Published in final edited form as:

J Geophys Res Planets. 2018 ; 123(2): 353–368. doi:10.1002/2017JE005465.

Dune-Yardang Interactions in Becquerel Crater, Mars

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Abstract

Isolated landscapes largely shaped by aeolian processes can occur on Earth, while the majority of Mars' recent history has been dominated by wind-driven activity. Resultantly, Martian landscapes often exhibit large-scale aeolian features, including yardang landforms carved from sedimentary-layered deposits. High-resolution orbital monitoring has revealed that persistent bedform activity is occurring with dune and ripple migration implying ongoing abrasion of the surface. However, little is known about the interaction between dunes and the topography surrounding them. Here we explore dune-yardang interactions in Becquerel crater in an effort to better understand local landscape evolution. Dunes there occur on the north and south sides of a 700 m tall sedimentary deposit, which displays numerous superposed yardangs. Dune and yardang orientations are congruent, suggesting that they both were formed under a predominantly northerly wind regime. Migration rates and sediment fluxes decrease as dunes approach the deposit and begin to increase again downwind of the deposit where the effect of topographic sheltering decreases. Estimated sand abrasion rates ($16\text{--}40\text{ }\mu\text{m yr}^{-1}$) would yield a formation time of 1.8–4.5 Myr for the 70 m deep yardangs. This evidence for local aeolian abrasion also helps explain the young exposure ages of deposit surfaces, as estimated by the crater size-frequency distribution. Comparisons to terrestrial dune activity and yardang development begin to place constraints on yardang formation times for both Earth and Mars. These results provide insight into the complexities of sediment transport on uneven terrain and are compelling examples of contemporary aeolian-driven landscape evolution on Mars.

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1. Introduction and Motivation

Landscape evolution on Earth is driven by the collective result of erosional and depositional processes, such as aeolian, glacial, fluvial, tectonic activity, and weathering. While isolated landscapes almost entirely shaped by aeolian processes occur on Earth, the majority of Mars' recent history has been dominated by wind-driven activity (Sagan & Bagnold, 1975). Because of this, Martian landscapes often exhibit aeolian features of greater magnitude than those on Earth (Day & Kocurek, 2015; Greeley & Iversen, 1985). Prominent landforms in arid parts of the Earth, Mars, and possibly the Saturnian moon Titan are yardangs (de Silva et al., 2010; Goudie, 2007; Radebaugh et al., 2015; Ward, 1979). Yardangs are streamlined erosional landforms often resembling inverted boat hulls. These features form as a result of abrasion by windblown sediment and deflation of the yardang bedrock and interyardang corridors (Barchyn & Hugenholtz, 2015; Blackwelder, 1934). Thus, yardangs are oriented parallel to the direction of predominant winds in the region. The size of most yardangs on Mars corresponds with what are described as mega-yardangs on Earth because of their large size (Barchyn & Hugenholtz, 2015; Kerber & Head, 2012; Kerber & Radebaugh, 2017). Although once thought to be remnants of former climates, repeat high-resolution imaging has confirmed sediment transport and wind-driven bedform activity on Mars (Bridges et al., 2011; Chojnacki et al., 2011; Silvestro et al., 2010), implying that surface erosion is ongoing as well.

In particular, sites across the Arabia Terra-Meridiani region of Mars have shown evidence for bedform activity in the form of dune and ripple migration (Chojnacki et al., 2011; Geissler et al., 2012; Silvestro et al., 2011). Variable sediment fluxes from 1 to $20 \text{ m}^3 \text{ m}^{-1} \text{ yr}^{-1}$ have been recorded for intracrater dune fields located in Endeavour crater and other relatively topographically simple regional craters (Chojnacki, Urso, Fenton, et al., 2017). While reports of dune activity continue to grow, little is known about the interaction between dunes and the topography surrounding them.

Ancient layered sedimentary deposits possessing prominent yardang fields are also frequently found within large impact craters in Arabia Terra (Edgett & Malin, 2002; Grotzinger & Milliken, 2012; Lewis et al., 2008). Many dune fields on Mars are found in topographically low-lying areas, occasionally in the presence of these layered deposits. Observations in Ophir Chasma and Gale crater indicate similarities in the morphology and perceived erodibility of layered sedimentary deposits across Mars (Grindrod & Warner, 2014; Grotzinger & Milliken, 2012). However, the relationship between sand dune transport parameters (e.g., transport directions and sediment fluxes) and local erosion is not well understood (Day & Kocurek, 2015). For example, ventifact orientations on Gale crater rocks were found to be inconsistent with the morphology of local dunes and their migration direction based on in situ data from the *Curiosity* rover (Bridges et al., 2014). Similarly, there exists ambiguity surrounding the factors contributing to and the rate of yardang development on Earth (Barchyn & Hugenholtz, 2015; Carling, 2013; Goudie, 2007; Perkins et al., 2015).

Here we investigate if a topographically prominent layered deposit in Becquerel crater influences sand dune migration and sediment flux rates. Numerous duneforms in this region

are located along both the north and south edges of the deposit, the plains to the west, and a smaller crater within Becquerel to the north of the deposit (Figures 1 and 2). Topography and surface roughness is known to influence atmospheric flow resulting in variations in shear stress that will affect both sand transport and abrasion rates (Greeley & Iversen, 1985; Pye & Tsoar, 1990; White & Tsoar, 1998). Staircase weathering patterns, knobs, and yardangs can be seen along the edges of the deposit suggesting prolonged erosion (Grotzinger & Milliken, 2012). Additionally, dark sediment, presumably mobile is found dispersed across the deposit and lining interyardang corridors. Some of this sediment could be locally derived or transported in as part of aeolian bedforms. Thus, observations of Becquerel crater create an opportunity to estimate abrasion rates due to saltating particles associated with migrating bedforms and compare them with layered deposit exposure ages derived from crater statistics in order to better understand local landscape evolution.

Our investigation starts with a summary of the regional context and methods (section 2). We then present the results of measuring and calculating dune migration, flux, and abrasion rates as well as crater statistics (section 3). Concluding with a discussion (section 4) and concise summary (section 5) of the effects of local topography on dune activity, dune sand abrasion rates in regards to yardang formation rates, and the possible implications for understanding yardang formation on Earth.

2. Study Area and Methodology

2.1. Site Locations and Topographic Setting

The study area covers dune fields adjacent to the thinly bedded (e.g., ~10 m), high albedo layered deposits in Becquerel crater (Lewis et al., 2008). The ~170 km diameter crater is found on the global dichotomy and transition from southern highlands to northern lowlands. Several, large (10–50 km in diameter) superposed craters are found throughout Becquerel crater, whereas the southern portion is dominated by the large interior mound and dark dunes, which are the primary focus of this work. These dunes are primarily barchan in morphology, but also barchanoid and linear dunes can be found. Topographically controlled dunes (e.g., echo dunes and lee dunes; Chojnacki et al., 2010; Greeley & Iversen, 1985; Pye & Tsoar, 1990) also occur depending on local boundary conditions (e.g., sediment supply, wind regime, and proximity to topography; Kocurek & Ewing, 2012; Lancaster, 2009). The study area is covered by four sets of HiRISE monitoring images and further subdivided into seven individual sites (see Figures 1 and 2). Sites are labeled with a number pertaining to the monitoring image set and, when necessary, a letter indicating the subset region. A general description of the topographic setting for each site can be found in Table 1.

2.2. Orbital Visible-Wavelength Images, Change Detection, and Calculations

Aeolian bedform activity was assessed using repeat images (25 cm/pix) from the High Resolution Imaging Science Experiment (HiRISE) (McEwen et al., 2007, 2010) onboard the Mars Reconnaissance Orbiter (MRO). Monitoring images along the layered deposit in Becquerel crater cover an interval of 4.5–7.5 Earth-years (2–3 Mars years) since the first image taken in 2006 (Mars-year 28; see Table 2). Table 2 shows the monitoring image parameters across the study area. When possible, repeat images with similar seasonality and

phase angles were chosen. These practices mitigate change detection error due to variation in lighting or viewing geometry. HiRISE stereo pairs were acquired for Digital Terrain Model (DTM) construction using SOCET SET[®] BAE system photogrammetry software (Kirk et al., 2008). The expected vertical precision for the HiRISE DTMs used in this study is ~30 cm and the horizontal post spacing is 1 m. These products were registered to Mars Orbiter Laser Altimeter (MOLA) profiles for absolute elevation (Smith et al., 2001). Additional monitoring images were orthorectified, along with the stereo images, to the corresponding DTM to aid in change detection. An assessment of any image-to-image offset is provided by SOCET SET as RMS error and is typically 0.3–0.7 of the HiRISE pixel scale (i.e., 25 cm) (Kirk et al., 2008; Sutton et al., 2015). Areas where miss-registration of orthoimages occurred (i.e., high RMS) or terrain artifacts were apparent were avoided.

Dune migration rates, detected by lee front advances of the slip face base of barchan dunes, were measured semiautomatically using ArcGIS software. Polyline tracing the base of each slip face were mapped manually for each monitoring image. Displacement vectors (Figure 3b) were computed from these lines assuming a local orthogonal migration of the slipfaces (Cardinale et al., 2016; Vaz et al., 2016), resulting in an average migration vector for each dune (Figure 3e).

The slip face height is derived continuously using an algorithm that analyzes the elevation and image reflectance along profiles that are perpendicular to the mapped slip face lines (Figures 3a, 3c, and 3d). This allows the automatic mapping of the brink points and the measurement of the slipface height, reducing the effect of DTM artifacts/smoothing, complex dune morphologies, and different illumination conditions. A robust method to identify the brink points consists in identifying the maximum of a marker function (equation (1)) that combines (1) the horizontal distance (D_{int}) to the intersection point between the dune surface and a plane that dips 30° (approximately the angle of repose, Figure 3c), (2) the morphological gradient (Soille, 2002) computed from the orthoimage using a linear structuring element with 7 m (MG(im)), and (3) the topography white top-hat transform (WTH(z)) and curvature (d^2z/dx^2).

$$\arg \max \left[\left(d^2z/dx^2 \right) \times \text{WTH}(z) \times \text{MG}(\text{im})/D_{\text{int}}^2 \right] \quad (1)$$

With the obtained dune migration and height measurements we computed sediment fluxes (Q_c) using equation (2):

$$Q_c = (H_d \times D_d)/t, \quad (2)$$

where H_d is dune slip face height (extracted from the DTM), D_d is the bedform displacement in the direction of migration, and t is the interval of time (in Earth-years) between images producing sediment flux in units of $\text{m}^3 \text{m}^{-1} \text{yr}^{-1}$ (Ould Ahmedou et al., 2007; Vermeesch & Drake, 2008).

Ripple migration rates were measured using orthorectified images under the assumption that displacement was less than one wavelength. Visual cues, such as small defects consistent between monitoring images, were used to identify individual ripples between images (Silvestro et al., 2010).

At site 4, a DTM and associated orthoimages were not available. Therefore map-projected images were manually registered to immobile tie points (e.g., craters and boulders) in ENVI software for change detection similar to prior work (e.g., Bridges et al., 2011; Chojnacki et al., 2011). Dune height (H) for sediment flux calculations in this area was estimated using equation (3):

$$H = L_{\text{SF}} \times \tan\theta, \quad (3)$$

where L_{SF} is the measured adjacent slip face length and θ is the assumed angle of repose (Bourke et al., 2006). Potential errors from high-emission angle images, which may foreshorten slip faces, were mitigated by taking measurements from the nadir-most image (i.e., $<5^\circ$ emission angles) of a monitoring sequence. An average value of 33° , common for both terrestrial and Martian dunes, was then used as the assumed angle of repose (Atwood-Stone & McEwen, 2013; Pye & Tsoar, 1990). Chojnacki, Urso, Fenton, et al. (2017) found slip face height measurements to be within $\sim 8\%$ (± 1 m) of those extracted from DTMs; however, this method generally yields a conservative estimate of dune height and sediment flux.

Estimates for abrasion rates were estimated using equation (4):

$$(S_a Q_i / z)(\alpha \cos\theta + \sin\theta), \quad (4)$$

where S_a represents susceptibility to abrasion, Q_i is the interdune sand flux, z represents the mean trajectory height on Mars, α is the ratio of saltation height to descending path length, and θ is the slope (0° being horizontal and 90° as vertical) of the target material (Bridges et al., 2012). Q_i can be estimated as roughly one-third of the average crest flux for the site (Ould Ahmedou et al., 2007). A range of S_a values have been determined in the laboratory (Greeley et al., 1982) along with z and α for saltating and reptating grains (Kok, 2010). A value of 2×10^{-6} was previously used as the S_a for basaltic sediment targeting basaltic rock, a range of 0.1 to 0.5 m was used for z , and ratios between 0.1 and 0.2 were used for α , similar to Bridges et al. (2012). Abrasion rate estimates using a higher S_a value to account for the nonbasaltic composition of the layered deposit are discussed in section 4.3. Other factors, such as sediment accumulation and sheltering of yardang corridors (Barchyn & Hugenholz, 2015), were not accounted for in our estimates but are noted in the discussion.

2.3. Crater Statistics and Surface Ages

To estimate surface ages using crater statistics (Hartmann, 2005), craters > 100 m in diameter were mapped using Java Mission-planning and Analysis for Remote Sensing (JMARS) geospatial information system (Christensen et al., 2009; Gorelick et al., 2003). Counting was

done using MRO's Context Camera (CTX) (Malin et al., 2007) observations on two separate areas: 990 km² covering the surface of the ILD and 10,644 km² covering the surrounding Becquerel crater floor. The resulting crater counts were analyzed using Craterstats 2.0 software to determine the ages of each surface (Michael & Neukum, 2010). The age of a resurfacing event was also estimated where smaller craters, relative to the size-frequency distribution, have been removed from the layered deposit's surface post deposition (Michael, 2013; Michael & Neukum, 2010).

3. Results

3.1. Orbital Observations of Bedform Activity and General Trends

The summit of the deposit reaches about 700 m above the mean crater floor and decreases in height from east to west (Figure 2). The western limb near sites 1A–C appears more eroded. This portion of the deposit ranges between 100 and 300 m in height and contains abundant, well-developed yardangs. Some of these corridors reach depths of up to 70 m. Yardangs tend to be less abundant and poorly developed toward the east, closer to the deposit summit. Consequentially, little-to-no basaltic sediment can be detected on the deposit at heights >300 m.

Aeolian activity in Becquerel crater has previously been observed with minor changes in sand distribution along the layered deposit (Geissler et al., 2012). Evidence for sand movement in the form of dune and ripple migration was sought across the crater where repeat HiRISE coverage exists. Dunes in the seven study areas are primarily barchans with slip faces oriented southward suggesting a southward wind regime with a limited sand supply. Change detection shows stoss- and lee-side displacements to the south consistent with this interpretation (Figure 4). Migrating dunes are located not only on flatter terrain farther from the deposit (sites 1A and 2A) but also along its edges (sites 1B, 2B, and 3) where slopes steepen (5–8°) (Figure 5 and Animations S1 and S2 in the supporting information). Slower climbing barchans can also occur on slopes approaching ~15°. Echo dunes, which form due to reversing flow and flow separation in the presence of steep topography ultimately retarding their motion (Pye & Tsoar, 1990), are observed where more developed knobs occur and ground slopes steepen >30°. In these cases, movement is generally prohibited except for on the edges where ripples continue to migrate upslope. Additionally, low-albedo sand ripple trains can be observed lining the floors of yardang corridors higher on the deposits and moving southward toward site 1C (Figure 6 and Animation S3). In some areas, small sand patches on the surface of the deposit have been removed between images through sediment deflation. Eastward toward the deposit summit (southeast of site 2), prominent staircase layering steepens (>30°) and appears to stop any significant upslope sediment movement (Figure 5c).

Bulk dune migration toward the south implies a predominantly unidirectional, northerly wind with velocities above the saltation threshold for sand-sized particles (Figure 4 and Animations S1–S4). Dune relief and migration measurements were made at each of the seven sites within Becquerel crater representing locations of varying topographic influence (Figure 2 and Table 1). Dunes range between 4 and 20 m in height. Slip face displacement averages between 0.69 and 1.2 m in the direction of migration (0.12–0.25 m yr⁻¹; all rates

are given in Earth years). An average ripple displacement of 1 m was observed in yardang corridors, corresponding to a migration rate of about 0.18 m yr^{-1} (Figure 6 and Animation S3).

3.2. Sediment Fluxes and Abrasion Rates

Average migration rates, heights, and sediment fluxes for each of the seven sites are shown in Table 1, and fluxes are shown graphically in Figure 7. The largest dunes are found at site 2B where barchans reach heights of up to 20 m and possess moderate sediment fluxes of $0.6\text{--}3.1 \text{ m}^3 \text{ m}^{-1} \text{ yr}^{-1}$. Dunes at this site line the northern (upwind) edge of the layered deposit. Large dunes were also found at site 1B, lining the northern edge of the deposit further west, and corresponded with the lowest migration rates. The greatest migration rates are observed at site 4 reaching up to 0.3 m yr^{-1} , which also correspond with the largest sediment flux estimates ranging from 0.5 to $5.1 \text{ m}^3 \text{ m}^{-1} \text{ yr}^{-1}$. These dunes are located on the floor of a small crater within Becquerel crater, slightly north of the layered deposit. Based on these sediment flux values, average abrasion rates for all dune sites range from a minimum (horizontal surfaces) of $0.2 \text{ } \mu\text{m yr}^{-1}$ to a maximum (vertical surfaces) of $16 \text{ } \mu\text{m yr}^{-1}$ assuming that both the saltating particle and target material are basaltic.

3.3. Crater Statistics

Over 1,400 craters reaching diameters of up to 2.7 km were measured across Becquerel crater floor. Craters were less abundant and significantly smaller on the surface of the layered deposit with only 140 distinguishable craters greater than 100 m. Analysis of the crater frequency and size distribution yielded an age of 3.6 Ga for the crater floor compared to a much younger age of 230 Ma calculated for the deposit's surface (Figure 8). An offset in the size-frequency distribution of craters on the deposit's surface was observed, and it is indicative of a resurfacing event. Resurfacing events most often occur due to erosional or depositional processes, which can obliterate or obscure craters in a particular diameter range. An isolated analysis of the affected crater range, according to the methods of Michael and Neukum (2010), was used to estimate a time frame of 2.6 Ga for the resurfacing event.

4. Discussion

4.1. Dune Activity and Proximity to the Layered Deposit

Sand dune migration rates appear to be greatly affected by the spatial proximity to the layered deposit in Becquerel crater. For all sites, average sediment flux increases with distance from the deposit (Figure 9). This phenomenon can be attributed to distinct topographic factors, two in the north and one in the south. In the north, the effects of an increasing ground slope ($\sim 15^\circ$) are interpreted to cause the up to 25% decrease of the average migration rate between unimpeded dunes at site 1A and dunes adjacent to the deposit at site 1B (Figure 9a). The channeling of atmospheric flow within the yardangs might enhance migration rates in a flatter setting, but this factor is offset with the decreased saltation trajectories due to the increased slope. Additionally, the effects of small-scale topography and complex secondary flows along the edge of the deposit impact dune morphologies and migration rates, as has been observed on Earth (Lancaster, 2009). Duneforms are in some places anchored or broken up by prominent topography and then

reformed as they funnel into yardang corridors (Figures 5a and 5c). This is consistent with the low migration rates of dunes approaching the northern edge of the deposit at sites 2A/B and 3 further east (Figures 5a and 5c). For example, all dunes at site 2B are located on the layered deposit itself, making it an exemplary illustration of inhibited sand movement due to increasing slopes, small-scale topography, and evidence for decelerating winds in the face of an obstacle. This site corresponded to the lowest migration rates compared to all other sites.

The second major factor influencing fluxes occurs with topographic sheltering on the south end of the deposit. At the extreme end of the spectrum, southward sand movement is almost completely prohibited with lee or shadow dunes, which occur when topographic obstacles induce zones of airflow deceleration or sheltering (Greeley & Iversen, 1985; Pye & Tsoar, 1990). These dunes can be observed across the southern cliff edge as the deposit increases in height toward the east (Figure 10). This does not appear to be the case on the western edge of the deposit, where a sand pathway exists between site 1A/B and 1C (Figures 4a and 4b). The effects of topographic sheltering can be seen through the variations in sediment fluxes of individual dunes at site 1C (Figures 5b and 9b). Sediment fluxes increase as dunes travel south, away from the deposit edge. An increase in flux at site 1C is also seen from east to west as the height of the deposit decreases. Therefore, the topographic sheltering at site 1C in the south appears to have a greater effect on sediment fluxes than upslope migration on the northern side of the deposit (site 2B).

However, the low migration rates at site 2B do not correspond to the lowest flux estimates due to the large size of the dunes. Variations in dune heights play a major role in sediment flux estimates in Becquerel crater and may be impacted by several factors. First, most dunes along the northern edge of the deposit (sites 1B and 2B) where yardangs are present have greater heights than those on flat plains (sites 1A, 2A, and 3) and those south of the deposit (site 1C). It is possible that these large dunes are the result of sediment accumulation as dunes approach the deposit and slow down, just before they breakup, reform, and funnel into yardang corridors (Figures 5a and 9a). The deposit acting as a saltation obstacle and the effects of small-scale topography associated with yardangs (e.g., knobs which anchor dunes) appears to reduce migration rates resulting in the secondary effect of increasing the local sediment supply and height of dunes. A similar effect on dune heights occurs due to sediment accumulation in the low-relief areas of craters. For example, site 4 located northward in a smaller, superimposed crater with ample sediment supply includes dunes with comparable dune heights to sites 1B and 2B. The sediment supply upwind (northward) of that site appears to be fairly even across the interior of Becquerel crater. In contrast, the dunes at site 1C on the southern edge of the deposit where sediment supply appears to be more limited have significantly lower heights (Figure 5b). Similarly, the lowest average sediment fluxes for all sites were found at site 3 where dunes are smallest. This trend is consistent with prior analysis of central Meridiani dunes that tended to have depressed fluxes and mobility when located near and around kilometer-scale topographic obstructions (e.g., central peaks and yardangs) as compared with dunes within shallow, degraded, flat-floored craters (Chojnacki, Urso, Fenton, et al., 2017).

4.2. Layered Deposit Characteristics

Becquerel crater is dated to the late Noachian period (Tanaka et al., 2014), but the deposit formation is thought to have occurred in the Hesperian or early Amazonian period (Andrews-Hanna et al., 2010; Grotzinger & Milliken, 2012). Our estimated age of 3.6 Ga for Becquerel crater floor and a resurfacing event placing the time of deposition shortly before 2.6 Ga supports these previous age estimates. The paucity of impact craters on the layered deposit indicates that the surface of the deposit is relatively young (Grindrod & Warner, 2014). Small (10–20 m) and isolated fans shedding light-toned sediment and occasionally boulders can be found at HiRISE-scale on the deposit. However, minimal mass wasting can be seen along the edges of the deposit, and little debris is found in yardang corridors (Figure 6). This evidence may indicate that mass wasting compounded with aeolian erosion is keeping these locations clear of sediment and allowing more effective yardang downcutting compared with flatter settings (Barchyn & Hugenholz, 2015). The young surface age estimate and the lack of substantial erosional debris on the deposit suggest that the sedimentary unit is fairly friable. In comparison, the rim of Becquerel crater shows fewer signs of erosion than the central deposit (Geissler et al., 2012). Arabia Terra intracrater mounds often have low-to-moderate thermal inertia values of their surface consistent with weakly consolidated materials (Ferguson & Christensen, 2008). Poorly lithified sediment such as dust, clay, and sulfate has been proposed as the primary composition of most layered deposits in Arabia Terra (based on spectroscopic, thermophysical, and hydrological modeling analyses) (Andrews-Hanna et al., 2010; Ferguson & Christensen, 2008; Grotzinger & Milliken, 2012), which would be consistent with these findings.

It can be inferred that much of the initial layered mound's bulk has been removed along with craters which were obliterated over the last several billions of years, similar to what has been suggested for the deposits in Ophir Chasma and Gale crater (Day et al., 2016; Grindrod & Warner, 2014). Hydrological modeling and analysis by Andrews-Hanna et al. (2010) proposed that intracrater deposits throughout the Arabia Terra-Meridiani region formed as a result of groundwater upwelling and intracrater evaporate deposition (e.g., sulfates). Alternatively, Ferguson and Christensen (2008) found that interior mound materials within the region were likely to have formed as the result of deposition and cementation of air fall dust. Regardless, both reports concluded that secondary erosion must have been responsible for the removal of significant portions of the mounds (Andrews-Hanna et al., 2010; Ferguson & Christensen, 2008). Prolonged aeolian abrasion documented herein would provide a means for that envisioned secondary erosion and mound removal.

4.3. Abrasion Rates, Long-Term Landscape Evolution, and Sediment Production

The orientation of barchan dunes and their migration direction are consistent with the orientation of local yardangs possibly suggesting a link. Local abrasion rates of $0.2\text{--}16\ \mu\text{m yr}^{-1}$ are similar to other estimates of erosion using other dunes or alternative methods (e.g., crater statistics) (Bridges et al., 2012; Chojnacki, Urso, Banks, et al., 2017; Golombek et al., 2014; Kite & Mayer, 2017). Results do not include wind erosion due to deflation or other types of surface erosion. These estimates used abrasion susceptibility (S_a) values for a basaltic target material, which is not likely the case for Becquerel deposits as they are constrained to be some combination of sulfates, phyllosilicates, and other secondary

minerals (Bibring & Langevin, 2008; Grotzinger & Milliken, 2012). An S_a value reflecting basaltic particles impacting more friable sedimentary materials, likely a weakly cemented sandstone (Grotzinger et al., 2005), would yield a faster rate. For example, if laboratory S_a values for hydrocal (gypsum cement) are used (Greeley et al., 1982) to reflect a more friable target material, then the range of abrasion rates increases to $0.4\text{--}40\text{ }\mu\text{m yr}^{-1}$. Also, rates will increase as dune activity heightens during high obliquity cycles and a thicker atmosphere (Chojnacki, Urso, Banks, et al., 2017; Laskar et al., 2004). Thus, we chose to use an interval of abrasion rates calculated among the sites lining the northern edge of the deposit ($16\text{--}40\text{ }\mu\text{m yr}^{-1}$) for the following example. Using an average yardang depth of 70 m, the calculated yardang formation time is $1.8\text{--}4.5\text{ Myr}$ if the erosion was focused on yardang corridor downcutting. These results are consistent with the analysis of layered deposits of presumably similar composition in Ophir Chasma, which were estimated to have had $\sim 500\text{ m}$ removed in $18\text{--}101\text{ Myr}$ (Grindrod & Warner, 2014) based on abrasion rates of $5\text{--}28\text{ }\mu\text{m yr}^{-1}$ (Bridges et al., 2012). Additionally, other erosional and weathering processes would contribute to landscape evolution (e.g., thermal stress, aqueous alteration/diagenesis, and mass wasting) (Kocurek & Ewing, 2012).

Evidence for the attrition of the Becquerel deposit also allows us to examine whether bedform sand abrasion is also contributing to the local sediment supply and the ultimate fate of the broken-down bedrock. Sediment provenance using remote sensing can be deduced from composition, along with other evidence described above (e.g., detrital material and transport direction) (Chojnacki et al., 2014; Tirsch et al., 2011). Martian dune sand has been dominantly documented to be basaltic in composition (e.g., pyroxene and olivine), but certain limited locations may have minor alteration products (e.g., hydrated sulfates) (Chojnacki et al., 2014; Grotzinger & Milliken, 2012; Squyres et al., 2006; Tirsch et al., 2011). Although layered deposits on Mars have been found to be largely composed of secondary minerals (e.g., sulfates, phyllosilicates, and iron oxides; Grotzinger & Milliken, 2012), some elements of a given deposit may have basaltic components (e.g., Yellowknife Bay formation at Gale crater; Grotzinger et al., 2014). Thus, it is plausible that some detrital material of either primary or secondary compositions derived from the deposit may be incorporated into downwind dunes, as has been proposed for other sand sources on Mars (Chojnacki et al., 2014; Tirsch et al., 2011). Any deposit phyllosilicate components likely deflate and get put into suspension relatively rapidly, as clay's characteristic grain size does not lend itself to saltation. Perhaps more likely would be for any liberated sulfate grains to be incorporated into downwind bedforms at site 1C. However, the layered deposit may only be a secondary sand source, as bedforms become sparser to the east where it seems less likely dunes from the north have crossed over the mound summit (Figure 10). Future spectral mapping may be able to constrain some of these compositional speculations.

Additionally, it is interesting to note that large dark dunes are absent from the Becquerel deposit summit, yet the whole mound is covered by yardangs and other wind-carved features. Clearly, much of the north flank of the mound is too steep for bedforms to climb, with exceptions on the east and west sides. Despite this, several areas of the summit do display dark rippled sand accumulations or larger transverse aeolian ridges (TARs) (Kerber & Head, 2012), frequently on benches adjacent to outcrops. These limited patches of sand were likely locally derived or possibly subaerially deposited (see Chojnacki et al., 2014).

Regardless, local sediment could contribute to some bedrock abrasion, but probably at an order of magnitude less than estimated above. Perhaps direct wind abrasion and deflation is the primary aeolian erosional process for these areas, as is likely the case for other areas on Mars with yardang fields but lacking dune populations (e.g., Medusae Fossae Formation; Kerber & Head, 2012). Moreover, aeolian erosion would be greater during periods of higher orbital obliquity that consists of increased atmospheric pressures and capacity of the wind to erode directly and through sediment entrainment (Armstrong & Leovy, 2005; Chojnacki, Urso, Banks, et al., 2017).

4.4. Terrestrial Comparisons

An interesting terrestrial analogue for Becquerel crater occurs in Chad around the Bodélé depression and surrounding area. The depression contains a heavily eroded lacustrine deposit from the early Holocene with meter scale yardangs (~4 m) that formed within the last 2,400 years (Bristow et al., 2009). Active dunes moving southward across the deposit with migration rates of 10–100 m yr⁻¹ (some of the fastest dunes on Earth) along with sediment flux estimates of over 200 m³ m⁻¹ yr⁻¹ were recorded by Vermeesch and Drake (2008). This would result in a range of abrasion rates (under Martian conditions for direct comparison) between 1,300 and 3,300 μm yr⁻¹, almost 2 orders of magnitudes greater than our estimates in Becquerel crater. At these rates, 4 m scale yardangs could form within 1,200–3,000 years, comfortably bracketing the Bristow et al. (2009) age estimate. As before, the softer target material and other compounding erosional processes (e.g., deflation and thermal cycling; Kocurek & Ewing, 2012) would suggest this to be an under estimate for a formation time. Additionally, abrasion rates under Earth conditions would yield a slightly faster yardang development. Dunes from this site can be traced farther north of the depression into an area containing mega-yardangs (Goudie, 2007). They are similar in size to those in Becquerel crater (~70 m) and contain chains of barchans migrating through the yardang corridors (Figure 11). To illustrate the great variability involved in yardang development due to sediment transport activity, the yardang formation time for these mega-yardangs can be estimated to fall between 21,000 and 54,000 years using the same abrasion rates calculated above for the meter-scale yardangs. Therefore, yardangs of a similar size in close proximity to highly active bedforms (Bodélé depression) can develop in a fraction of the time it would take those close to moderately active bedforms (Becquerel crater).

It is also possible that the presence of dunes could inhibit, rather than drive, yardang formation. Goudie (2007) argues that yardangs are not often found in relation to active dunes, but rather persistent unidirectional winds and a low sediment supply. It is possible for the accumulation of sediment (including bedforms) along yardang corridor floors to shelter host rock from erosion and slow yardang formation (Barchyn & Hugenholtz, 2015). In the case of the Becquerel deposit and Bodélé depression, almost all yardang corridors are clear of loose sediment other than what we perceive to be mobile. The dunes in Chad provide us with an idea of how past wind regimes on Mars may have shaped the planet. It is possible that a comparison of the effects of sediment abrasion on Mars and in arid environments on Earth could begin to shed light on the ambiguities surrounding landscape evolution and in particular yardang formation.

5. Conclusion

The varying migration rates, morphologies, and sediment fluxes of different bedform sites with unique boundary conditions provide insight into interactions between dunes and topography. Dune activity is influenced by topography, while abrasion from transported sediment adds to a landscape's complexity. In Becquerel crater, we saw migration rates and sediment fluxes decrease as dunes approach the layered deposit and begin to increase again downwind of the deposit. The effects of topographic sheltering also increase with the height of the deposit. In turn, saltating particles from these dunes abrade the layered deposit, a more friable surface than the crater floor, forming pronounced erosional features including yardang landforms. The computed abrasion rates imply a yardang formation timescale of just a few million years. In addition, the trend of yardang orientations is congruent with that of present-day bedform migration, which denotes a north-south sediment transport direction. This illustrates that yardangs on Mars must be cautiously used as paleoenvironmental markers (i.e., wind vanes), since they may better represent current sediment transport settings. Just as the study of terrestrial processes can add to our understanding of Martian landscape evolution, examining yardang formation on Mars, a planet dominated by aeolian processes, may provide constraints for studying the developments of yardangs under various climatic conditions on Earth. The dune fields in Becquerel crater provide insight into the complexities of sediment transport on uneven terrain and are compelling examples of how contemporary sediment transport activity is shaping the surface of Mars.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We would like to thank William Yingling and Sarah Sutton for assistance with DTM production at the HiRISE Operations Center (HiROC). Helpful discussions on crater statistics with Stuart Robbins are most appreciated. Thank you to Gary Kocurek and an anonymous reviewer for their thoughtful and helpful input. We are also grateful for the efforts of the many people responsible for the success of the MRO mission, particularly those at HiROC, as well as the MO and MEX mission teams. This research was supported in part by NASA MDAP grant NNN14ZDA001N and the HiRISE mission. D. Vaz was supported by the Italian Ministry of University and Research through grant FIRB-RBFR130ICQ. Supplemental animated GIFs are available in the online version of the paper. All of the data used for this investigation can be found at the HiRISE website (<http://hirise.lpl.arizona.edu/>) or the Planetary Data System (<http://pds.nasa.gov/>).

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Plain Language Summary

Becquerel Crater, located in Arabia Terra on Mars, provides an interesting opportunity to study the interactions of sand dunes and large-scale topography. A dune field can be seen lining the northern and southern edges of a layered mound in the crater's interior. The peak of the mound reaches 700 m above the crater floor. Additionally, its surface has been eaten away by years of erosion exposing patterns resembling staircases and protrusions reminiscent of inverted boat hulls. The latter are streamlined erosional landforms known as yardangs and form due to abrasion caused by wind-blown sediment. Corridors between yardangs along the western edge of the mound in Becquerel Crater reach up to 70 m in depth. Activity due to wind-blown sediment has been detected in dunes lining the deposit as well as sediment within the yardang corridors. These results are consistent with the alignment of the yardang field and provide insight into local wind patterns. Sand abrasion rates calculated using observed dune activity indicate that these yardangs have been forming over the past 1.8–4.5 Myr. This study explores the complexities of transporting wind-blown sand across uneven terrain and illustrates changes occurring to landscapes on Mars today.

Key Points

- The topographic effects of a sedimentary mound largely influence Becquerel atmospheric flow and bedform dune sediment transport rates
- Estimated abrasion rates from dune sand fluxes help constrain yardang formation times and the young exposure ages of the deposit
- This study shows the complexities of sediment transport on uneven terrain and gives examples of contemporary landscape evolution on Mars

Figure 1. Study region in Becquerel crater with HiRISE observation stamps indicated in red and the light-toned layered deposit outlined in blue. THEMIS day infrared (IR) 320 m/pix global mosaic base map with HiRISE images overlaid: (top) ESP_025782_2020, (left) ESP_016077_2015, (middle) ESP_017211_2015, and (right) PSP_001546_2015.

Figure 2.

Locations of individual dune sites (yellow). MOLA topographic profile a–a' inset from western edge to summit of the layered deposit (blue). CTX base maps: (a) (left) D18_034419_2014_XN_21N008W and (right) T01_000873_2016_XI_21N008W and (b) D08_030160_2021_XN_22N008W. HiRISE images: (a) (left) ESP_016077_2015, (middle) ESP_017211_2015, and (right) PSP_001546_2015 and (b) ESP_025782_2020.

Figure 3.

Overview of the methods used to compute sand fluxes from dune slip face migration. (a) Mapped slip face lines and computed brink points (see e for location). (b) Detailed view of the migration vectors computed from the mapped lines. (c) Topographic profile (see Figure 3a for location) showing the intersection point between the surface and an plane dipping 30° as well as the final location of the brink point defined according with equation (1). (d) Normalized display of the parameters used to identify the top of the slip face (see equation (1) for details). (e) The measured migration vectors and dune heights are used to compute sedimentary fluxes for each dune. Flux rates and migration direction labels are placed on dune slipfaces and are indicative of individual dunes.

Figure 4.

Examples of sand displacement and migrating dunes on the west end of the Becquerel deposit with the left column representing t_0 (MY30, L_s 31°) and right t_1 (MY33, L_s 19°). The upper left-most inset shows MOLA overlaid CTX. (a) HiRISE view of sand displaced (arrows) on the stoss side of a sand bed at site 1B. The arrows indicate areas of sediment modification along the edges of the sand sheet. Also see Animation S2. (b) Southward migration observable in advancement of dune slip faces at site 1C. Also see Animation S4. (c) Closer view of slip face advancement for one of the dunes from Figure 4b. The white arrow indicates dune advancement toward a stationary boulder.

Figure 5.

Perspective views of Becquerel crater dune locations. (a) Looking downwind (south) of dunes entering yardang corridors at site 1B. Approximately 4 km wide view at base and vertical exaggeration is $\sim 3\times$. HiRISE image ESP_033707_2015. (b) Looking upwind (north) of dunes exiting the south side of the deposit and on to the Becquerel floor at site 1C in the same image. ~ 5 km wide view at base and vertical exaggeration is $\sim 3\times$. (c) Looking downwind (south) of dunes migrating onto the deposit and within yardangs at sites 2A and

2B. Approximately 6 km wide view at base and vertical exaggeration is $\sim 3x$. HiRISE image ESP_045140_2015.

Figure 6. Yardang corridors on the western portion of the layered deposit (site 1B). The insert shows low-albedo ripple trains lining corridor floors between sites 1B and 1C. HiRISE image ESP_016077_2015. Also see Animation S3.

Figure 7.

Sediment flux plot of average migration rates and average dune heights for each of the study sites. 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. The error bars are provided for manual displacement measurements.

Figure 8. Crater frequency histogram created with craterstats 2.0. Ages calculated for the light-toned layered deposit (red), Becquerel crater floor surrounding the deposit (green), and the approximate commencement of a resurfacing event (black).

Figure 9.

Examples of sediment flux rates for individual dunes at sites (a) 1B and (b) 1C. HiRISE base map image colorized with DTM elevation. (a) Fluxes decrease as saltation rates are dampened by increased slope. Also see Figure 4. (b) Fluxes increase with distance from the deposit as well as from east to west as the height of the deposit decreases.

Figure 10.
Putatively immobile lee dunes along the south edge of the deposit east of site 1C. CTX base map image B19_017211_2015_XN_21N008W.

Figure 11.

(a) Barchan dunes actively migrating southward through a mega-yardang field north of the Bodelé depression in Chad. Google Earth image ($18^{\circ}44'28.06''\text{N}$, $19^{\circ}18'13.42'\text{E}$). (b) Google Earth perspective view looking upwind.

Table 1
Summary of Average Dune Activity^a and Topographic Characteristics at Each of the Seven Sites

Dune site	Rate (m yr ⁻¹)	Height (m)	Flux (m ³ m ⁻¹ yr ⁻¹)	Error (m ³ m ⁻¹ yr ⁻¹)	Topography
1A	0.19	9.5	1.8	±0.04	Becquerel crater floor N of the deposit; flat plains
1B	0.16	10.6	1.53	±0.07	NW edge of the deposit; entering large yardangs
1C	0.15	7	0.95	±0.05	SW edge of the deposit; exiting large yardangs
2A	0.15	9.4	1.1	±0.07	Becquerel crater floor N of the deposit summit; flat plains
2B	0.12	11.5	1.09	±0.06	N edge of the deposit near summit; climbing staircase weathering
3	0.16	6.1	0.89	±0.04	N edge of the deposit near summit; sheltered alcove
4	0.23	10.5	2.44	±0.04	Small crater within Becquerel and N of the deposit; flat plains

^aTransport parameters are averaged using the longest baseline image pair and are provided in Table 2.

Table 2

Summary of HiRISE Image Parameters,^a Including Mars Year (MY)^b and Solar Longitude (L_s), for the Four Monitoring Series Covering Each of the Seven Sites

	Lat. (°)	Lon. (°)
W Becquerel: 1A*-C	21.25	351.52
Images	MY	L_s (°)
ESP_016077_2015	30	31.26
ESP_042173_2015	33	18.5
DTEEC_ESP_034419_2015_ESP_033707_2015_A01		
	Lat. (°)	Lon. (°)
C Becquerel: 2A-B	21.27	351.82
Images	MY	L_s (°)
ESP_017211_2015	30	70.46
ESP_045140_2015	33	122.1
DTEEC_ESP_045140_2015_ESP_044784_2015_A01		
	Lat. (°)	Lon. (°)
E Becquerel: 3	21.44	351.89
Images	MY	L_s (°)
PSP_001546_2015	28	140.41
ESP_037043_2015	32	149.52
DTEEC_ESP_045140_2015_ESP_044784_2015_A01		
	Lat. (°)	Lon. (°)
N Becquerel: 4*	21.98	351.78
Images	MY	L_s (°)
ESP_025782_2020	31	62.11
ESP_047052_2020	33	200.97

^a Images and sites where manual registration was used are indicated by an asterisk.

^b Mars-year 1 began on 11 April 1995, and each subsequent year is defined by a solar longitude range of 0–360° (Piqueux et al., 2015).