Climbing and falling dunes in Valles Marineris, Mars

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[1] Multiple occurrences of “wall dunes” are found several kilometers above the Valles Marineris canyon floor. Dune slip face orientation and bed form morphologies indicate transport direction and whether the wall dunes are climbing dunes or falling dunes. On Earth, these types of dunes form in a unidirectional wind regime and are strongly controlled by the local topography. Newly acquired Mars Reconnaissance Orbiter (MRO) images and topography of the walls of Valles Marineris show similar sand dune morphologies, as wind blown sediment has interacted with local and regional topography. Primarily found in Melas and Coprates Chasmata, these climbing and falling dunes are relevant for understanding aeolian sediment flux, sediment sources, and wind directions. Falling dunes show photogeologic and thermophysical evidence of their sand being provided by adjacent outcrops. Citation: Chojnacki, M., J. E. Moersch, and D. M. Burr (2010), Climbing and falling dunes in Valles Marineris, Mars, Geophys. Res. Lett., 37, L08201, doi:10.1029/2009GL042263.

1. Introduction

[2] Aeolian activity has likely been the most consistent geologic process throughout Mars’ history. Low-albedo, fine-grained bed forms are commonly found scattered at landing sites and in orbital images [Herkenhoff et al., 2008]. Viking studies of Valles Marineris (VM) noted the dark mantles found on the chasm floors, interpreted as dunes [Kieffer and Zent, 1992, and references therein]. These studies speculated that the putative dunes were composed of basaltic sediment derived from local outcrops. Although significant progress has been made over the past three decades in understanding aeolian processes and landforms on Mars, questions remain regarding dune composition, age, morphology and sediment supply under present and past Martian surface conditions.

[3] As part of a near-global dune study, Hayward et al. [2007] cataloged dunes widely distributed over a range of elevations and terrain types. Equatorial dune fields are typically found in classic low albedo features, such as Syrtis Major, Terra Meridiani and Valles Marineris. Indeed, the majority of dune field area between 0° and 30° S are in VM, with 20 dune fields on VM trough floors [Hayward et al., 2007]. Regional meteorology is largely influenced by the ~9 km of VM topography and the resulting atmospheric pressure gradient [Rafkin and Michaels, 2003].

[4] As part of a regional study we mapped 50 dunes fields in VM (Figure 1a) to identify significant trends in composition, thermophysical properties, morphology and possible provenance [Chojnacki and Moersch, 2009]. That study found VM dune fields could be broadly divided into two classes: floor- and wall-related dune fields. Wall-related dune fields, or “wall dunes,” are found proximal to or on walls (Figure 1). We have identified nearly two-dozen occurrences of wall dunes (sub-classified as either climbing or falling dunes) found high on the spur-and-gully walls. Based on available data, these dunes are located preferentially on north-facing slopes in Melas and Coprates Chasmata (Figures 1b and 1c). While previous studies have described Martian climbing and falling dunes within crater rims and troughs [Fenton et al., 2003; Bourke et al., 2004], the climbing and falling dunes found in VM are more abundant, arealally larger and are formed on greater relief. In addition, the climbing and falling dunes in VM possess distinct slip faces, unlike those previously described elsewhere on Mars. The VM climbing and falling dunes are relevant for understanding aeolian sediment flux, sediment sources, and wind direction at the time of their most recent activity. For example, dune slip face orientation preserves a record of the prevailing wind direction at the last time of major dune activity, which may be compared with atmospheric circulation models.

2. Climbing and Falling Dunes on Earth

[5] As discussed by Pye and Tsoar [1990], sediment and airflow interactions with topography at all length scales in mountainous regions significantly affect dune location, size, shape, and orientation. Topography can accelerate and decelerate airflow, and create turbulence, often leading to enhanced erosion, deposition and/or transport of sediment. In areas with a near-unidirectional wind regime, topographically-related dunes can be divided into two classes depending on whether they form upwind or downwind of an obstacle. Upwind accumulations of sand include echo dunes (anchored) or climbing dunes (not anchored), whereas downwind accumulations form lee dunes (anchored) or falling dunes (not anchored). The morphology and geometry (steep cliffs >50°) required for echo and lee dune fields [Tsoar, 1983; Liu et al., 1999] are not observed in the local topography [Neukum et al., 2004], and will not be discussed further.

[6] Climbing dunes are formed when migrating dunes encounters and ascends a substantial slope or cliff (>10°), where there is no major wind flow blockage (Figure S1) [Pye and Tsoar, 1990]. A wind direction aligned with the maximum gradient is also important in formation of climbing dunes [Liu et al., 1999]. Climbing dunes often cascade over the topography through local low points (i.e., passes) to become falling dunes as part of sediment pathways [Evans, 1962; Koscielniak, 1973].

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Figure 1. (a) THEMIS daytime infrared mosaic of Valles Marineris with dune fields mapped in orange. Context boxes for Figures 1b and 1c are in white. Mosaics of (b) southern Melas Chasma and (c) central Coprates Chasma with climbing and falling dunes shown in red and indicated by red arrows. Context boxes for Figures 2 and 3 are also shown in Figures 1a–1c, and black arrows represent viewing angles for Figure S2. (THEMIS image credit: Gorelick and Christiansen [2005]).
Falling dunes, found on the downwind side of large topographic highs, are formed by unidirectional down slope winds and gravity in two main environments (Figure S1). One example of falling dunes is found in Kuwait, where size and morphology are largely influenced by the size, slope and orientation (with respect to the prevailing wind direction) of their host wadis, or desert valleys [Al-Enezi et al., 2008]. The slip face of these dunes may be parallel to wadi walls (resembling a linear dune morphology), arcuate, perpendicular to them (and crescent shaped), or absent altogether (resembling a linear dune morphology), arcuate, perpendicular to them (and crescent shaped), or absent altogether [Al-Enezi et al., 2008]. Bed forms encountering mountainous areas with greater relief than wadis may form the falling dune class [Liu et al., 1999]. If the cliff face is without a prominent protuberance, less streamline convergence, reduction of wind velocity, and sediment deposition may result in falling dunes [Pye and Tsoar, 1990].

Climbing and falling dunes have characteristic slopes and sediment pathways. The underlying topographic slopes for climbing dunes are generally shallower (~10°) than the slopes under falling dunes (~25°) [Evans, 1962; Tsoar, 1983; Liu et al., 1999]. Falling dunes preferentially are transported down gullies (or wadis) as the path of least resistance, whereas climbing dunes may encounter and ascend either gullies or spurs [Koscielniak, 1973; Al-Enezi et al., 2008]. In addition, falling dunes may act as feeders for other dune forms within the trough or valley, whereas climbing dunes may allow sediment to escape from a topographic low [Bourke et al., 2004].

The morphological characteristics that together uniquely define climbing and falling dunes are given in Figure S1. Definitions of wall dune types are somewhat ambiguous in the terrestrial literature. In the present work, we define climbing dunes as bed forms with lee faces on the uphill side and falling dunes as bed forms with lee faces on the downhill side, both lying on topography >8° in slope (Figure S1). Climbing dunes are expected lower on a wall and are often linked to floor dunes with similar slip face orientations, indicating a common transport direction. Also, dune horns of falling dunes may point upwind opposite of the transport direction, contrary to simple barchans.

3. Study Region and Methods

Valles Marineris is a geologically rich region with large landslides [e.g., Quantin et al., 2004], aqueous mineralogical alteration [e.g., Gendrin et al., 2005], and aeolian sedimentation [e.g., Hayward et al., 2007]. The VM dune fields show a large range of dune morphologies, thermophysical properties, and potential sand sources [Chojnacki and Moersch, 2009]. The topography and meteorology of the expansive rift system is distinct from intra-crater terrain (Figure 1a) [Hayward et al., 2007]. The VM aeolian morphologies are likewise distinct from those in intra-crater plains, and include a variety of bed forms found several kilometers above the canyon floor on steep walls, within gullies, and atop landslide heads.

All of the observed VM wall dunes are located on much steeper (≥10°) underlying topography than are the floor dunes in the region (<4°). Lee-faces slip faces must be identifiable to determine dune class (i.e., climbing or falling), otherwise we use the more general term of wall dunes. As discussed above, morphological evidence for transport directions, such as the presence of bed forms above or below the wall dune, near vertical topography and feasible sand pathways are also considered in our determination of whether a given dune is a wall dune. These wall dune fields are small (300 m–3 km wide, 2–7 km long) and have not been previously described in the literature, possibly due to the scarcity of high-resolution images.

With improved spatial resolution and areal coverage, many of these dunes can now be properly classified using data from the Mars Reconnaissance Orbiter (MRO). Images from both the Context Camera (CTX) [Malin et al., 2007] and High Resolution Imaging Science Experiment (HiRISE) [McEwen et al., 2007] were examined for photogeologic evidence of wall dunes. Thermal inertia maps were derived from Mars Odyssey’s Thermal Emission Imaging System (THEMIS) [Christensen et al., 2004; Ferguson et al., 2006] data using the model of Putzig and Mellon [2007], as implemented in the “jENVI” software suite [Platek and Moersch, 2006]. The Mars Express High Resolution Stereo Camera (HRSC) [Neukum et al., 2004] level 4 digital elevation models (DEMs) were used to quantitatively investigate surface morphology (slope profiles, dune orientation) at 50–150 m/pixel. In addition, a DEM was produced from the one available HiRISE stereo pair of VM wall dunes for extraction of dune field slope profiles with ~1 m/pixel horizontal and vertical precision at 1 m/pixel spatial resolution [Kirk et al., 2008].

3.1. Valles Marineris Climbing Dunes

Climbing dunes, primarily in Melas Chasma (Figure 1b), are only found on north-facing walls. Figures 2a and S2a shows a series of climbing dunes extending ~5 km up a prominent gully in the extreme southwest corner of the chasma. This dune field atop a 15° slope shows multiple slip face morphologies (crescent and linear), all indicating unidirectional, upslope gully wind. Another unambiguous group of climbing dunes is found in Coprates Chasma (Figure 2b), but with a slightly different morphology. These streamlined dunes appear nearly halfway up the ~9-km-tall wall, with several minor slip faces and a prominent single sand ridge or slip face parallel to the cliff face above.

The most spatially extensive climbing dunes are found in a series of dark-toned bed forms drapped over the preexisting topography of spur-and-gully walls in south Melas Chasma. Images of this area (Figures S2b, 3a and 3b) show a series of distinct slip faces on the uphill side of the dunes, both within gullies and atop spurs. A large dune field (Figures 1b and S2b) is located on the floor of the chasma 10 km to the north and 1 km lower in elevation. Because of its proximity to the climbing dunes and its slip face orientations indicating a southward wind direction, this floor dune field is the probable sand source for the climbing dunes (Figure S2b). The THEMIS mosaic shows a gradual increase in thermal inertia upslope, up to a thermal boundary (Figure 3b, black arrows). This trend of increasing thermal inertia with elevation is interpreted as evidence for a mixed sand and dust surface lower in the sequence (Figure 3a, blue) with a gradual decrease in dust and increase in grain-size uphill (Figure 3a, cyan). Inspection shows that this boundary corresponds with the upper slip faces and higher-lying, dark-toned aeolian material. We infer it to mark the contact between the lower thermal inertia sand-sized sediment and the higher albedo (~0.15), higher thermal inertia (>800 J m⁻² K⁻¹ s¹/², units hereafter assumed) wall material. A “halo” of dark-toned
(possibly finer-grained) material blankets the wall rock above the slip faces, lowering its thermal inertia substantially (i.e., 900 to 350). Together, these two observations suggest a high level of aeolian activity, with wind driving sand (preferentially fine sand (100–150 μm) as the easiest entrained particle sizes [Kieffer and Zent, 1992]) upslope and removing dust.

3.2. Valles Marineris Falling Dunes

[15] Eastern Coprates Chasma (Figure 1c) hosts a dense and varied population of aeolian morphologies, including: barchan, sand sheet, and climbing and falling dunes that are found within craters, canyon floors, reentrant depressions and gullies several kilometers above the chasma floor [Chojnacki and Moersch, 2009]. The dunes found in depressions and gullies, primarily interpreted as falling dunes (Figures 2c, 2d, S2c and S2d), exhibit a range of sizes, shapes and orientations. All falling dunes discussed here are found on the southern wall of the main chasm and both sides of an isolated ~200 km long eastern wall remnant (Figure 1c, red polygons). Bed forms are not always oriented perpendicular to the local maximum slope, but instead are oriented diagonally across walls, indicating sediment transport in that direction (Figure 2d). These dunes appear to be largely affected by mesoscale topography: a ~3-km-long spur between two dune fields suggests leeward deceleration and consequent deposition (Figure 2d, eastern dune field).

[16] One ~90 km stretch of the southern walls has at least eight wall dunes within neighboring gullies, 2–3 km above the ubiquitous floor dune fields (Figure 1c). Many of these wall dunes have a similar symmetric “lobate” morphology.
Figure 3. Multiple climbing dunes in southern Melas Chasma shown in (a) THEMIS thermal inertia and (b) a CTX image shows increasing thermal inertia southward and upslope to a distinct thermal boundary (black arrows), above which high thermal inertia wall rock is located. In visible-wavelength images (Figure 3b) this same location marks the contact between the furthest extent of the slip faces and dark-toned sediment higher on the slope. A HRSC DEM profile (a to a') is provided with a mean slope value (MS) and axes in units of kilometers. (c–e) A series of falling dunes in southern Coprates Chasma shown in Figure 3c a CTX image colorized with THEMIS thermal inertia data and Figures 3d–3e shows a HiRISE image. In Figure 3d a distinct, arcuate lobate morphology common to other local wall dunes is observed. HiRISE DEM elevation (top) in meters and slope angle (bottom) profiles (a to a') are provided across the bottom three dunes. Closer examination (Figure 3e), confirms slip faces are located on the downhill and flank sides of the dunes.
of repetitive, slightly arcuate slip faces, with horns oriented uphill (Figures 3c–3e and S2d). On a flat surface, this barchan-like bed form would indicate a wind direction uphill. However, inspection of HiRISE DEMs shows material (inferred sand) at the angle of repose (~34°) and likely slip faces on the downhill sides of the dunes (Figures 3d and 3e), indicating downward movement as falling dunes. Several falling dunes in the U.S. Great Basin have strikingly similar arcuate, lobate morphologies and orientations. Koscielniak [1973] found falling lobate dunes to be caused by dune crest overburden that, along with sand saltation, advances the dune crest faster than the flanks (Figure S3). Additionally, the falling dunes in Figures 3c and S3a are clearly restricted to the bottom of the gully and its thermal properties and tone are consistent with local provenance.

4. Discussion

[17] The existence of climbing and falling dunes in VM has many broad implications for the VM-regional and Martian-global aeolian regime. These intriguing aeolian morphologies are the result of a wind environment largely dictated by the micro- and mesoscale topography and large relief of VM. For example, falling dunes found in Coprates Chasma often have horns pointing upwind (Figures 2c, 3c–3e, and S3a). In contrast, the majority of terrestrial and Martian crescent-shaped dunes that occur on relatively flat topography (i.e., barchans) have horns pointing downwind. This morphology suggests slip face advancement occurs at a greater rate towards the center of the dune as compared to the flanks, presumably due to a higher velocity and/or more consistent airflow over the center of the dune. Three-dimensional models of airflow down terrestrial wadis support this notion, with higher wind velocity vectors near the center of the wadi and decreased wind flow on the flanks [Al-Enezi et al., 2008], potentially due to airflow separation of the walls.

[18] Micro- and mesoscale topography has a direct consequence on sediment transport direction. In many cases (e.g., Coprates Chasma), the climbing and falling dune slip faces orientations are inconsistent with those of dunes found on the canyon floor [Hayward et al., 2007], suggesting a more complex picture than simple up- or down-canyon winds. Contrasting with this, south Melas Chasma climbing dunes indicate a strong, southward wind direction during periods of dune activity, which agrees with meteorological model predictions for the region under current conditions [Rafkin and Michaels, 2003].

[19] To date, no dark-toned dunes have been located near the rim of VM, nor on the plateau surrounding the chasma system. The closest major dune field concentration, in Argyre Planitia, is more than 2000 km away [Hayward et al., 2007]. Although minor light-toned transverse aeolian ridges (TARs) are common to adjacent plateaus, and no doubt over time some of this sediment has blown into the rift system, these TARs have inconsistent thermal inertia and albedo with dune material discussed herein (e.g., Figures 3c and S3) [Chojnacki and Moersch, 2009]. All the falling dunes discussed here, which are located in east Coprates Chasma, appear isolated from extra-rift sand sources. The plateau above the south wall dunes (Figure 1c (bottom left)) show a barrier (cantena) to sediment transport and currently lacks visible aeolian features. Climbing and falling dunes, on Earth and Mars, have been found to be part of larger aeolian sediment pathways across troughs or mountains [Lancaster and Tschakerian, 1996; Bourke et al., 2004]. If the Mars dune sediment source were the plateau regions outside of VM, we would expect to find falling dunes proximal to chasma rims (i.e., on the upper half of canyon walls). Rather, falling dunes on lower reaches of canyon walls that have eroding outcrops above them and floor dunes below them (Figures 1c, 3c–3e, and S3a) provide evidence that dune material is locally derived. This dune provenance may mark a distinction between terrestrial and Martian examples of falling dunes, as terrestrial falling dunes have not been reported to form in situ.

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