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Aeolian dune sediment flux heterogeneity in Meridiani Planum, Mars

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Abstract

It is now known unambiguously that wind-driven bedform activity is occurring on the surface of Mars today, including early detections of active sand dunes in Meridiani Planum's Endeavour crater. Many of these reports are only based on a few sets of observations of relatively isolated bedforms and lack regional context. Here, we investigate aeolian activity across central Meridiani Planum and test the hypothesis that dune sites surrounding Endeavour crater are also active and part of region-wide sediment migration driven by northwesterly winds. All 13 dune fields investigated clearly showed evidence for activity and the majority exhibited dune migration (average rates of 0.6 m/Earth-year). Observations indicate substantial geographic and temporal heterogeneity of dune crest fluxes across the area and per site. Locations with multiple time steps indicate dune sand fluxes can vary by a factor of five, providing evidence for short periods of rapid migration followed by near-stagnation. In contrast, measurements at other sites are nearly identical, indicating that some dunes are in a steady-state as they migrate. The observed sediment transport direction was consistent with a regional northeasterly-to-northwesterly wind regime, revealing more variations than were appreciated from earlier, more localized studies. Craters containing shallow, degraded, flat-floored interiors tended to have dunes with high sediment fluxes/activity, whereas local kilometer-scale topographic obstructions (e.g., central peaks, yardangs) were found to be inversely correlated with dune mobility. Finally, the previous, more limited detections of dune activity in Endeavour crater have been shown to be representative of a broader, region-wide pattern of dune motion.

1. Introduction and motivation

It is now known unambiguously that wind-driven bedform activity is occurring at scattered locations across Mars today (Bourke et al., 2008; Sullivan et al., 2008; Silvestro et al., 2010; Chojnacki et al., 2011; Bridges et al., 2011). Data at these locations which possess detected bedform movement demonstrate that winds driven by contemporary atmospheric conditions can entrain sediment and are likely contributing to landscape evolution and the dust cycle. However, many of these reports are only based on one or a few sets of observations of relatively isolated bedforms, which lack regional context. Moreover, volumetric sand fluxes,

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which are independent of dune size and therefore provide a normalized value that can be used to compare dune activity at different sites, have only been documented for a few locations on Mars (Bridges et al., 2012; Chojnacki et al., 2015). This metric is useful for comparison to other planetary dune fields and can be used to assess landscape evolution based on estimated abrasion rates (Bridges et al., 2012; Urso and Chojnacki, 2016).

The equatorial Meridiani Planum-Arabia Terra region is host to abundant bright and dark wind streaks, sand patches, plains of ripple fields, and intracrater dune fields (for a review see Fenton et al. (2015)). All of these features are present near the Mars Exploration Rover (MER) Opportunity, at the time of this writing located on the western edge of Endeavour crater (Arvidson et al., 2015). The Opportunity rover has previously detected evidence for near- and far-field aeolian-driven activity, with observations of dark streak activity, sediment movement in the rover workspace, bedform albedo alteration, dust-lifting events, and far-field aeolian dune changes (Geissler et al., 2008; Chojnacki et al., 2015).

Orbital detections of dome and barchan dunes within the Endeavour basin reveal that they migrate and/or deflate at relatively high rates as compared with other reports of active dunes on Mars (Chojnacki et al., 2015). Indeed, dunes in Endeavour and those found in Nili Patera (Bridges et al., 2012) show seemingly high volumetric sediment fluxes, yet it is ambiguous if these earlier reports are typical or outliers for the rest of Mars.

These locations, and Meridiani in particular, do have abundant data coverage both spatially and temporally. Thus the question remains: are Endeavour bedforms and their apparent high level of activity representative of the broad surrounding region or were earlier reports merely a case of observational bias? Related questions include: If other dunes are found to be active, what are the regional and temporal variations of aeolian bedform transport rates, migration directions, and volumetric sediment fluxes? Similarly, are there substantial spatial differences in dune (re)construction times (e.g., turnover times) and do those point to variations in climate? Finally, is there any correlation between dune activity and host crater parameters or topographic context?

Here, we investigate dune activity across central Meridiani and test the hypothesis that sand dunes in the area surrounding Endeavour are also active and part of region-wide sediment migration driven by a northwesterly wind regime. This study area includes the $12^{\circ} \times 12^{\circ}$ region surrounding the Opportunity rover ($\sim 500,000 \text{ km}^2$). We begin by providing a concise summary of the data products used and our methodology. We then present results related to aeolian activity in the study area, including an assessment of the surrounding area. Finally, we close with a discussion associated with previously posed driving hypotheses and questions and their implications for the rest of Mars.

2. Data Sets and methods

2.1. Orbital visible-wavelength images, topography, and change detection

To estimate dune migration rates, bedform displacements were measured using multiple fine-scale (25–50 cm/pixel) images from the High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007) onboard the Mars Reconnaissance Orbiter (MRO). That

mission began collecting data of Mars and the study area dunes in 2006, which was MRO's first Mars-year of operation in Mars Year¹ (MY) 28. Due to the multiple successes of the MRO mission and ability to target HiRISE, several locations possess multiple annual or seasonal time steps. In one case, paired lower resolution images from the MRO's Context Camera (CTX) (5–6 m/pixel; Malin et al., 2007) were used to assess changes. Initial images of dark dunes were retargeted at similar seasons ($L_s \approx 20^\circ$) and viewing geometries (e.g., differences in phase angle of 12° or less) for optimal change detection. A few cases have large offsets in image parameters (e.g., lighting conditions, season), and thus surface change detection required more caution. Image parameters for each investigated site, including stereo status, and notable seasonal offsets from earlier images, are listed in Table 1.

For five dune fields, HiRISE stereo pairs were acquired for the construction of Digital Terrain Models (DTMs) using SOCET SET[®] BAE system photogrammetry software (see Kirk et al., 2008). The resulting DTMs possess a horizontal post spacing of 1 m, where the quality of pixel matching is provided by SOCET SET as a RMS error that is typically 0.3–0.7 of the HiRISE pixel scale (i.e., 25 cm) (Kirk et al., 2008; Sutton et al., 2015). DTMs were registered to Mars Orbiter Laser Altimeter (MOLA) (Smith et al., 2001) shot points for absolute elevation. Expected vertical precision of the elevation values is determined by the convergence angle and spatial resolution of the stereo pair (Kirk et al., 2003), giving HiRISE DTMs a precision of tens of centimeters (typically 10–30 cm). All stereo and monitoring images for a given site were then orthorectified to the DTM to facilitate change detection and bedform displacement measurements at the full native resolution of 25 cm/pixel. In addition to image orthorectification, dune heights were extracted from DTMs using topographic profiles for volumetric sand flux estimates of migrating bedforms. Although bland or deeply shadowed areas can produce obvious “faceted” surfaces from the photogrammetric terrain mapping method, these artifacts are recognized and avoided in co-registered HiRISE Figure of Merit (FOM) maps (Mattson et al., 2012).

The chronologically earlier image (e.g., the t_0 or time zero image) served as the base image from which the later image (e.g., the t_1 image) was compared to. Sand flux at the crests of dunes (Q_c) can be obtained using Eq (1):

$$Q_c = (H_d \times D_d) / t, \quad (1)$$

where H_d is the dune height, D_d is the bedform displacement in the direction of migration between images, and t is the intervening time (in Earth-years) producing sediment flux in units of $\text{m}^3 \text{m}^{-1} \text{yr}^{-1}$ (Ould Ahmedou et al., 2007; Vermeesch and Drake, 2008). Note that particles associated with large dark dune motion on Mars have been demonstrated to be in the range of sand (i.e., 63–2000 μm in diameter), based on *in situ* observed physical properties and wind tunnel estimates (Iversen and White, 1982; Herkenhoff et al., 2008); thus, we use “sand” and “sediment” flux interchangeably.

¹As per convention, the solar longitude (L_s) range of 0° – 360° defines a Mars-year and April 11, 1955 ($L_s = 0^\circ$) is the start of the Mars calendar at MY01. See Piqueux et al. (2015) for a complete description.

For sites with migrating dunes but without stereo data and DTMs, dune heights (for sediment flux estimates) were estimated using a slip face length-height technique (Bourke et al., 2006) and Eq. (1):

$$H = L_{SF} \times \tan\theta, \quad (2)$$

where L_{SF} is the measured adjacent slip face length, and θ is the assumed angle of repose, yielding dune slip face relief (H). A slip face angle of 33° was used, a common average value for terrestrial (Pye and Tsoar, 1990) and martian (Atwood-Stone and McEwen, 2013) dunes. To mitigate potential errors from high-emission angle images and the foreshortening of slip faces, measurements were made from the nadir-most images (i.e., emission angles of $<5^\circ$) of a monitoring sequence. This technique generally underestimates the maximum dune height and therefore the sediment flux, as the dune crest is often stossward of the slip face brink and the bottom of the dune can be difficult to assess. Slip face height measurements were within $\sim 8\%$ of those measured with DTMs in one trial (typically -1 – 3 m). Related measurements could be referred to as “slip face fluxes”, but all results will be presented as “crest fluxes” for simplicity. Manual registration of map-projected sub-regions to common immobile tie points (e.g., craters, boulders) was performed using Exelis Visual Information (ENVI) software for change detection at these locations. This time-intensive methodology required that small areas that only contained a few dunes be analyzed at a time. Image pairs with large offsets between emission angles ($>10^\circ$) were rejected, as they can produce apparent changes in dune relief and position that are not real. The quality of registration was evaluated quantitatively from the reported RMS values, allowing errant tie points to be removed and a better fit to be obtained.

For both manually- and orthorectified-images, change detection analysis was carried out in either ENVI software or ArcGIS software. Six to fifteen dunes were measured per site, distributed across the overlapping monitoring sequence field of view (FOV). Barchan displacement measurements were recorded for lee front advancement at the perceived center of the slip face bottom. Areas where obvious lee-face avalanches had occurred were avoided, since they are not representative of the bulk dune displacement. In the singular case of dome dune measurements in east Endeavour crater, the average displacements of the stoss and lee front advances were estimated along the perceived central line of migration using the orthorectified images available for the site. The estimated displacement error is ± 0.22 m, given the maximum RMS errors reported from SOCET SET or ENVI for image registration (0.7 pixel) combined with human error in manual measurements (0.5 pixels). Multiple topographic profiles were made and an average dome height was determined for crest flux estimates. Dunes whose spatial area changed appreciably due to aeolian deflation were not included for sediment flux estimates. If dunes changed heights between time steps, it was assumed to be minimal and within the margin of error.

The geologic context of the terrain surrounding the dune monitoring locations was examined in CTX images and daytime infrared mosaics of Mars Odyssey’s Thermal Emission Imaging System (THEMIS) images (100 m/pixel; Christensen et al., 2004). To test if dune activity was correlated with crater parameters we utilized data from the Robbins and Hynek (2012)

crater database. The dune field site naming convention shown in Fig. 1b is described in Table 2.

3. Results

3.1. Orbital observations of study area bedforms' activity

Thirteen dune fields were examined with repeat images separated by one-half to four Mars-years (Fig. 1a). Sites were classified into two categories of detection: sand dune migration (7) and bedform change (6). Other dark dunes in the map area (Hayward et al., 2007; Fenton et al., 2015) did not possess sufficient HiRISE or CTX images for analysis. Many dune locations also possessed underlying transverse aeolian ridges (TARs), which did not show activity in short- or long-baseline paired observations (up to $\Delta t = 4$ Mars-years).

3.1.1. Bedform change and ripple migration—At six sites clear changes had occurred, but bulk dune migration was ambiguous or problematic to measure (Fig. 1b; Table 1). These locations showed evidence for ripple movement, bedform deflation, or dune border modification (Animation 1 and 2). For example, ripples superposed on Xainza crater dunes advanced up to one ripple wavelength in paired images (Fig. 2a; inset). Broad, decameter- to hectometer-scale surface changes occurred on the lee-side of the dune field where large sand bedforms changed shape or position and predominantly lost area (Fig. 2a, Animation 1). Similarly, aeolian changes in Bopolu crater were detected with ripple, sand patch, and dune slip face displacements or modifications. These events were detected within a single Mars-year interval (MY 31–32) and in coarser than usual images (50 cm per pixel). Larger-scale ($\sim 600 \times 300$ m) surface modifications were detected in a small unnamed crater in the southeast quadrant of the study area, where paired CTX images ($\Delta t = 3$ Mars-years) showed the formation of sand patches north of the main dune field and adjoining sand sheets (Fig. 2b). HiRISE views of these locations reveal smooth patches of dark sand without the prominent ripples that are observed on adjacent dunes (Fig. 2b; inset).

3.1.2. Migrating dunes and sediment flux estimates—Seven of the thirteen dune fields showed evidence for dune migration in HiRISE time series (Fig. 1b; Table 1 and 2; Animation 3–7). Locations with migrating dunes include those found in craters south of Xainza, east of Firsoff, Endeavour, and several unnamed craters, all in the north half of the study area. Sand dunes were detected translating distances of 0.5–6 m between intervening images. Average migration rates, using the longest baseline images available and assuming steady rates over the one to four Mars-years between images, are 0.1–3.8 m/yr (0.2–7.2 m/Mars-year; time periods are in Earth-years (EY) unless explicitly stated). These values are provided spatially (Fig. 1b) and graphically (Fig. 3), as well as morphologic examples of migrating dunes detected in manually co-registered (Fig. 4a) and orthorectified (Fig. 4b) images. The observed sediment transport was in a dominantly south-southwestward to south-southeastward direction, consistent with a regional northerly wind regime (Fig. 5).

Dome dunes within Endeavour crater which were documented before to decrease in spatial area (25%–100%) in MY 25–32 pre-MRO, CTX, and HiRISE images (Chojnacki et al., 2011, 2015; Figs. 4–6) continued to primarily lose area, as evidenced by the MY 33 images (Animation 6). This loss in area was likely the result of aeolian deflation, evidenced by the

persistent degradation of sand ripples. Observations indicate that this happened for many larger Endeavour dunes that were also translating to the south, until their motion appeared to stall as deflation took over. Other bedforms in the study area did not decrease in area significantly, with the exception of those in Xainza crater (Fig. 2a, Animation 1).

Heights of migrating dunes were estimated from DTMs or by using the slip face length-height technique. Although collectively their heights ranged from one to 40 m, all but two study sites had average values between 6 and 8 m. The vast majority of dunes in the study area fall in this range regardless of whether they were detected to be active or not. An inverse relationship between dune rate and height is apparent, with taller dunes migrating more slowly (Fig. 3). Volumetric sand fluxes for Meridiani dunes ranged from 0.3 to 13.0 m³ m⁻¹ yr⁻¹ and can span an order of magnitude within a given location (Table 2; Fig. 3). Average sand flux values per site also show regional variations across the study area, with larger values in the central area (Fig. 1c). Dunes on the stoss-, upwind-side of their fields generally had the largest flux values with a steady decrease in migration rate leeward, similar to what has been previously documented (Bridges et al., 2012; Chojnacki et al., 2015).

Five dune fields possess HiRISE images in three or more Mars-years. This allows sand flux estimates to be made for several different time steps, usually in annual increments (Fig. 6; Table 2). Three dune fields had very similar flux values ($Q_c \approx 0.5 \text{ m}^3 \text{ m}^{-1} \text{ yr}^{-1}$) over the two time steps (Fig. 6b). Alternatively, a large degree of sediment flux heterogeneity was observed with respect to time for the remaining two dune fields ($Q_c \approx 2\text{--}5 \text{ m}^3 \text{ m}^{-1} \text{ yr}^{-1}$ for sites 3592+040 and 3548-023). Some sites possessed greater fluxes during the initial t0-t1 time step (i.e., MY 28/29-31/32), while others had greater values in the later t1-t2 period (i.e., MY 31/32-33; Fig. 6).

Additionally, these values can be examined spatially across a given dune field. For example, several moderate to large barchans in the small crater informally named South Xainza (Fig. 1b) showed consistent flux measurements, while climbing dunes on the south crater wall had notable variations (Figs. 4c-d, 7a). These climbing dunes, superposed on steep slopes (from 7° to 20°), decreased in migration rate by half in the latter MY 32-33 time step. Dunes in another crater (informally named East Firsoff crater) had variable sediment fluxes across the site (Fig. 7b), but the average crest flux stayed nearly the same between time steps (Fig. 6b). Likewise, most barchan dunes in Endeavour crater's "Greeley dune field" (named after late planetary scientist Ronald Greeley (Zimbelman, 2012)) displayed very consistent migration rates over the two time steps (Figs. 6b and 8a; Animation 8). In contrast, the eastern Endeavour dune field showed substantial sand flux heterogeneity over time, with an overall decrease in the later time period (Fig. 8b).

3.2. Dune turnover times

All active transverse bedforms possess a characteristic time period referred to as the turnover time, which is the period a bedform takes to travel its own stoss-to-lee length in the downwind direction – a metric that can be related to climate (Allen, 1974) (see Section 4.2). Given dune migration rates using long-baseline measurements and lengths along the direction of transport (50–350 m), average dune site turnover times span 50–1300 Earth-

years (25–680 Mars-years) (Fig. 1d). Many individual dunes across the region were found to possess turnover times between 10 and 300 Earth-years.

3.3. Relation to crater parameters and topographic setting

Host craters' parameters and local topography, particularly in the inferred upwind direction, were qualitatively assessed in relation to the study sites (Tables 1 and 3). All 11 craters that contained dunes studied herein are complex craters, with seven of them being classified as “complex, flat-floored”, whereas the remaining four craters have central peaks or pits (Robbins and Hynes, 2012). Crater diameters ranged from 9 to 69 km, and little apparent correlation with crater size and dune activity was found – although the largest three craters ($D > 50$ km) did have lower fluxes and apparent activity (Table 3). Shallower craters (< 1 km) possessed dunes with higher sediment fluxes and activity compared with deeper craters. Dune fields with moderate kilometer-scale or smaller topography (in the horizontal; e.g., pits, peaks, yardangs, craters) within 1–2 dune field diameters tended to have decreased activity with no or low migration rates. More generally, those craters that are flat floored, shallower, and more degraded tended to have dunes exhibiting higher sediment fluxes.

4. Discussion

4.1. Regional aeolian activity

All of the dune sites in the study area with sufficient orbital data clearly showed aeolian activity (Fig. 1). Ripple migration, bedform deflation, and/or dune border modification were observed at all sites containing HiRISE pairs, whereas lee-front advancement and bulk dune migration occurred for most locations (54%). Sites without the detection of migration tended to have large, contiguous dark dunes superposed on low-albedo underlying surfaces (e.g., Xainza crater). Alternatively, image pairs with a small temporal separation (e.g., 1 Mars-year) or large offsets in lighting conditions were not ideal for change detection. These dunes may be migrating at a rate below the HiRISE detection limit for the given time span and image resolution (e.g., < 0.4 m/Earth-year for a 25 cm/pixel image pair separated by one Mars-year (Bridges et al., 2013)). Most activity was detected as meter-scale morphologic changes requiring properly co-registered, high-resolution HiRISE data (Fig. 4), but larger decameter- to hectometer-scale changes were also found (Fig. 2). Migration rates of most Meridiani dunes are near the averages from global studies (~ 0.7 m/Earth-year) (Bridges et al., 2013; Banks et al., 2014), but several outliers showed evidence for rapid sediment transport. Some of these detections are likely due to spatially-heterogeneous short-term diurnal and seasonal winds.

As described above, dark dune migration ranged from a south-southeastward to a south-southwestward direction (Fig. 5). Examples in Fig. 7 show some of these directionality variations (Fig. 7a compared with Fig. 7b). These results are in slight contrast to an earlier analysis of Endeavour crater where dune-moving winds were reported to be predominantly northwesterly (Chojnacki et al., 2015). Dunes in the southern parts of the study area (e.g., Endeavour crater) tended to migrate toward the southeast, whereas those in the northern portions (e.g., East Firsoff crater) were more variable, but generally translated to the southwest. Fenton et al. (2015) identified dune crests and morphology in the central part of

this study area (e.g., Endeavour and Bopolu craters) that were consistent with dominant dune-constructing winds from the northwest (and thus producing southeasterly migration), matching the observed migration directions of these dunes. That study also identified a secondary set of dune crestlines consistent with northeasterly winds (and thus southwesterly migration), present even on dunes that were only observed to migrate to the southeast. Investigating ripple orientation and migration in a region centered ~700 km to the northeast of this study, Silvestro et al. (2011) found two overlapping sets of ripples, in which the most prominent set indicated migration toward the southwest and a less prominent set that indicated migration toward the southeast. These two distinct sand-moving winds seem to occur throughout much of Meridiani Planum and Arabia Terra, appearing (as suggested by Fenton et al., 2015) to produce relatively more southwesterly transport in the northeast and relatively more southeasterly transport in the southwest of these regions. Other variations of wind regimes are recognized in the study area with active wind streaks (i.e., southeasterly winds), morphologic trends of various inactive bedforms (e.g., TARs, plains ripples, etc.), and collective dune crestline orientations, which are documented in detail by Fenton et al. (2015). Additionally, detailed insight into the contemporary wind regimes of the broader area can be gained by mesoscale atmospheric modeling results and should be considered (Chojnacki et al., 2011; Michaels, 2014; Cardinale et al., 2016). For example, Michaels and Fenton (2015) found that large craters (>2 km in diameter) selectively enhanced inflowing northerly winds in the study area, consistent with slip face orientations described herein.

Ultimately, flux differences are due to spatial variations in boundary conditions, such as sediment supply, transport capacity of the wind, and non-dune topographic effects on near-surface wind flow (see Section 4.2 for discussion of topographic effects) (Long and Sharp, 1964; Kocurek and Lancaster, 1999; Kocurek and Ewing, 2012).

Dune crest fluxes also displayed substantial geographic variation across the study area (Figs. 1c and 3; Table 2). For comparison, data for dunes at Victoria Valley, Antarctica (Bourke et al., 2009) and the Salton Sea, California (Pelletier, 2013) are provided in Fig. 3, and demonstrate that most terrestrial barchan sand fluxes are an order of magnitude higher than those on Mars. Gale crater dunes (Silvestro et al., 2013) at the “Bagnold Dune Field” (Fig. 3) exhibited overall lower sediment flux rates compared with those in Meridiani Planum. It is important to note that the locations where a slip face length-height technique was used (indicated by a “*” following the site ID in Figs. 3 and 6) likely have dunes possessing slightly underestimated heights and resultant sediment fluxes, accounting for some of the site-to-site variations. The largest individual dune crest fluxes ($>9 \text{ m}^3 \text{ m}^{-1} \text{ yr}^{-1}$) in the study area correspond with tall, but slowly-advancing barchan dunes (e.g., Figs. 3, 4c–d and 7a; Animation 4 and 5) and for low-relief, extremely fast-translating dome dunes (e.g., Fig. 8a; Animation 6 and 7). Even subtle differences in barchan dune morphology may contribute to migration rate variations. For example, dunes possessing more concave slip faces may produce convergent avalanches advancing the lee slope faster than a comparable sized planar-shaped barchan (Sutton et al., 2013). A spectrum of slip face concavity can be observed across the study area; although it is unclear how much of a factor this was as moderate fluxes ($\sim 5 \text{ m}^3 \text{ m}^{-1} \text{ yr}^{-1}$) were observed for dunes with both concave and planar slip faces (e.g., Figs. 7a and 8a).

We also note one seldom acknowledged antecedent factor directly affecting site-to-site results – the spatial placement of the HiRISE monitoring sequence FOV. The placement of the initial t0 time step HiRISE image, which dictated subsequent images, might have been motivated by factors other than detecting bedform motion (e.g., imaging other target geology). For example, the monitoring sequence for site 3488+005 is located downwind of the crater's central uplift, where dune morphology is clearly topographically influenced. Had this sequence FOV been shifted north to cover the stossward portions of the dune field, where disruption of the boundary layer would be reduced (Jerolmack et al., 2012), greater migration rates likely would have been detected.

Spatial variations are prominent at every site, with some dunes estimated to have fluxes five times greater than adjacent dunes (e.g., 1.1 vs. 6.3 m³ m⁻¹ yr⁻¹). Besides potential displacement measurement errors, these trends are in part due to variation in the heights of neighboring bedforms (Fig. 3). Another factor determining bedform mobility is a given dune's location within the field, and thus the local dune density and sand availability. For example, Fig. 7a shows leading-edge barchans followed by closely-spaced barchans and barchanoids downwind where sand availability increases and fluxes decrease, similar to dunes at White Sands, New Mexico and Nili Patera (Kocurek et al., 2007; Bridges et al., 2012). This variation may be caused by the increased roughness associated with the leading-edge dunes and the resultant thickening of the internal boundary layer, causing decreased surface wind stress and resultant sand transport (Jerolmack et al., 2012). Conversely, some sites showed dunes with more consistent flux values dispersed across the fields. For example, moderately-spaced barchans and domes in Endeavour (e.g., Figs. 8 and 9) appear to allow the wind to flow between stossward dunes relatively unperturbed, resulting in comparable rates of transport for the leeward dunes.

Locations with multiple sand flux measurements through time are providing insight into surface winds produced by the current climate system of Mars (Ayoub et al., 2014). For example, the sediment flux values for dunes at Nili Patera were found to increase threefold during the local perihelion season (southern summer) in multiple seasonal measurements (Ayoub et al., 2014), as northerly cross-equatorial return flow from the large-scale Hadley circulation constructively combines with both northeasterly trade winds and daytime easterly upslope flow from Isidis Planitia. Sites in Meridiani with two to three time steps with typical time intervals of a Mars-year can exhibit crest flux values that vary by a factor of five, providing evidence for short periods of rapid migration followed by near-stagnation (Fig. 6). In contrast, multiple annual measurements at other sites are nearly identical, indicating that some dunes are in steady-state as they migrate at these broad time scales. The annual measurements described herein all include the potentially higher-flux period near perihelion (Fig. 6b; near the dashed red lines), masking its impact relative to other periods (Ayoub et al., 2014), but one location in Endeavour crater possessed seasonal images serendipitously acquired overlapping MY 31 perihelion (MY 31 (L_s 174°)–MY 32 (L_s 49°). Interestingly, fluxes for these two seasons alone were greater than the entire preceding Mars-year (site 3548–023 in Figs. 6b and .8b; Animation 6 and 7). Peak insolation (and thus surface heating) in the near-equatorial study region generally occurs from L_s ~240° (perihelion is at L_s ~ 251°) to late southern summer (L_s ~ 340°), with areas north of the equator lagging those to the south. Atmospheric circulations on Mars are partly driven by surface heating,

and indeed, initial mesoscale modeling of Endeavour (Chojnacki et al., 2011) indicated that the strongest winds there occur around two seasons (broadly between/around $L_s \sim 210^\circ$ and 300°) that are roughly coincident with the peak heating in the region. While this increased heating near perihelion and during southern summer is known to contribute to other seasonal phenomena such as enhanced dust lifting (Armstrong and Leovy, 2005; Wang and Richardson, 2015) and recurring slope lineae activity (McEwen et al., 2013), there may be a more widespread effect on sand movement than was previously recognized.

4.2. Sand dune turnover times and the potential implications for climate systems

As described above, planetary sand dune turnover times are estimates of the period over which a bedform significantly reacts to wind patterns, including any response to shifts in climate systems. Average study area sand dune turnover times are 50–1300 Earth-years (25–680 Mars-years) (Fig. 1d), but variations show that individual dunes might turnover in tens to hundreds of Earth-years. These estimates come with an assumption of steady-state migration, which earlier results indicate is not necessarily valid. Additionally, these estimates are likely over-estimates as a bedform's patterns can change significantly without a bedform actually completely turning over. Nevertheless, Meridiani turnover times are several orders of magnitude less than modeled obliquity cycles of $\sim 10^5$ Earth-years (Laskar and Robutel, 1993; Laskar et al., 2004). Variations in Mars' obliquity cycle can drive climate change and have associated effects on dune forming wind regimes (Carr and Head, 2010). Previous studies have proposed that some regional dunes formed in ancient climate systems, based on various observations and assumptions (Malin and Edgett, 2001; Schatz et al., 2006; Claudin and Andreotti, 2006; Fenton and Hayward, 2010). For example, Fenton and Hayward (2010) found compelling evidence for dune stabilization based on dune morphology and regional neutron data for bedforms poleward of $\sim 50^\circ$ S. In that case it was suggested that bedforms were rendered inactive, possibly due to climate change. That does not seem to be the case for equatorial Meridiani Planum, where youthful dunes and ripples migrate and respond to modern-day winds.

4.3. Dune field context and topographic boundary conditions

Antecedent environmental boundary conditions, such as host crater parameters and local topography, are considered as they relate to bedform activity. Other boundary conditions for dune fields (e.g., sediment supply, wind transport capacity) are also important to consider (Kocurek and Lancaster, 1999; Kocurek and Ewing, 2012; Fenton et al., 2015), but will not be discussed here (see Fenton et al., 2015 for a thorough discussion on local wind regime and sediment state). For the 11 craters with active dunes, crater diameter was not determined to be a major factor (Table 3). For example, South Xainza ($D \approx 9$ km) and Endeavour ($D \approx 22$ km) both had dunes with moderate to high crest fluxes. Although the largest craters studied herein ($D > 50$ km) did have lower apparent activity, other tropical dune sites within large circular structures on Mars have documented evidence for prolonged activity (e.g., Nili Patera caldera $D \approx 50$ km, Herschel crater $D \approx 300$ km) (Ayoub et al., 2014; Cardinale et al., 2016). Rather, an advanced crater degradation state and a lack of interior moderate topography (e.g., pits, peaks, yardangs, craters) in the inferred upwind direction appeared to be the leading factors for dune activity. Dunes located on hummocky terrain (Fig. 4a) showed relatively low flux values versus sites possessing smoother topography (Figs. 4b, 7a,

8 and 9). Notably, East Firsoff dunes located within a yardang field have clearly been affected by prominent yardangs, which impede their migration (Fig. 7b and 9). This finding is likely related to the close relationship between smaller-scale roughness versus shear stress (Jerolmack et al., 2012; Pelletier, 2013).

Perhaps related to crater degradation state, a moderate inverse correlation with crater depth and activity was found (i.e., shallower craters (<1.2 km deep) contain more active dunes). Many regional craters are interpreted to have had ancient aggradation including the deposition of the Burns Formation sedimentary unit (Hynek and Di Achille, 2014), with Endeavour crater being a prominent example. Both crater rim degradation, which would allow sand-transporting wind greater intra-crater accessibility, as well as deposition of materials in the crater (effectively making them shallower), seem likely to be important contributing factors. Given that these results are based on small-sample statistics, future efforts will test these trends more rigorously using a larger sample size over a wider range of contexts in which we find dune fields. It is interesting to note that higher flux values will lead to enhanced surface erosion, which in turn leads to further-muted topography, forming the basis of a positive feedback system that may be present at some locations on Mars. This relationship assumes continual aeolian activity over prolonged periods of time, which is thought to be the case for much of Mars' history (Bibring et al., 2006). If confirmed, this finding would be an important component of landscape evolution models for Mars (Day and Kocurek, 2015).

5. Conclusions

Large, dark dunes across central Meridiani Planum were detected to be active using nearly a decade of observations (2007–2016). This dune activity was primarily indicated from small, meter-scale morphologic changes observed in repeat, fine-scale images from HiRISE, but also was apparent from larger, decameter- to hectometer-scale events that are recorded in HiRISE and CTX data. The Meridiani Planum region, particularly the ~500,000 km² area surrounding the Opportunity rover, is now known to be one of the most active regions of the planet in terms of wind-driven phenomena. Future studies of regional aeolian systems may continue to show that Mars is a dynamic planet where eroded sediment frequently interacts with (and is transported by) the atmosphere.

Ultimately, the stated hypothesis that dunes in the area surrounding Endeavour crater are also active and part of a region-wide sediment migration driven by a northwesterly wind regime was largely confirmed, with the noted caveat of variations in migration direction. Additionally, we note other results from this case study:

- All 13 study area dune fields with sufficient data clearly show evidence for activity, including ~54% which were determined to have dunes which were migrating. Ripple migration, bedform deflation, and/or dune border modification were observed at all sites containing HiRISE pairs.
- The observed sediment transport direction was consistent with a regional northeasterly-to-northwesterly wind regime, revealing more directional variation than was appreciated from earlier, more localized studies.

- Observations indicate substantial geographic and temporal heterogeneity of dune crest fluxes across the study area and each site. Sites with two or more time steps indicate that dune fluxes can vary by a factor of five, providing evidence for short periods of rapid migration followed by near-stagnation. In contrast, multiple annual measurements at other sites are nearly identical, indicating that on the timescale of image acquisition, some dunes are in steady-state as they migrate.
- Turnover times for dunes in Meridiani Planum are much shorter than modeled obliquity cycles, making it unnecessary to resort to paleo-climate wind regimes to explain the existence or morphology of dark dunes.
- Craters containing shallow, degraded, flat-floored interiors tended to have dunes with high sediment fluxes/activity. Conversely, kilometer-scale (in the horizontal) topographic obstructions (e.g., interior craters, peaks, yardangs) found in the upwind direction were determined to be negative factors in dune mobility.
- Finally, the previous, more limited detections of dune activity in Endeavour crater have been shown to be representative of a broader, region-wide pattern of dune motion.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.aeolia.2016.07.004>.

Fig. 1.

Study region in central Meridiani Planum with dune field locations and estimated parameters. Time periods for all figures are in Earth-years unless explicitly stated. (a) Broader area with the interior box shows the study area and FOV for (b-d). MOLA shaded relief with elevation overlaid and dune fields mapped in yellow (Hayward et al., 2007; Fenton et al., 2015). Locations for remaining figures are provided. (b) Dune activity classifications shown on a THEMIS day infrared mosaic. Migration rates are averages, using the longest baseline images and assuming steady migration over the one to four Mars-years between images. (c) The same map as (b) but showing average dune sand flux estimates of HiRISE-monitored sites and using similar assumptions. (d) The same map as (b) but with average turnover times per active dune site.

Fig. 2.

Examples of sites where dune changes had occurred but migration was ambiguous or difficult to measure. (a) Xainza crater ($D \approx 24$ km) dunes in MY 29 and 32 HiRISE images where several bedforms changed position or area (black arrows). (right inset) Transverse bedforms also were displaced roughly one wavelength, shown here as a difference map produced from the two images (t_0-t_1). (left inset) MOLA elevation (-1.5 to -2.4 km) overlaid on CTX G14_023527_1818_XI_01N004 W, with HiRISE and location of the subfigure FOV. Also see Animation 1. (b) Large-scale changes in an unnamed crater ($D \approx 14$ km) south of Endeavour where sand patches appeared in the MY 32 CTX image compared with the initial MY 29 image (black arrows). (right inset) HiRISE view showing little surface texture or evidence for ripples associated with the sand patches. (left inset) MOLA elevation (-1.5 to -2.4 km) overlaid on CTX P18_007994_1787_XN_01S004 W.

Fig. 3.

Comparison of dune migration rates vs. heights for martian and terrestrial dunes. Plot is in log-log space and diagonal lines are isopleths of sand flux. Migration rates for dunes in the study areas are averages using the longest baseline images available. Vertical error bars of 22 cm are provided, which are based on estimated RMS error in image registration (e.g., 0.7 pixel) and human error in assessing dune displacement (e.g., 0.5 pixel). Sites where slip face length-height and manual image registration techniques were used are indicated by a “*” following the site ID, and likely have dunes possessing slightly underestimated height and sediment flux. Additional data plotted are dunes at Gale crater (Silvestro et al., 2013), Victoria Valley, Antarctica (Bourke et al., 2009), and Salton Sea, California (Pelletier, 2013). Note that only migration rates were reported at Gale crater by Silvestro et al. (2013), and the corresponding dune heights used here were extracted using HiRISE DTM DTEEC_001488_1750_001752_1750_U02.

Fig. 4.

Examples of migrating dunes. (a) Active dunes in a medium-sized ($D \approx 50$ km) unnamed crater with relatively rough intra-crater terrain in the northeast section of the study area, using manually registered HiRISE images. Dunes here showed relatively low sediment fluxes while small sand patches show displacement (black arrows) in the three Mars-years between images. (left inset) MOLA elevation (-1.5 to -2.4 km) overlaid on CTX G14_023527_1818_XI_01N004W with HiRISE images and location of the subfigure FOV. Also see Animation 3. (b) Closer view of large barchan advancement (white arrows). (c) Dunes with high sediment fluxes in a small ($D \approx 9$ km) crater informally referred to as South Xainza crater using orthorectified HiRISE images. Note the large slip face changes (black arrows). Also see Animation 5. (left inset) MOLA elevation (-1.5 to -2.4 km) overlaid on CTX P18_007994_1787_XN_01S004W with context for the HiRISE images and location of the subfigure. (d) Closer view of a barchan advancing (black arrows).

Fig. 5.

Sand rose diagrams for dunes in Meridiani Planum. Sand fluxes and displacement directions use the longest baseline images available and can be compared with Fig. 3. Flux values are from 0 to 7 $\text{m}^3 \text{m}^{-1} \text{yr}^{-1}$, and no dune migration was detected in the northern directions.

Fig. 6.

Temporal trends of dune sediment fluxes. Compare with Fig. 3. Sites where slip face length-height and manual image registration techniques were used are indicated by a "*" following the site ID and have dunes possessing slightly underestimated height and sediment flux. (a) Comparison of dune migration rates vs. heights for Meridiani dunes possessing two time-steps for seasonal and annual measurements. Plot is in log-log space and diagonal lines are isopleths of sand flux. Each dune field has a similar color scheme with lighter colors for latter measurements. An individual dune can be traced in a vertical line, as dune height measurements did not change. Vertical error bars are provided and described in Fig. 3. Time (t) of the initial image is given as "t0" and follows chronologically. Note that only two of three time steps for 3592+040 are plotted and the MY 32–33 interval was omitted. Additional data plotted are dunes at Gale crater for comparison. (b) Average sediment flux values per dune field, plotted with respect to time. Sites have one to three time steps. Symbols at the start or end of lines represent image acquisitions. Vertical dashed lines in orange indicate perihelion. Note that these measurements assume steady state migration, which is likely not the case over such long time periods.

Fig. 7.

Annual sediment flux results. Compare with Fig. 6. (a) South Xainza crater with sediment flux estimates per dune, assuming steady migration over the time period between images, and with the latter measurements positioned in the direction of migration. Note the climbing dunes on the south wall, where underlying slopes ranged from 7° to above 20° .

DTEEC_043742_1800_043597_1800_A01 elevation overlaid on ESP_043597_1800. Also see Fig. 4c inset, Animations 4 and 5. (b) As with (a) but for an unnamed crater referred to as East Firsoff crater ($D \approx 52 \text{ km}$). Dune migration here appears be largely retarded by yardangs interspersed throughout the dune field (e.g., white arrows).

DTEEC_042951_1820_043017_1820_A01 elevation overlaid on ESP_043017_1820.

Fig. 8.

Annual and seasonal sediment flux results in Endeavour crater ($D \approx 22$ km). Compare with Fig. 6. (a) Moderate-sized barchan dunes in the western “Greeley dune field” with sediment flux estimates per dune, assuming steady migration over the time period between images, and with the latter measurements positioned in the direction of migration. Most dunes here appear to be in steady state, as many dunes only showed minor variations in migration rate. Using elevation from an unpublished DTM using ESP_040828_1775 and ESP_040973_1775 overlaid on ESP_040973_1775. Also see Animation 8. (b) Seasonal and annual sediment flux results for small dome dunes in east Endeavour crater. Dunes here showed a particularly active first time step, with fluxes for these two seasons alone being greater than the entire preceding Mars year. DTEEC_042674_1775_042740_1775_A01 elevation overlaid on ESP_042674_1775. Also see Animations 6 and 7.

Fig. 9. Perspective views of dune fields using HiRISE DTMs and orthoimages. Compare with Fig. 7 and 8 where image data information is provided. Vertical exaggeration is 2× except for examples in Endeavour, which are at 5×. North is up unless noted.

Table 1

Orbital observation ^a and dune field site ^b characteristics, including mean migration rates and directions.

3548-023 E. Endeavour crater	Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:
	-2.3	354.8	Y	25 cm	Dunes on central floor far from crater wall. No upwind topography at two Dune Field (DF) diameters.
Image	MY		L _s (°)		Activity?
ESP_028815_1780*	31		174		
ESP_034208_1775	32		49		Migration and/or deflation of dome and transverse dunes. 3.7 m/Earth-year to the SSE
ESP_042674_1775	33		37		Migration and/or deflation of dome and transverse dunes. 1.0 m/Earth-year to the SSE
3547-023 W. Endeavour crater	Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:
	-2.3	354.7	Y	25 cm	Dunes on central floor far from crater wall. No upwind topography at two DF diameters.
Image	MY		L _s (°)		Activity?
PSP_005779_1775	28		334		
ESP_032006_1775	32		325		Migration of barchan dunes. 0.7 m/Earth-year to the SSE
ESP_040828_1775	33		325		Migration of barchan dunes. 0.7 m/Earth-year to the SSE
3537-030 W. Bopolu crater	Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:
	-3.0	353.7	Y	50 cm	Dunes on central floor and adjacent to S wall. Minor upwind topography at two DF diameters.
Image	MY		L _s (°)		Activity?
ESP_029804_1770	31		219		
ESP_039338_1770*	32		255		Ripple movement, dune perimeter change, and slip face events. Minor stoss/lee front advancement.
3553-053	Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:
	-5.3	355.3	N	25 cm	Dunes on crater floor and adjacent to S wall. Crater relatively bowl-shaped. No upwind topography at two DF diameters.
Image	MY		L _s (°)		Activity?
ESP_011976_1745	29		210		
ESP_038441_1745	32		201		Small peripheral sand patch deflation. Ripple movement.
3559-035	Lat. (°)	Lon. (°)	DTM?		Resolution Site notes:
	-3.5	355.9	N	25 cm, ~6 m for CTX	Dunes on floor and adjacent to S wall. No upwind topography at two DF diameters.

3548-023 E. Endeavour crater		Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:	
		-2.3	354.8	Y	25 cm	Dunes on central floor far from crater wall. No upwind topography at two Dune Field (DF) diameters.	
Image		MY		L _s (°)		Activity?	
P18_007994_1787_XN_01S004W		29		57		Dark sand patches moved north.	
ESP_034564_1765		32		61		Minor sand sheet border change. Dark sand patches moved north.	
D19_034564_1762_XN_03S004W		32		61		Site notes:	
3524+023 East Firsoff crater		Lat. (°)	Lon. (°)	DTM?	Resolution		
		2.3	352.4	Y	25 cm	Dunes on stoss (N) side of dune field and scattered between yardangs. Other yardangs upwind at 1-2 DF diameters.	
Image		MY		L _s (°)		Activity?	
PSP_007414_1820		29		36		Migration of barchan dunes. 0.2 m/Earth-year to the SSW	
ESP_034129_1820		32		46		Migration of barchan dunes. 0.3 m/Earth-year to the SSW	
ESP_042951_1820		33		46		Site notes:	
3518+014		Lat. (°)	Lon. (°)	DTM?	Resolution		
		1.4	351.8	N	25 cm	Dunes on floor and adjacent to S wall. Moderate upwind topography at one DF diameter.	
Image		MY		L _s (°)		Activity?	
ESP_035830_1815		32		104		Ripple movement, dune perimeter change, and slip face events.	
ESP_044850_1815		33		112		Site notes:	
3556-002 South Xainza crater		Lat. (°)	Lon. (°)	DTM?	Resolution		
		-0.2	355.6	Y	25 cm	Dunes on central floor and adjacent to S wall. Crater relatively bowl-shaped with terrace. No upwind topography at one DF diameter.	
Image		MY		L _s (°)		Activity?	
PSP_009075_1800		29		94		Migration of barchan dunes. 0.3 m/Earth-year to the S to SSE	
ESP_035131_1800		32		80		Migration of barchan dunes. 0.3 m/Earth-year to the S to SSE	
ESP_043597_1800*		33		68		Site notes:	
3561+007 Xainza crater		Lat. (°)	Lon. (°)	DTM?	Resolution		
		0.7	356.1	N	25 cm	Dunes surrounding central uplift with rugged, sometimes streamlined terrain. Moderate upwind topography at one DF diameter.	

3548-023 E. Endeavour crater		Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:	
		-2.3	354.8	Y	25 cm		Dunes on central floor far from crater wall. No upwind topography at two Dune Field (DF) diameters.
Image		MY		L _s (°)			Activity?
PSP_006781_1810		29		14			
ESP_033997_1810*		32		41			Deflation and mobility of sand patches to the SE and N. Minor stoss/lee front advancement.
3561-077		Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:	
		-7.7	356.1	N	25 cm		Dunes on stoss side (N), behind mostly smooth terrain. Some downwind of large crater, but no other upwind topography at two DF diameters.
Image		MY		L _s (°)			Activity?
ESP_016789_1720		30		56			
ESP_034063_1720		32		44			Ripple movement, dune perimeter change, and sand patch movement.
ESP_043663_1720*		33		70			Ripple movement, dune perimeter change, and sand patch movement.
3488+005		Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:	
		-0.5	348.8	N	25 cm		Dunes on central floor and downwind (S) of central uplift. Moderate upwind topography at one DF diameter.
Image		MY		L _s (°)			Activity?
ESP_024213_1805		31		6			
ESP_033483_1805*		32		23			Migration of barchan/barchanoid dunes. 0.6 m/Earth-year to the SSE
3590+037		Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:	
		3.7	358.9	N	25 cm		Dunes on central floor and downwind (S) of hummocky, layered terrain and yardangs. Minor upwind topography at one DF diameter.
Image		MY		L _s (°)			Activity?
PSP_006860_1840		29		17			
ESP_035355_1840*		32		88			Migration of barchan dunes. 0.2 m/Earth-year to the SSW
3592+040		Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:	
		3.7	358.9	N	25 cm		Dunes on central floor and downwind (S) of hummocky, layered terrain and yardangs. Moderate upwind topography at one DF diameter.
Image		MY		L _s (°)			Activity?
PSP_008798_1840		29		84			

3548-023 E. Endeavour crater	Lat. (°)	Lon. (°)	DTM?	Resolution	Site notes:
	-2.3	354.8	Y	25 cm	Dunes on central floor far from crater wall. No upwind topography at two Dune Field (DF) diameters.
ESP_017580_1840	30		83		Migration of barchan dunes. 0.4 m/Earth-year to the S
ESP_035566_1840	32		95		Migration of barchan dunes. 0.2 m/Earth-year to the S
ESP_044309_1840	33		93		Migration of barchan dunes. 0.3 m/Earth-year to the S

^aImages which had an offset of >15° in solar longitude relative to rest the of the series possessed notable offsets in lighting conditions compared with the earlier image and are indicated by a “*”.

^bDune field site IDs, where the first four digits are the monitoring site’s centroid east longitude, the last three digits are the site’s latitude (each coordinate given to the first decimal place without the decimal), and the separating+or – sign indicating which hemisphere.

Table 2

Migration rates^a, sediment fluxes, and turnover times for dune fields studied, in Earth- and Mars-years.

Site ID	Images	Migration rate		Sediment flux		Turnover time	
		m/EY	m/MY	m ³ m ⁻¹ EY ⁻¹	m ³ m ⁻¹ MY ⁻¹	EY	MY
3524+023							
	PSP_007414_1820/ESP_034129_1820	0.23 ± 0.04	0.43 ± 0.08	1.76 ± 0.7	3.31 ± 1.35	817	434
	ESP_034129_1820/ESP_042951_1820	0.30 ± 0.12	0.50 ± 0.26	2.00 ± 1.38	3.70 ± 2.58	1371	737
3590+037							
	PSP_006860_1840/ESP_035355_1840	0.19 ± 0.09	0.37 ± 0.17	1.29 ± 0.78	2.42 ± 1.51	1286	684
3592+040							
	PSP_008798_1840/ESP_017580_1840	0.40 ± 0.08	0.70 ± 0.15	3.30 ± 2.08	6.10 ± 3.87	402	215
	ESP_017580_1840/ESP_035566_1840	0.20 ± 0.08	0.30 ± 0.16	1.20 ± 0.44	2.30 ± 0.85	1106	588
	ESP_035566_1840/ESP_044309_1840	0.3 ± 0.18	0.50 ± 0.35	2.9 ± 1.28	5.40 ± 2.38	369	198
3488+005							
	ESP_024213_1805/ESP_033483_1805	0.55 ± 0.23	1.04 ± 0.39	4.28 ± 1.58	8.05 ± 3.00	535	284
3547-023							
	PSP_005779_1775/ESP_032006_1775	0.66 ± 0.25	1.22 ± 0.46	4.45 ± 1.07	8.23 ± 1.98	293	158
	ESP_032006_1775/ESP_040828_1775	0.70 ± 0.19	1.20 ± 0.34	4.90 ± 2.31	9.30 ± 4.37	267	142
3548-023							
	ESP_028815_1780/ESP_034208_1775	3.69 ± 0.80	8.20 ± 1.76	7.30 ± 3.66	16.10 ± 8.07	22	10
	ESP_034208_1775/ESP_042674_1775	1.03 ± 1.31	1.94 ± 2.44	1.69 ± 1.30	3.18 ± 2.46	158	84
3556-002							
	PSP_009075_1800/ESP_035131_1800	0.30 ± 0.09	0.60 ± 0.18	5.30 ± 1.97	10.00 30 ± 3.70	818	434
	ESP_035131_1800/ESP_043742_1800	0.30 ± 0.11	0.60 ± 0.19	4.70 ± 2.74	8.90 ± 5.14	1013	539

^aMigration rates and sediment flux estimates are provided with mean and standard deviation values for the collective dune population at each monitoring location.

Table 3

Crater parameters^a for active dune field sites.

Site	Diam.	Depth	Crater Morphology ^b	Interior Morphology	Degradation State ^b	Activity ^c	Notes
3547-023, 3548-023	21.85	0.46	Complex, flat-floored	Floor Deposits	1	Moderate to high sediment fluxes	Dunes in center of flat floor (3548-023) and along SW edge (3547-023)
3556-002	8.57	0.78	Complex, flat-floored		2	High sediment fluxes	Dunes covering flat floor and climbing slight terrace in S
3488+005	27.15	1.65	Complex, central summit pit	Floor Deposits	3	Moderate sediment fluxes	Dunes along S/SE of a slight central summit (with shallow pit) on hummocky terrain
3590+037, 3592+040	49.63	1.12	Complex, flat-floored	Slump Deposits/Floor Deposits	2	Low sediment fluxes	Dunes along NE (3592+040) and S (3590+037) of floor with rugged terrain/heavily eroded layered deposits, yardangs/knobs
3524+023	51.8	1.16	Complex, flat-floored	Ejecta Deposits/Floor Deposits	2	Low sediment fluxes	Dunes along E/SE edge of flat floor with numerous yardangs/knobs, greatest infill and most abundant yardangs along the N rim
3537-030	18.89	1.61	Complex, flat-floored	Dunes/Slump Deposits/Floor Deposits	3	Moderate activity	Dunes in center/S of flat floor with some rugged terrain/layered deposits in the SE
3561+007	23.96	1.98	Complex, central pit	Floor Deposits	3	Moderate activity	Dune S of and in central pit surrounded by relatively smooth/flat floor
3559-035	13.59	0.79	Complex, flat-floored	Slump Deposits	3	Moderate activity	Dunes in the S on flat floor approaching hummocky terrain from backwasting in the SW
3561-077	68.66	2.87	Complex, central peak	Slump Deposits	3	Minor activity	Dunes adjacent to central peak with crater (D ≈ 2 km) upwind of some dunes, very rugged terrain
3518+014	15.81	1.24	Complex, central pit	Floor Deposits	3	Minor activity	Dunes to the S of central pit, hummocky terrain and wall slumping
3553-053	10.16	1.08	Complex, flat-floored	Floor Deposits	3	Minor activity	Dunes on flat floor, slight topographic high to W anchoring some dunes

^aCrater data from the Robbins and Hynes (2012) crater database for all columns other than site, activity, and notes.^bCrater degradation state, where 1 = “most modified” and 4 = “most pristine”.^cA qualitative dune activity assessment based on the study results (Table 1). “Low” (<2 m³ m⁻¹ yr⁻¹) and “High” (>4 m³ m⁻¹ yr⁻¹) sediment fluxes are indicated for sites with migrating dunes, whereas “minor” and “moderate” activity is provided for the remaining sites.