations were formed under the same unidirectional wind regime.

326 4.1. MarsWRF GCM output

327 To illustrate annual wind fields (Figure 7) we count MarsWRF surface
 328 wind vectors in 64 angular bins and plot the normalized frequency of vectors
 329 1) unweighted 2) weighted by the vector mean stress 3) weighted by flux
 330 defined by Fryberger (1979) (Equation 2) 4) weighted by Fryberger flux with
 331 a stress threshold $\sigma_t = 0.008 \text{ Nm}^{-2}$ 5) weighted by Fryberger flux with $\sigma_t =$
 332 0.016 Nm^{-2} , and 6) weighted by ‘yardang flux’, where $\tau \propto \rho u_*^4 (u_* - u_{*t})$
 333 and $\sigma_t = 0.008 \text{ Nm}^{-2}$.

334 4.2. Dunes

335 Transverse dune crest orientations at each site are plotted as trend lines
 336 with 180° symmetry (Figure 8). In Figure 8 we show the predicted ori-
 337 entations of bedform trend lines calculated by the numerical formulations
 338 involving maximizing GBNT (Equation 3) for various wind stress thresh-
 339 olds. We also show the orientation of a significant secondary GBNT maxi-
 340 mum observed at Iani Chaos only. If MarsWRF wind vectors represent the
 341 present dune-forming wind field and our chosen dune fields are active, then
 342 the predicted trend lines (red lines in Figure 8) should agree with the mean
 343 transverse dune crest trends observed.

Figure 7: Azimuth distribution of surface wind vectors produced by the MarsWRF GCM over one Mars year in the present climate regime. Lines are drawn between frequency counts in each of 64 bins of angular width 5.625° . Black solid lines are vector frequency in each bin. Dashed lines are weighted by wind stress, σ , which takes into account atmospheric density (Equation 1). Green, blue and red lines represent wind vectors weighted by the wind stress formulation of Fryberger (1979) (Equation 2) with threshold stresses of 0, 0.008 Nm^{-2} and 0.016 Nm^{-2} , respectively. Magenta lines represent vectors weighted by yardang flux (Equation 4) with a threshold of 0.008 Nm^{-2} (to investigate yardang erosion dependancies presented by Anderson (1986)).

Figure 8: Rose diagrams of trend lines representative of average dune crest orientation. Angular bins are 6° and bar radii are sized according to percentage of the total population of each feature. Also shown are the results from two different methods for prediction of transverse dune crest trends by maximizing GBNT calculated from the MarsWRF GCM's annual vector wind field (Equation 3). For Iani Chaos, a secondary but significant local maxima in GBNT is also plotted (see Figure 6).

4.3. Yardangs

For yardangs, unambiguously inferred transport directions (in the case of tear drop shaped features) were retained when plotting directions (Figure 9). 180° ambiguous yardangs were rare and typically numbered less than ~10%, but where they occurred yardang direction was plotted in the same sense as neighbouring unambiguous yardangs, which were assumed to be exposed to similar wind fields. For Danielson crater, sufficient ambiguity was present for all yardangs that we plot them as 180° ambiguous trends.

The most likely yardang-forming weathering directions are plotted on Figure 9 as the directions of principle and secondary maxima in weighted vector frequencies in Figure 7. Secondary orientations in dashed circles indicate vector frequency maxima that are present for low-order weightings, but that become subdued for higher order weightings of u_*^3 and u_*^5 (yardang flux). Winds in these directions with lower erosive power may therefore be less likely to contribute to yardang formation.

If modeled wind fields are of the same orientation as those that formed measured yardang populations, then principle wind stress directions (numbers in Figure 9) should match yardang long axis orientations. However yardang formation in multi-directional wind field is currently not well understood, even on Earth, and further investigation into the relationship between non-unidirectional wind fields and yardang orientation is warranted.

5. Discussion

5.1. Dunes and GBNT

Good matches are seen between dunes and maximum GBNT at 4 of 7 sites: Danielson Crater, Gale Crater (east and west) and Gordii Dorsum south. Use of higher stress thresholds ($\sigma_t = 0.016 \text{ Nm}^{-2}$) typically improves matches where wind regimes are multi-directional. Sites where GBNT is least impacted by choice of threshold tend to show predominantly uni-directional wind regimes with respect to Fryberger flux (i.e., Danielson Crater and both sites in Gordii Dorsum).

At Candor Chasma dune orientations are within 15-30° of predicted and the match improves for progressively higher stress thresholds. At Iani Chaos the best match is seen for the highest threshold 0.016 Nm^{-2} . However, Iani Chaos shows a low amplitude in GBNT over the total angular range (Figure 6), implying a distribution of wind vectors from many directions over the course of the year, which is reflected in the angular dispersion of high vector

Figure 9: Rose diagrams showing the orientation of yardang long axes (blue). Angular bins are 6° and bar radii are sized according to percentage of the total population of each feature. Also shown are the primary and secondary (where present) wind vector frequency maxima, derived from MarsWRF GCM's annual vector wind field shown in Figure 7. Secondary orientations in dashed circles indicate directions prominent when low-order u_* weightings were applied.

380 frequencies in Figure 7. Consequently, the direction of the second highest
 381 GBNT inflexion for Iani Chaos in Figure 8 (green lines) also shows moderate
 382 agreement with observed dune populations.

383 Aeolis shows the worst match between modeled and observed dune ori-
 384 entations, with the maximum GBNT at all thresholds more nearly perpen-
 385 dicular to, than aligned with, the observed dune orientations. We discuss
 386 plausible reasons for this mismatch in Section 5.3.

387 5.2. Yardangs

388 There is good agreement for most regions between yardang long axis ori-
 389 entation and primary or secondary wind stress maxima, with the exception
 390 of Aeolis (Figure 9). Arabia Terra yardangs are dispersed over about a 50°
 391 range, but match well with the secondary maximum, defined by low-order
 392 weighted and non-weighted peak in wind vector frequency. The direction of
 393 the primary transport flux maximum is offset from the edge of the yardang
 394 population by about $\sim 15^\circ$. Candor Chasma also shows a good match to
 395 the secondary direction (‘2’ in dashed circle, Figure 9), which shows up as a
 396 maxima only if no wind stress weightings are included (i.e., though winds are
 397 predicted to occur often in this direction, their associated fluxes are predicted
 398 to be far weaker than those in the direction labeled ‘1’). Danielson Crater
 399 could be regarded as a good fit if yardang sense were able to be constrained
 400 to a unique 180° angular range. Excellent matches are seen between pre-
 401 dicted and observed yardang orientations at both sites in Gale Crater. Both
 402 Gordii Dorsum south and north sites show similar offsets of $\sim 10\text{-}20^\circ$ between
 403 GCM dominant wind directions and yardangs, but dunes at the south site
 404 show a better match to GBNT predictions from the GCM. Therefore Gordii
 405 Dorsum presents a reasonable case for further investigation into consistent
 406 offsets between dunes and yardangs, which may yield information on wind
 407 field change if present dune fields are active and if higher spatial resolution
 408 wind models produce similar predicted orientations. Yardangs poorly match
 409 GCM predicted orientations, as well as dunes, at the Aeolis site. Local ter-
 410 rain is somewhat variable (Figure 2), perhaps implying that higher-resolution
 411 modeling is required to resolve dune- and yardang-forming winds (also see
 412 discussion of Aeolis in Section 5.3). In Iani Chaos the primary GCM-wind
 413 stress orientation matches one of the several yardang populations, but both
 414 GCM vectors and yardang orientations are spread over a wide angular range
 415 (Figure 9). In sites where multiple yardang populations occur, such as Iani
 416 Chaos, they are clustered into separate regions of homogeneous orientation.

417 If unidirectional wind fields are required for yardang formation (which is
 418 not clear from terrestrial or planetary studies, though seems plausible given
 419 the nature of their formation), then yardangs could be formed in localized
 420 areas of unidirectional winds that are beyond the spatial resolution of the
 421 GCM. In modeled wind fields that show more than one dominant direction
 422 (e.g. Iani Chaos, Figure 7) then one or more directions could be selectively
 423 halted or diverted by local topography in sub-regions, leaving some surfaces
 424 exposed to an effectively unidirectional erosion regime. This effect may ex-
 425 plain observations of multiple yardang populations in close proximity that
 426 are oriented differently. However, this discussion would be aided by a firmer
 427 answer to whether yardangs can form in bidirectional winds or whether the
 428 very existence of yardangs implies unidirectional winds. For some locations,
 429 weighting of modeled wind vectors by u_*^5 , instead of u_*^3 , tends to produce
 430 a unidirectional ‘spike’ in the primary direction, but a greater angular dis-
 431 persion for secondary directions (Figure 7). In these cases (Gale Crater east
 432 and west) yardangs are aligned with only the sharp primary direction, sup-
 433 porting the theory that yardang formation tends to occur only in effectively
 434 unidirectional wind fields.

435 5.3. Overall match of dunes and yardangs to GCM predictions

436 Poor matches between maximum GBNT and dune orientation at Aeolis
 437 may be due to the choice of metric (GBNT, Fryberger (1979) flux and
 438 threshold choice). However, the GCM spatial resolution of 2° is far lower
 439 than the dunes themselves and hence may not represent the dune-forming
 440 winds, especially in regions of complex topography where sub-grid cell topo-
 441 graphic diversion is not resolved. Use of a higher spatial resolution model
 442 may better resolve localized dune-forming winds. If neither of these factors
 443 could be verified as responsible for the mismatch i.e. the present GCM does
 444 resolve dune-forming (and yardang-forming) winds and our choice of metric
 445 is an accurate bulk representation of the dune-forming process, then it would
 446 be possible to more confidently ascribe the offset as due to disequilibrium of
 447 both feature populations with the present day wind regime, implying a more
 448 ancient origin for dunes and yardangs under a different wind field. In any
 449 case, this site presents an opportunity for further study to investigate the
 450 impact of higher resolution GCMs.

451 We found no dunes at the Arabia Terra or Gordii Dorsum (north) loca-
 452 tions, but yardangs at Arabia Terra deviate approximately $\sim 30^\circ$ from the

453 peak vector frequency of GCM winds, while those at Gordii Dorsum (south)
454 show a better match with a deviation of $\sim 10^\circ$.

455 At Gale Crater (east and west) both dunes and yardangs show excellent
456 agreement between predicted and observed orientations, perhaps a surprising
457 result given the variable local topography. Though at 2° lateral resolution the
458 GCM does not resolve the detailed crater circulations that one might expect
459 to strongly influence these dune fields. While the excellent match shown
460 here suggests that the crater circulations might be dominated by regional
461 flows, this may also be coincidental and a focus of future work will be using
462 mesoscale (~ 1.5 - 4 km resolution) modeling to assess the impact on predictions
463 of resolving any crater flows.

464 Observation of active ripples in NW Gale Crater (Silvestro et al., 2013)
465 supports a modern age for dunes in Gale but does not necessarily imply the
466 same for dunes in this study because their ripple locations do not coincide
467 with our study areas. Proof that dunes in our Gale study areas are in equilib-
468 rium with the present-day wind field could be sought through 1) observation
469 of present-day dune activity and 2) agreement of mesoscale models with our
470 GCM results.

471 Dunes at Danielson crater show excellent agreement with maximised
472 GBNT, while yardangs agree less well, but still match within $\sim 15^\circ$. While
473 yardang-forming winds predicted from GCM output are predominantly uni-
474 directional, those that are unweighted and weighted by vector mean wind
475 stress show a wide angular range and several significant maxima (Figure 7).
476 This could contribute to the uncertainty in determining unique yardang sense
477 at this location, i.e. minor yardang erosion in a non-principle direction may
478 have weathered direction specific-features.

479 Close matches at Candor Chasma are seen between predicted orienta-
480 tions and dunes (within $\sim 25^\circ$) and yardangs (within $\sim 10^\circ$ of the secondary
481 maximum marked '2'). Gordii Dorsum (south) shows similarly good matches
482 with a slightly greater offset for yardangs. The significance of this offset re-
483 mains to be tested, but could imply that yardangs are less in equilibrium
484 with present dune-forming wind regimes that are well represented by GCM
485 output, or that the yardang-forming wind regime is not well captured by our
486 interpretation of GCM output.

487 While there is tentative agreement between the orientations of dunes and
488 some yardangs at Iani Chaos (Figures 8 and 9), there are additional yardang
489 populations that may be representative of very localized unidirectional wind
490 regimes unresolved by the GCM, or alternately by past wind fields. In either

case, complex local topography warrants the use of a mesoscale GCM to resolve the variation in wind fields and therefore feature orientation over short distances.

6. Conclusions

We studied nine sites that are expected to be representative of modern day wind fields on Mars and measured the orientations of features with short (dunes) and long (yardangs) timescales of formation.

We selected interior layered deposits because they are young and easily wind-eroded. Model crater retention ages derived for ILDs via comparison of crater size frequency distributions to those defined by (Hartmann, 2005) were found to be on the order of 0.1-10 Ma, in moderate agreement with previous estimates (available for Iani Chaos only (Warner et al., 2011)), and confirming ILDs applicability to modern wind field determination. Remaining uncertainties in isochron development are reflected by factor of 2 error bars on model ages. For sites where yardangs and dune orientations disagree, model ages represent an upper limit on yardang age and therefore timescales for changes in the local wind field.

Transverse dunes were counted at 7 of 9 sites, while yardang orientations were analysed at all sites. Feature orientations were compared to output from the MarsWRF GCM running at a spatial resolution of 2° . Dune orientations agreed very well with predictions made by maximising gross bedform-normal transport (Rubin and Hunter, 1987) and weighting by flux as defined by Fryberger (1979). Better agreements were generally observed when wind stress thresholds were applied, with the maximum applied threshold $\sigma_t = 0.016 \text{ Nm}^{-2}$ giving the best match for several sites. Application of wind stress thresholds had the greatest effect on predicted dune orientation for sites with multi-directional wind fields. Sites with annually invariant, unidirectional wind fields showed no change with threshold. Poor agreement was seen for sites with extreme local topography such as chasma and chaos regions, implying that local topographic effects are important and therefore higher resolution mesoscale models are required before further model comparison can be made.

Yardang orientations agree well in most cases with a primary or secondary transport-weighted maxima in annual wind vector frequencies. Close inspection of maxima in weighted annual wind vector frequencies thus appears to provide a basis for meaningful prediction of yardang orientations

527 in multidirectional wind fields in future studies. The agreement of multiple
 528 different yardang populations in close proximity with multiple maxima in
 529 an annual wind field may indicate local scale topographic blocking of some
 530 dominant wind directions and/or focusing of one, thus producing the highly
 531 unidirectional wind regime that appears required for yardangs to form.

532 The number of regions with good agreement between measured and pre-
 533 dicted feature orientations by the MarsWRF GCM increases our confidence
 534 in using this model to predict winds elsewhere on Mars. Broadly, aeolian
 535 features on ILDs provide an excellent way to measure present day wind di-
 536 rections and validate GCMs, however, care must be taken in areas of high
 537 topographic relief and higher resolution models are required to make more
 538 complete comparison. We find that comparison of yardang long axes to direc-
 539 tional maxima in modeled wind vector frequencies, and comparison of dune
 540 orientation to maximum GBNT are appropriate treatments.

541 Finally, we demonstrate that comparison of past and present wind fields
 542 inferred from aeolian feature orientations to those predicted by GCMs may
 543 be both a viable technique for model validation and for gaining insight into
 544 recent climate variations on Mars.

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