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Review Article

Recent developments in planetary Aeolian studies and their terrestrial analogs

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ABSTRACT

This report summarizes the many advances that have been made in the study of planetary Aeolian processes that have taken place since the first Planetary Dunes Workshop was held in May of 2008, through 2011. Many of the recent studies are facilitated by the wealth and variety of high resolution imaging and spectra data still being returned by multiple spacecraft in orbit and on the surface of Mars, as well as Cassini radar and imaging data for the unique linear dunes on Titan, the large moon of Saturn. The report is divided into seven broad topics: exploring the Martian rock record, the action of the wind, sediment composition, sediment transport, Aeolian bedforms, modification processes, and Titan. Analog studies of terrestrial landforms and processes continue to improve our understanding of the operation of Aeolian processes on other planetary surfaces in each of these topics. Four subjects are likely to see increased emphasis during the coming years: Martian aeolianites, sand compositional diversity, active versus inactive features, and deposition versus erosion. Continued growth of the planetary Aeolian literature is expected as several spacecraft continue to provide high-quality data, including the successful arrival of the Curiosity rover at Mars in August of 2012.

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1. Introduction

Aeolian studies encompass a range of processes and landforms that are the result of the interaction between the wind and the rocks or soils that comprise the surface materials. The work of the wind on the surface is primarily accomplished through the motion of loose particles induced by the wind flow over them (e.g., Bagnold, 1941; Greeley and Iversen, 1985; Lancaster, 1995), although some would argue that wind alone is capable of producing geomorphic work (e.g., Whitney, 1978). Distinctive landforms result from various Aeolian processes, including (but certainly not limited to) sand ripples, various types and shapes of sand dunes, yardangs (bedrock materials eroded into a myriad of shapes), ventifacts (rocks abraded by the wind and sand), loess (dust deposits), sand sheets, and certain gravel plains. If loose particles and wind sufficient to move them is readily available, Aeolian activity is not restricted to only the surface of the Earth. Robotic spacecraft missions to the planets have revealed how prevalent Aeolian deposits and landforms are on practically any solid planetary surface possessing an atmosphere, and in particular a host of recent spacecraft have examined the Martian surface in unprecedented detail, leading to new documentation of many Aeolian features across the Red Planet. Supplementary to these wonderful new data sets from the planets, an improved understanding of the details associated with how certain Aeolian features form and evolve often requires careful observation and instrumentation of terrestrial analogs for features observed on other planets. The purpose of this report is to provide a brief review of recent developments in Aeolian studies of planetary bodies, along with recent studies of analog sites for some planetary landforms and deposits.

Studies of Aeolian processes throughout the solar system have benefited greatly from two recent NASA-supported workshops devoted to this subject. The first Planetary Dunes Workshop was held in Alamogordo, New Mexico, during May of 2008, where about 50 participants presented research results and also took part in a one-day field excursion to nearby White Sands National Monument (Titus et al., 2008a,b). Participants included roughly equal numbers of researchers focused either on the study of planetary Aeolian features or investigations of diverse planetary Aeolian environments; the synergistic interchange between these groups resulted in the identification of several specific subject areas needing further study in the future (Titus et al., 2008b). This first workshop resulted in publication of a special issue of *Geomorphology* (September, 2010) containing nine papers dealing with a wide range of Aeolian topics, including a paper that served both as an introduction to the special issue and as a review of planetary Aeolian studies up to the time of the first workshop (Bourke et al., 2010). The Second Planetary Dunes Workshop was held in Alamosa, Colorado, during May of 2010, where about 60 participants from both the planetary and terrestrial Aeolian communities presented results and took part in a one-day field excursion to nearby Great Sand Dunes National Park and Preserve (Titus et al., 2010; Fenton et al., 2010). Plans are in place for a special issue of *Earth Surface*

Processes and Landforms to publish papers built around work presented at the second workshop. The present report is restricted to a discussion of various published results that came after the first workshop, through all of 2011 (with only sparing citation of later work that bears directly upon the results being discussed). Readers are referred to Bourke et al. (2010) for treatment of results prior to and including the first workshop, and to Greeley and Iversen (1985), Lancaster (1995, 2009) for more in-depth discussion of a host of earlier Aeolian studies.

This review is divided into seven broad topics or themes: exploring the Martian rock record, the action of the wind, sediment composition (including possible sources), sediment transport, Aeolian bedforms, modification processes (particularly gullies on dunes), and Titan. The first six topics are dominated by results derived from the new data from Mars, but the seventh topic indicates that the on-going Cassini mission continues to reveal surprises about the intriguing but perplexing dunes on Titan. Venus is not mentioned here because most of the Aeolian studies for this planet resulted from the Magellan mission in the early 1990s, as reviewed in Bourke et al. (2010), and there are no major revisions at present to the Magellan conclusions. Relevant terrestrial analog studies are covered under each topic that is most closely associated with the reported results, emphasizing terrestrial projects that have a particularly strong potential as analogs for the interpretation of planetary Aeolian features. However, the reader should be cognizant that this report is not intended to represent a thorough review of recent terrestrial Aeolian studies; see Livingstone et al. (2007) for an excellent review of recent studies of terrestrial dunes.

2. Exploring the Martian rock record

There is considerable evidence that the rock record on Mars includes many examples of sedimentary (layered) deposits (e.g., Malin and Edgett, 2000), some of which are more likely the result of transportation by the wind as opposed to deposition out of water. Perhaps the most dramatic evidence of massive wind-driven sandstones comes from the Opportunity rover's explorations in the Meridiani Planum region of Mars. In particular, exposures in Victoria crater reveal dramatic examples of cross-bedded sandstones (Fig. 1) that are at least a dozen meters in thickness (Squyres et al., 2009; Hayes et al., 2011), greatly expanding the stratigraphic thickness of the Aeolian sandstones seen earlier in Endurance crater (Grotzinger et al., 2005). Opportunity also found evidence of dunes with a strong sulfate signature (perhaps more the result of pore-filling materials than of the sand itself), with wet interdune areas, during exploration of Erebus crater (Metz et al., 2009). Hematite concretions within the sulfate-bearing sandstones are interpreted to indicate that a considerable flow of groundwater took place through the sandstones following their emplacement (Squyres et al., 2004a). Orbital data are providing evidence that the discoveries made by Opportunity likely represent large portions of Meridiani Planum (Hynek and Phillips, 2008). Sedimentary rocks derived from wind-blown sands thus appear to represent a

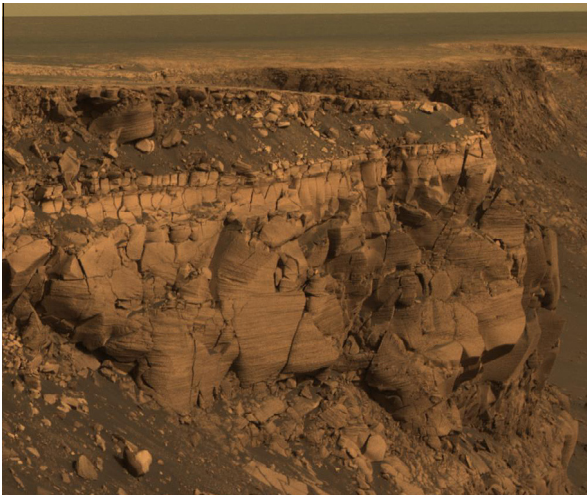


Fig. 1. Cross-bedded Aeolian sandstone outcrop at Cape St. Vincent on the north rim of Victoria crater, Mars. The promontory has ~12 m of vertical relief. PanCam image taken on sol 1167 (May 7, 2007) by the Mars Exploration Rover Opportunity. NASA PIA09694.

very important part of the early history of Mars (Squyres et al., 2009); such rocks may be far more widespread around the planet than would have been considered likely prior to the in situ investigations by Opportunity.

High resolution orbital imaging has revealed that layered rock outcrops are present across Mars at a variety of scales (e.g., Brown et al., 2008; Lewis et al., 2008; Malin et al., 2010; McEwen et al., 2010; Milliken et al., 2010), including the basal unit of the north polar layered deposits (Selvans et al., 2010) and the exhumed but cratered south polar layered deposits (Kolb and Tanaka, 2001; Fenton and Hayward, 2010). Some outcrops include cross-bedding and unconformities clearly visible even from orbital altitudes (Fig. 2; Malin et al., 2010), interpreted to be the result of Aeolian deposition and erosion. Image coverage in places is now sufficient to allow detailed stratigraphic columns to be developed for large layered deposits. For example, within the 154-km-diameter Gale crater basin is a 5-km-tall central mound where an unconformity correlates to major changes in rock composition, signaling a change from sulfate- and clay-rich deposits near the base to uniformly layered deposits with a composition similar to that of the Martian dust at the upper portions of the mound (Milliken et al., 2010). The Gale crater location is destined to reveal much about the history of Mars preserved in these layered rocks as the Curiosity rover explores the Gale mound. Orbital spectrometer measurements are allowing investigators to dissect layered deposits present within Candor Chasma, one portion of the huge Valles Marineris canyon system near the equator of Mars; contrary to the situation at Gale crater, many of the Candor Chasma layered rocks give no indication that water must have been involved in their emplacement (Murchie et al., 2009a,b). Dusty regions on Mars, including broad areas surrounding the enormous shield volcanoes which comprise the Tharsis Montes, northwest of the Valles Marineris canyons, have a complex surface texture that is interpreted to perhaps result from wind action on sand-sized aggregates of dust, some of which eventually lithify to form what may be an Aeolian version of a claystone (Bridges et al., 2010). A possible terrestrial analog to such aggregate wind-blown materials is parna, an Australian word for silt-clay aggregates that undergo saltation and form crescentic dunes around ephemeral playa-lakes; subsequent rain can break down the aggregates to leave silt-clay-rich deposits in the crescentic shape of the former dunes (Greeley and Williams, 1994).

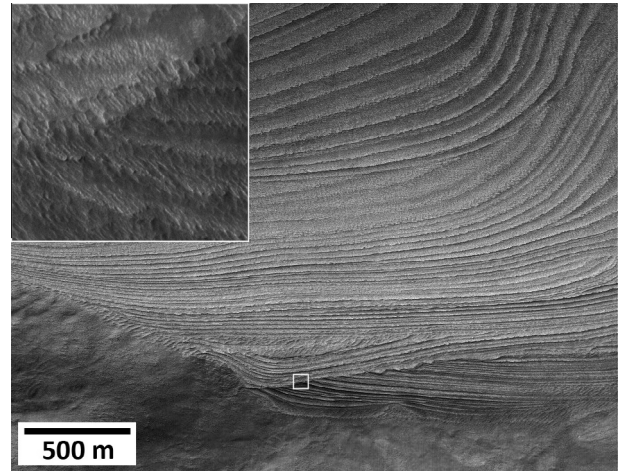


Fig. 2. Exposure showing unconformities in cross-bedded layered sedimentary rocks rocks interpreted to be Aeolian in origin, in the southern part of Galle crater, Mars (see Fig. 19 of Malin and 8 colleagues, 2010). Portion of MOC image M14-02055, centered at 52.3°S, 330.0°E; scene width is 2.9 km, NASA/JPL/MSSS. Inset is portion of HiRISE PSP_003855_1275; scene width is 125 m, NASA/JPL/UA.

3. The action of the wind

The wind is the primary present-day (non-fluvial) agent of movement of materials on terrestrial planets with atmospheres (Craddock, 2011), particularly the Earth, Mars, Venus, and Saturn's large moon Titan. The growing number of spacecraft contributing to the exploration of Mars necessarily focuses considerable attention on the study of Mars, but the dunes on Titan have been receiving increasing attention since their discovery by the Cassini spacecraft in 2004. The spacing of large terrestrial linear dunes may reflect the average depth of the atmospheric boundary layer (Andreotti et al., 2009), which could have considerable relevance to abundant the linear dunes on Titan, but Mars appears to have a dearth of linear dunes. Global monitoring by the Mars Color Imager (MARCI) is documenting changes across the Red Planet for both climatological and meteorological studies, tracking movement of water ice and dust clouds and providing insights into the atmospheric dynamics related to dust lifting (Malin et al., 2008).

Detailed images of dune patterns in Olympia Undae, the large dune field that surrounds the north pole of Mars (e.g., Tanaka et al., 2008), is providing documentation of recent transporting winds through the mapping of ripple orientations across individual dunes, providing important new insights into the formation of this largest area of dunes on Mars (Ewing et al., 2010). The margin of the north polar sand sea is where changes in Martian sand dunes were first documented, illustrated through the disappearance of sand dunes over three Martian years (almost 6 Earth years) (Bourke et al., 2008). Steep scarps present along the margins of the north polar chasmata (canyons), large reentrants carved through the polar cap and into the underlying polar layered deposits, strongly influence the direction and intensity of prevailing winds coming off of the polar ice fields (Warner and Farmer, 2008). The location and orientation of sand dunes near the north polar chasmata indicates the likely source of the polar sand is from within the layered deposits themselves (Warner and Farmer, 2008; Kocurek and Ewing, 2010). The southern high latitudes do not have a large erg comparable to the one surrounding the north polar cap, but 1190 dune fields have been identified poleward of 50°S latitude (Fenton and Hayward, 2010), indicating that Aeolian activity is likely as much a part of the story in southern polar regions as it is in the north.

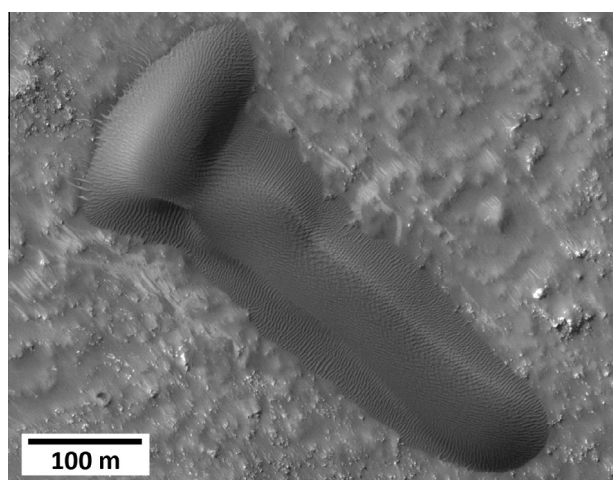


Fig. 3. An example of a tear-drop-shaped dune on Mars, likely formed by bimodal winds (see Parteli et al., 2009b). Note ripple orientations around margin of dune. Portion of HiRISE PSP_007663_1350; scene width is 535 m, NASA/JPL/University of Arizona.

New data are providing important new insights into wind patterns on Mars. Asymmetric arm development on barchans dunes provides evidence for bi-modal winds on Mars, although some caution is warranted since collisions can also produce some dune asymmetries (Bourke, 2010). Modeling of sand transport under a bimodal wind regime, which can result from seasonally varying wind directions, provides insight into conditions that produce some dune shapes; the angle between the dominant wind directions, and the duration of those respective winds, have a strong influence on dune shape, which can account for some unusual dune shapes observed on Mars (Parteli et al., 2009b; Fig. 3), as well as provide insight into temporal changes in wind patterns. Thousands of individual accumulations of sand dunes have now been mapped on Mars (Hayward et al., 2007); the widely distributed dune locations are proving to be very useful as ‘ground truth’ for constraints on atmospheric modeling of Mars, at both global and regional scales (Hayward et al., 2009). Orbital imaging data is now of sufficient resolution to document the movement of both ripples and the margins of sand dunes at locations across Mars (e.g., Bridges et al., 2012; see Section 6.3), confirming earlier indications of localized movement (Silvestro et al., 2010a) while also demonstrating that widely distributed sand movement takes place under current environmental conditions. Not only are images documenting current activity, but they are also providing new tools for investigating past wind patterns. Distinct high-albedo markers of prior locations of slip faces for some barchans dunes provide a new means for mapping sand migration paths within the dunes, and they may also prove to be useful sites for investigating the geochemical implications for cementation of Aeolian sediments (Gardin et al., 2011). On a very local scale, Aeolian scour marks were recently identified around some Martian boulders, so that erosion as well as deposition may now be utilized in investigating local wind patterns (Bishop, 2011).

The capability to make direct comparisons between rover/lander information and high resolution orbital imaging is providing new perspectives on Aeolian features. The Spirit rover carried out both remote and in situ investigations of Aeolian bedforms at Gusev crater (Greeley et al., 2008; Sullivan et al., 2008), including the first images documenting ripple movement on Mars, and fascinating comparisons of features seen from both orbital and surface perspectives. Close-up examination of wind-abraded rocks (ventifacts Laity and Bridges, 2009) revealed that the winds responsible for the abrasion recorded on the rocks are often from

different orientations than those responsible for nearby wind streaks (those visible in the vicinity of the rover), but are more consistent with the orientations of small, second-order ripples documented on the sides of larger Aeolian bedforms in the region examined by the rover (Thomson et al., 2008). The Phoenix Mars Lander became the first spacecraft to successfully land at a polar region of Mars in May of 2008, and while its chemical studies were focused on identifying water ice, the lander also carried instruments that provided the first ground measurements of the atmosphere at polar latitudes. A ‘telltale’ (a hanging mass suspended 1 m above the deck of the spacecraft) was imaged repeatedly, providing evidence of surface wind strength and direction during the 152 days that the spacecraft operated (Holstein-Rathlou et al., 2010). Coordinated observations between the Phoenix lander and the Mars Reconnaissance Orbiter provided the first ‘ground truth’ for atmospheric monitoring of polar latitudes (Tamppari et al., 2010).

Analog studies provided new insights into wind-related processes and their influence on certain surface features. Barchan dunes are common on both Earth and Mars (Fig. 4), so a comparison of barchans planforms observed in the Namib Desert and on Mars revealed both similarities and differences in dune dynamics on both planets (Bourke and Goudie, 2009). The frigid conditions in Antarctica provided a unique opportunity for field investigations of sand dunes under Mars-like temperatures, which will provide important constraints for the development of ground penetrating radar instruments for eventual use on Mars (Bristow et al., 2010a). The Mars rovers confirmed the presence of granule-coated megaripples at both landing sites (Greeley et al., 2004; Sullivan et al., 2005); a prolonged strong wind event at Great Sand Dunes National Park and Preserve (in central Colorado) allowed the movement rate of granule ripples to be measured and then extrapolated to current Martian conditions, suggesting that megaripples common at the Opportunity site should require hundreds to thousands of years to move 1 cm under wind

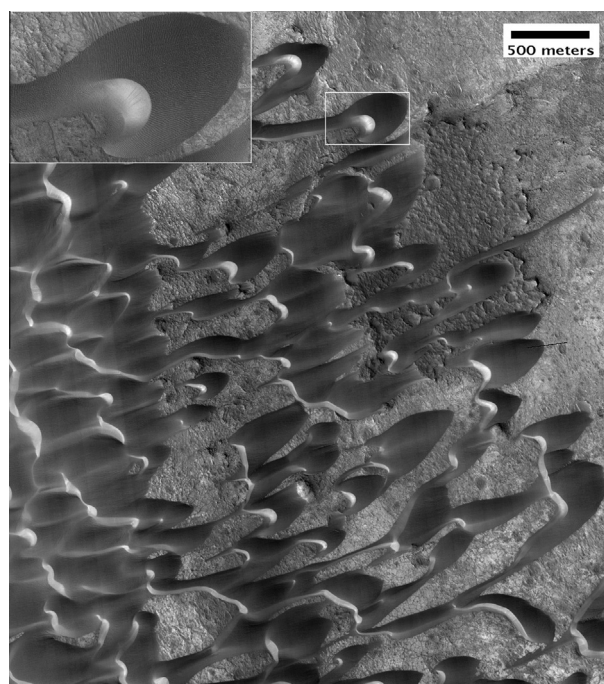


Fig. 4. Barchans and barchanoid ridges in Nili Patera, Mars. Portion of HiRISE PSP_004339_1890 browse image, with inset showing one dune at high resolution. NASA/JPL/University of Arizona.

conditions like those experienced at the Viking landers (Zimbelman et al., 2009). Measurement of the rates of activity for various Aeolian actions, both depositional and erosional, will be increasingly important to understanding the implications of the amazingly detailed information now being obtained by multiple spacecraft.

4. Sediment composition on Mars

The basaltic North Polar dunes in the Olympia Undae are enriched with hydrated minerals (most likely gypsum, Langevin et al., 2005; Fishbaugh et al., 2007; Horgan et al., 2009), in contrast to the mafic composition inferred for other dark dunes on Mars (e.g., Rogers and Christensen, 2003; Ruff and Christensen, 2007; Tirsch et al., 2011). Recent mapping efforts using Observatoire pour la Mineralogie, l'Eau, les Glaces et l'Activité (OMEGA) and Compact Reconnaissance Imaging Spectrometer (CRISM) data show that hydrated minerals are concentrated in the large dark dunes of the circumpolar and adjacent dunefields, as well as in the dust deposited from out of the atmosphere that veneers the surface of the polar cap (Calvin et al., 2009; Horgan et al., 2009; Massé et al., 2010, 2012).

A spectral analysis of the composition of individual dunes in Olympia Undae indicate that the gypsum concentration is strongest at the dune crests, lower along the flanks and weakest in the inter-dunes (Calvin et al., 2009). At the dunefield scale, the strongest gypsum signatures are found in the closely spaced dunes of Olympiae Undae, Abalos Undae and Hyperborea Undae, located close to their proposed sediment sources (Masse et al., 2012). Decreasing strength in spectral signature, particularly clockwise across Olympia Undae, may be due to the increase in dune spacing, which exposes underlying strata that do not have a strong gypsum spectral signature. It may also be due to the reduction in grain size or concentration of gypsum minerals with transport distance. A smaller gypsum grain is more difficult to detect with the OMEGA instrument (Masse et al., 2012). The analog of terrestrial gypsum dunes provide useful insights into the chemical stability of gypsum dunes at Olympia Undae (Szykiewicz et al., 2010).

Materials beneath the polar ice cap are the proposed sediment source for the circumpolar dunefields (Thomas and Weitz, 1989; Howard, 2000; Byrne and Murray, 2002; Edgett et al., 2003; Rodriguez et al., 2007; Tanaka et al., 2008; Warner and Farmer, 2008). Spectral analysis of strata visible in the Basal Unit and the Upper Layered Deposits (ULDs), exposed in troughs eroded through the polar ice cap, have provided support for this hypothesis. Further, the work identifies the gypsum source in the sediment-rich layers beneath and within the polar cap (Calvin et al., 2009; Massé et al., 2010, 2012). Massé et al. (2012) suggest that the gypsum-rich sediment is ablated from the icy strata at arcuate scarps in the polar cap and from the exposed surface of Planum Boreum which underlies the Olympia Undae. These winds are also important in the distribution of Aeolian sediment around the pole.

Mechanisms for the formation of the polar gypsum are not well understood and the two originally proposed hypotheses remain plausible: (a) interaction of Ca-rich minerals with snow containing H₂SO₄ derived from volcanic activity or (b) formation as an evaporite during warm climatic incursions (Langevin et al., 2005). The gypsum detected in the walls of the ULD and deposited as surface veneers on the polar cap are proposed to form either by weathering of dust particles, in the atmosphere prior to their deposition in the ice cap, and/or in the ice cap after following their deposition (Massé et al., 2010).

Mid to low latitude dunefields are also dominantly pyroxene and olivine, and some have hydrated mineral signatures (e.g., Ara-

bia Terra and Meridian Planum, Tirsch et al., 2011). In general, the hydrated dune minerals occur close to rock outcrops that are similarly rich in hydrated minerals, suggesting a bedrock source rather than in situ alteration. Dunes rich in sulfate are located adjacent to the sulfate-rich interior layered deposits (ILDs) in east and west Candor Chasma (Murchie et al., 2009a; Roach et al., 2009). Results from the Spirit rover suggest that the chemistry and particle shape analyses of basaltic soils at Gusev crater are consistent with an origin through Aeolian modification of impact-generated sediments (McGlynn et al., 2011). Thirty percent of dunes in the mid to low latitudes have an olivine signature (Tirsch et al., 2011); similar to the dunes rich in hydrated minerals, dunes rich in olivine are located adjacent to olivine-rich basalt outcrops (e.g., in the Isidis basin, Ehlmann et al., 2010; Mustard et al., 2009). Olivine is frequently detected in small active-looking dunes. As olivine weathers quickly, it suggests that the dune deposits are young and have not undergone chemical weathering. The concentration of olivine in dunes has recently been shown to be a product of Aeolian sorting (Mangold et al., 2011). As smaller grain sizes of olivine are difficult to detect in OMEGA spectra, its absence in the majority of dunefields might reflect its faster physical breakdown under Martian conditions (Tirsch et al., 2011).

The cumulative data on dune mineralogy in the mid to low latitudes is increasingly suggesting local, rather than regional sediment sources for dunefields. The composition of dune fields within craters or chasmata are similar to the composition of the walls or floor of the crater or chasma (Cornwall and Titus, 2010; Tirsch et al., 2011). Tirsch et al. (2011) determined that dark layers in crater floor pits are local sources of dunefields; they propose a working hypothesis of a 'global' layer of dark sediment originally deposited as a thick layer of volcanic ash in the Early to Mid Noachian (4.2–3.9 Ga), rapidly buried by impact ejecta and lava. Large craters that formed in the later Hesperian–Amazonian eras exposed the volcanic ash and subsequent smaller impacts continued release sediments for Aeolian transport. Both spectral and petrologic studies of basaltic sands from the Ka'u Desert in Hawaii suggest that the dark dunes on Mars may be reconcilable with the abundance of basaltic volcanism across Mars without requiring unique mono-mineralic sources that otherwise might be difficult to justify or explain (Tirsch et al., 2012). The dune compositions are a distinct contrast from hydrated silicate minerals (Ehlmann et al., 2009) and the very limited exposures of carbonate rocks (Ehlmann et al., 2008) observed elsewhere in spectral data of Mars,



Fig. 5. Active saltation across damp sand, Bruneau Dunes State Park, central Idaho, USA. View is looking north, centered on a reversing dune ~115 m high; taken on May 9, 2011.

aided in part by the typically strong albedo contrast between Martian dunes and their dusty surroundings.

5. Sediment transport

The movement and transport of sediments by the wind is a common component to all planetary Aeolian studies (Fig. 5). We start with several research efforts that investigated different components of the physics involved in sediment transport by the wind under conditions other than those on the surface of the Earth. Since 2008, many new observations of Martian wind-related features have come out of the host of spacecraft currently active at Mars, including analyses of extensive dune deposits in the polar regions. Laboratory simulations have advanced our understanding of how particulates may be set in motion on other planetary surfaces, and several terrestrial studies are discussed that have direct relevance to obtaining a better understanding of wind-surface interactions on other planets.

5.1. Modeling

Several advances have been made recently in the modeling of Aeolian sediment transport, usually with important implications for possible sediment transport on Mars. Almeida et al. (2008a) addressed a long-standing challenge of being able to constrain particle trajectories relevant within fully developed turbulent flow. The scaling laws they derived allowed these researchers to calculate the motion of saltating grains by directly solving the turbulent wind field and its interaction with saltating particles, with the result that Mars sand grains saltate in trajectories 100 times higher and longer than equivalent saltating grains on Earth, attaining velocities 5–10 times higher than the equivalent grains on Earth (Almeida et al., 2008a). The 'giant' saltation for Mars inferred by Almeida et al. (2008a) was challenged by Andreotti (2008), who said that their model ignored the ability of the transported grains to expel other grains from the sand bed; with this correction, Andreotti (2008) argued that the grain trajectories become independent of u_* (the wind shear velocity) with saltation paths much smaller than those predicted by the new model. Almeida et al. (2008b) responded to the criticism by saying that they did not adopt any maximized flux value but rather determined it during the calculation, and that the model does allow transported grains to eject other grains but rather than including a poorly constrained empirical splash function, the model assumed that in the flux saturation regime each grain-bed collision resulted in one ejected grain. Given the controversy, interested readers should delve into the described models themselves, but the ultimate size of the saltation path length on Mars may not be quite as large as stated in the original article.

In spite of the saltation path length issues, the Almeida model successfully predicted both the shape and the horizontal scale of barchan dunes imaged on the floor of Arkhangelsky crater on Mars (Parteli et al., 2009a), provided the entrainment rate on Mars is an order of magnitude higher than the corresponding value on Earth. The Parteli et al. (2009a) results are also based on a u_* value of 3 m/s, which corresponds to the strongest winds inferred from surface particle distributions as observed by the Mars Exploration Rovers (Sullivan et al., 2005; Jerlomack et al., 2006). The model also is remarkably successful in reproducing unusual 'teardrop'-shaped dunes, such as those observed in Wirtz crater on Mars (Fig. 3), when the sand is subjected to bimodal wind conditions (Parteli et al., 2009a), and the model also provides constraints on the likely divergence angle between the two wind directions required to reproduce several distinctive dune shapes recently observed on Mars (Parteli et al., 2009b; Zhu and Chen,

2010). Modeling sand transport is dependent upon how the wind interacts with surface materials; a study of the effects of large (>0.25 m) roughness elements, such as large rocks (common to all landing sites on Mars), used a shear stress partitioning approach to determine that higher regional wind shear stresses are required on Mars than on Earth for equivalent distributions of roughness elements, primarily due to the low Martian atmospheric density (Gillies et al., 2010).

Kok (2010a) showed that saltation on Mars can be maintained by wind speeds up to an order of magnitude smaller than the wind speed required to initiate saltation. This result could have important implications for dune and ripple development on Mars, particularly if less extreme wind speeds could maintain saltation once it became initiated. One way to obtain new constraints on the likely intensity of winds blowing across Mars is to use observed dune fields around the planet as 'ground truth' for atmospheric modeling of the winds on Mars (Hayward et al., 2009). A global database of sand dunes on Mars (Hayward et al., 2007) was used to measure the dune centroid azimuths and slipface orientations across the planet, for comparison with results from both global and meso-scale climate models; the study concluded that dune centroid azimuth reflects wind patterns on a regional to global scale, and therefore are well represented by global climate models, while slip face orientation is more easily influenced by local factors (like nearby topographic relief) so that the winds responsible for the present orientation are best understood using mesoscale models (Hayward et al., 2009). Fenton and Michaels (2010) ran large eddy simulations that provide a parameterization for wind gusts produced by daytime convective turbulence, which can be used with mesoscale models to increase the daytime sand transport, something generally underestimated in current models. Finally, modeling of the electric fields present within a Martian saltation cloud showed that electric discharges do not occur during saltation on Mars (Kok and Renno, 2009).

Clear documentation of sand movement under current Martian conditions provides impetus for improved modeling of sand transport in the rarified Martian atmosphere. Calculations show that Mars sand grains should saltate in trajectories that are 100 times longer and higher, and reach velocities that are 5–10 times higher, than equivalent sand grains on Earth (Almeida et al., 2008a), leading to models of dune formation and modification under diverse wind regimes (Parteli et al., 2009a, b). Similarly, a recent comprehensive numerical model of steady state saltation (Kok and Renno, 2009) was used to calculate that the wind speed needed to maintain saltation on Mars is an order of magnitude less than the wind speed required to initiate saltation (Kok, 2010a), leading to the possibility of a hysteresis effect that would allow for maintenance of saltation at wind speeds much lower than previously thought (Kok, 2010b). The on-going monitoring of documented sand movement rates on Mars should provide a steadily growing data set for future applications to a variety of numerical modeling efforts.

5.2. Mars observations

Both of the Mars Exploration Rovers Spirit (Squyres et al., 2004a) and Opportunity (Squyres et al., 2004b) have provided a wealth of new data, including results particularly relevant to Aeolian processes. Microscopic Imager close-up views obtained of undisturbed soils along the traverse route of Spirit were used to determine the sedimentological characteristics of >3100 individual particles, which revealed at several locations a distinct uniform population of medium sand that has been redistributed locally by ongoing dynamic Aeolian processes (Cabrol et al., 2008). The deposit "El Dorado" was examined directly by Spirit, the only areally extensive sand deposit visited by either rover; well-rounded

medium basaltic sand here has many ripple bedforms, but localized thermal vortices that swept across El Dorado locally removed dust without perceptibly damaging the cohesionless sandy ripple crests (Sullivan et al., 2008). The apparent contradiction between the mobilization of dust while not significantly affecting more easily entrained sand-sized particles is the result of (1) dust occurring on the surface as fragile, low-density, sand-sized aggregates that are easily entrained and disrupted, and (2) pervasive induration of Martian surface materials in areas outside of active sand deposits (Sullivan et al., 2008). Spirit also provided the first documentation on Mars of small sand ripples having migrated ~ 2 cm in rover images taken only two days apart (Sullivan et al., 2008). On the other side of the planet, Opportunity performed the first in situ investigation of a dark wind streak on Mars, a streak emanating from Victoria crater; results indicate that the Victoria wind streak is produced by the deposition of basaltic sand blown out of the crater from dark bedforms collected below the crater rim, providing an explanation for the serrated margin of Victoria crater through Aeolian abrasion of relatively soft bedrock (Geissler et al., 2008). Opportunity documented beautifully crossbedded rocks exposed along the Victoria crater rim (Fig. 1), providing strong evidence that the bedrock materials here were emplaced as ancient wind-blown dunes (Squyres et al., 2009).

Views from orbit continue to reveal a host of Aeolian landforms across the planet. The High Resolution Imaging Science Experiment (HiRISE) obtained >9100 images of Mars during the primary science phase of the Mars Reconnaissance Orbiter mission (between October 2006 and December 2008), many with a resolution as good as 25 cm/pixel, which included many sites targeted to study wind-driven processes (McEwen et al., 2010). Repeated targeting of many dune locations by HiRISE provided the first documentation from orbit of sand ripple migration on sand dunes in the Nili Patera region of Mars, indicating a minimum of ~ 2 m of migration to the WSW during the fifteen weeks between the two HiRISE images (Silvestro et al., 2010a). Bridges et al. (2012) subsequently documented dune and ripple movement in repeat HiRISE images from across the planet, confirming that under present-day conditions observable changes are now being documented for numerous Aeolian deposits on Mars (Fig. 6). As HiRISE continues to monitor dune locations, undoubtedly more documented cases of dune and ripple movement will become available. Orbital data also have documented discreet sand transport pathways in the Thaumasia region on Mars, including identification of the possible source areas for the sand (Silvestro et al., 2010c), analogous to sand pathways identified in the southwestern United States (e.g., Zimbelman

et al., 1995; Muhs et al., 2003). The dust mantle known to cover the broad Tharsis Montes volcanic region, as well as the Elysium and Arabia regions (e.g., Kieffer et al., 1977; Christensen, 1986), is now considered to consist (most likely) of sand-sized dust aggregates, built up over time from fine airfall dust, that organizes itself into distinctive m-scale bedforms and features now visible in HiRISE images (Bridges et al., 2010). Widespread dust aggregates on Mars raises the possibility that a Martian equivalent to parna (Greeley and Williams, 1994) might produce fine-grained lithified deposits that could potentially be included in the general term 'aeolianites' (see Section 9.1).

5.3. Lab simulations

Interesting progress has been made through several laboratory simulations that are directly relevant to planetary Aeolian processes, but the very limited quantities of lunar soil returned to Earth makes it impractical to conduct laboratory experiments on actual extraterrestrial materials. Seiferlin et al. (2008) provide a thorough review of various simulants that have been used as analogs for planetary regolith materials, documenting the measured physical properties of both the analog materials and what is known at present about the properties of various planetary regoliths; they conclude that many meaningful laboratory experiments can continue to be conducted on simulated regolith materials, as long as the community remains cognizant of both the similarities and differences between the simulants and actual regolith conditions. Merrison et al. (2008) employed a wind tunnel chamber in which runs using a Mars simulant to explore the effects of Aeolian transportation under Martian conditions (simulating atmospheric composition, pressure, wind speed, temperature, and dust aerosol suspension), resulting in valuable insight into the possible Aeolian development and movement of dust aggregates; this facility should prove helpful for the development, testing, and calibration of flight instruments that are to be used on the Martian surface. Detschel and Lepper (2009) exposed a Martian simulant to the solar spectral irradiance expected at the Martian surface in order to evaluate its potential effect on optically stimulated luminescence (OSL) as a dating tool for Martian sediments. OSL has become a significant tool for unraveling the complex histories of many terrestrial dune sands, so this study has important implications for the eventual application of OSL techniques on Martian samples, either in situ or eventually as returned to terrestrial laboratories. The results of their work are that OSL techniques should not be compromised by enhanced Martian UV radiation for use with K-feldspar,

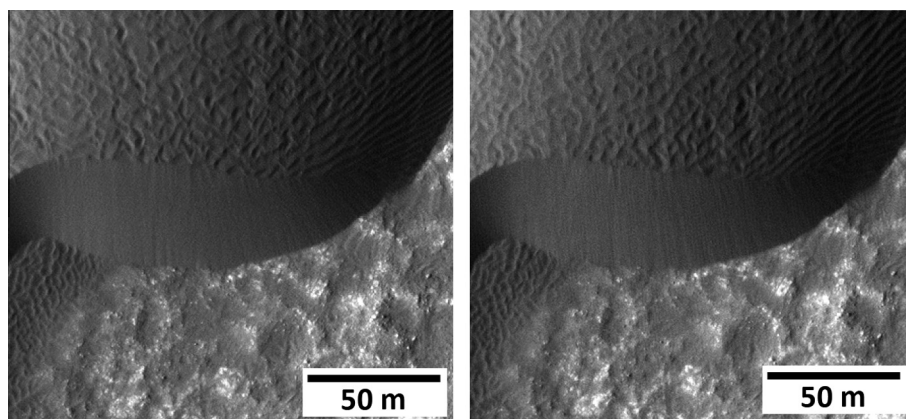


Fig. 6. Slight changes in ripple pattern are documented in two HiRISE images taken 1366 days apart. Images are near 14.8°S, 127.9°E; scene width is 170 m. Left: Portion of PSP_002860_1650. Right: Portion of ESP_020384. NASA/JPL/U of A. (After views on pages 23 and 24 of the Data Supplement for Bridges and 12 colleagues, 2012).

Ca-feldspar, anhydrite, or hydrous Ca and Mg sulfates, but Na-feldspar is capable of acquiring and retaining a signal that could influence OSL interpretations (Detschel and Lepper, 2009). Merrison et al. (2010) performed a unique experiment of tumbling a mixture of silica quartz and magnetite sand for 212 days under Martian atmospheric conditions (which they estimate would be equivalent to about 9 years of continuous sand movement on Mars), after which time they observed the generation of 9% (by volume) fine-grained (<18 μm) hematite dust essentially independent of the atmospheric composition used in the chamber, providing the first experimental evidence of the oxidation of magnetite to hematite through the mechanical effects of simulated Aeolian transportation under Martian conditions. Experimental studies such as these hold great potential for improving our understanding of how various materials should respond to Aeolian processes under diverse planetary conditions.

5.4. Analogs

Investigations of specific landforms here on Earth have provided new insights into how such features may be active on other planetary surfaces. Zimbelman et al. (2009) documented the rate of movement of granule ripples at Great Sand Dunes National Park and Preserve in central Colorado, from which they then calculated the probable rate of movement of comparable granule ripples on the surface of Mars. They concluded that a 25-cm-tall granule-coated megaripple, similar to features traversed by the Opportunity rover at Meridiani Planum, would be expected to move 1 cm in from several hundred to a few thousand years, based on current best estimates of the frequency of saltation events on Mars (Zimbelman et al., 2009). Yizhaq et al. (2009, 2012) made detailed investigations of both the generation and evolution of megaripples in Israel, producing models that should have applicability to megaripple development on other planetary surfaces. Rodriguez et al. (2010) used wind streaks present downwind of several playas in the desert of Argentina as analogs for wind streaks associated with impact craters on Mars; the Argentina features show several morphologic and planform similarities to the Martian wind streaks, and the distinct chemistry of the Argentina streaks makes them very amenable to remote documentation.

Antarctica has long been recognized as one of the best places on Earth to simulate some of the harsh environmental conditions anticipated to be common on Mars. Bourke et al. (2009) documented the rate of movement of sand dunes in Victoria Valley, Antarctica, making use of several decades of aerial photography; the results are not only instructive of the current Aeolian environment in the Antarctic dry valleys, but also relevant to understanding the interactions of mobile sand with snow and ice that seasonally interacts with the dunes. Fieldwork on both reversing sand dunes (Bristow et al., 2010a) and whaleback dunes (Bristow et al., 2010b) in the dry valleys of Antarctica document the niveo-Aeolian actions on these sand dunes, including ground penetrating radar (GPR) surveys of the internal structure of the dunes, all of which will be directly relevant to understanding the possible movement of sand dunes in the polar regions of Mars. Alaska also provides several good locations for monitoring dunes under subarctic environmental conditions (e.g., Necsoiu et al., 2009), which should have application to planetary conditions. As with the laboratory work discussed above, continued analog investigations of well chosen dune localities on Earth will provide important insights into how dunes might be expected to form and move under the diverse environmental conditions.

Dust mobilization through the action of atmospheric vortices ('dust devils') has received increased attention through synergistic studies of dust devil features observed on both Earth and Mars, as well as in the laboratory. Data from multiple spacecraft have

revealed both seasonal and location-related details of dust devils on Mars, including observations from the MER Spirit rover (Greeley et al., 2010), the Phoenix lander at high northern polar latitude (Ellehoj et al., 2010), the High Resolution Stereo Camera on the European Mars Express (Reiss et al., 2011a), and HiRISE (Choi and Dundas (2011). Field studies of dust devil tracks on Earth (Reiss et al. (2010a) were complemented by new temporal data for the development of dust devil tracks on Mars (Reiss et al., 2011b). Innovative field techniques led to in situ measurements of many attributes of dust devils (Metzger et al., 2011), and laboratory simulations have documented the growth and evolution of dust devils (Neakrase and Greeley, 2010a, b). Dust devils have been observed in action so often that the statistics of their occurrence can be explored quantitatively for both Earth and Mars (Pathare et al., 2010; Lorenz, 2011; Kurgansky, 2012). Recent work on dust lifting mechanisms is shedding new light on the causes of dust suspension within the thin Martian atmosphere (Wurm et al., 2008; Spiga and Lewis, 2010; Gheynani et al., 2011).

6. Aeolian features on Mars

Considerable recent advances have been made in identifying and studying individual Aeolian bedforms on Mars, driven in large part by the incredible images available from HiRISE (e.g., Fig. 7), which has been collecting giga-pixel images of virtually every part of Mars (McEwen et al., 2007, 2010). A summary of results obtained by HiRISE includes a section about Aeolian processes and landforms (Section 5.8 of McEwen et al., 2010), but many individual papers make use of HiRISE (as well as other spacecraft) data in addressing issues related to bedforms developed through either wind-related deposition or erosion. The following sections provide a glimpse into what has been learned recently about specific Aeolian-related features on Mars.

6.1. Dunes

Imaging capable of clearly resolving dune morphology is now sufficiently abundant to support global identification of sand dune localities around Mars, supporting the development (Hayward et al., 2007) and refinement of a Mars Global Digital Dune Database (Hayward et al., 2009; Fenton and Hayward, 2010; Hayward, 2011). The database locates thousands of dune fields across the planet, including classification of various dune types, data that has proved useful as ground truth for both Global Climate Models

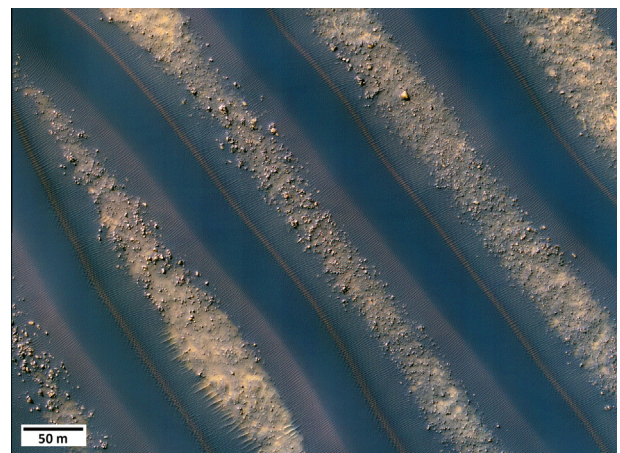


Fig. 7. Detailed view of linear dunes on Mars, with albedo patterns repeated across adjacent dunes. Portion of HiRISE ESP_016036_1370; scene width is 510 m. NASA/JPL/U of A.

(GCMs) and mesoscale climate models (Hayward et al., 2009). The manual identification of dunes can be augmented by automated techniques that have been developed for detecting Martian dune fields, which achieved a detection rate of $\sim 95\%$ for 78 Mars Orbiter Camera (MOC) images obtained from diverse locations around the planet (Bandeira et al., 2011). Regional studies of dune fields as indicators of recent wind patterns on Mars (Hayward et al., 2009; Gardin et al., 2012) that soon should be able to be expanded to comparisons with GCM predictions (e.g., Hayward et al., 2009), something that should soon be able to be expanded to nearly complete global coverage, yet deviations between observed wind patterns inferred from the dunes and the surface wind orientations predicted by atmospheric models indicate that considerable refinement of the modeling is still needed. What is learned from these efforts at understanding the formation and modification of dunes on Mars should be valuable for spatial analysis of remote sensing data and modeling the development and evolution of dune fields on Earth (e.g., Diniega et al., 2010a; Bo and Zheng, 2011a,b; Hugenholtz et al., 2012).

Regional studies of sand dunes on Mars are providing insights into sand mobility on the Red Planet. Climbing and falling dunes have been identified within the enormous Valles Marineris canyon system, including dunes located on canyon walls at elevations that are kilometers above the canyon floor (Chojnacki et al., 2010). Six dune fields in the Thaumasia region were interpreted to indicate the presence of distinct corridors along which the sand movement took place (Silvestro et al., 2010c). Imaging coverage at resolutions capable of monitoring dune planform is revealing that sand dunes in the Arabia and Meridiani Terrae regions show signs of change at several locations, such as inside Endeavor crater (Chojnacki et al., 2011), in the Arabia and Meridiani Terrae regions (Silvestro et al., 2011), in the north polar area (Hansen et al., 2011; Horgan and Bell, 2012), and indeed across the planet (Bridges et al., 2012; see Section 6.3), while other Aeolian features on Mars are likely stable over time scales of from thousands to millions of years (see Section 6.4). Directional radiometry of thermal infrared imaging data holds new potential for constraining surface slopes (Bandfield and Edwards, 2008), a technique that could be applicable to the largest Aeolian bedforms, such as within major dune fields,

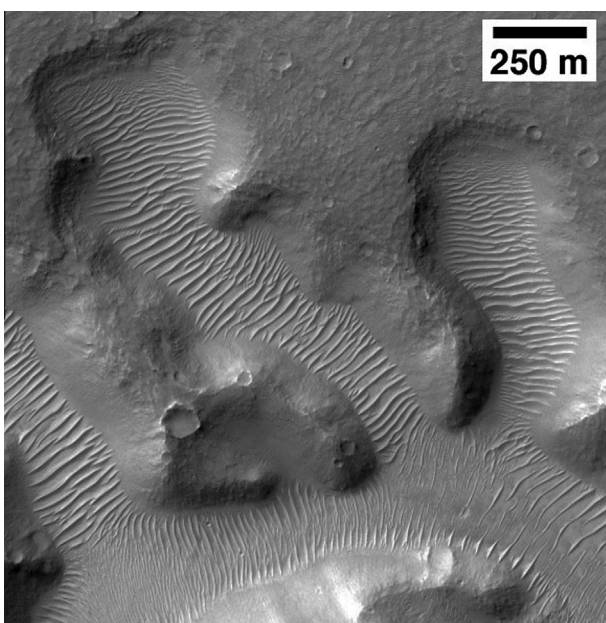


Fig. 8. Transverse Aeolian Ridges (TARs) cover the floor of Nirgal Vallis. Portion of MOC E02-02651, centered on 27.8°S, 316.7°E. NASA/JPL/MSSS.



Fig. 9. A dust devil (white) casts a sinuous shadow across Amazonis Planitia. Portion of HiRISE ESP_026051_2160; scene width is 640 m. NASA/JPL/U of A.

information that should augment what can be derived from visual imaging alone.

6.2. Transverse Aeolian Ridges (TARs)

Martian Aeolian features with widths and/or wavelengths on the scale of ~ 10 m may be either small sand dunes or large wind ripples (Fig. 8), landforms that develop from significantly different emplacement processes; this ambiguity led to the use of the non-genetic term 'transverse Aeolian ridge' (TAR) to describe these features in order to preserve an open mind as to their formation mechanism (Bourke et al., 2003; Wilson and Zimelman, 2004). Assessments of TARs have been conducted at both regional and global scales, making use of MOC and THEMIS images (Balme et al., 2008) and, more recently, HiRISE images (Zimelman, 2010; Berman et al., 2011). The evidence indicates that both small dunes and large ripples (megaripples) are found at the 10-m scale, so that continued use of a non-genetic term still seems warranted (Zimelman, 2010; Berman et al., 2011). However, there is preliminary evidence that the vertical height, profile shape, and height/width aspect ratio of individual bedforms may be able to distinguish between megaripples and small dunes, and also that large, symmetrical TARs are likely to be reversing sand dunes (Zimelman, 2010).

6.3. Active bedforms

Perhaps one of the most exciting recent developments in the study of Aeolian features on Mars is the steadily growing body of evidence that both dunes and ripples are active under current Martian conditions. While there were early indications that some of the dunes in the polar regions of Mars showed observable changes over a time scale of several Martian years (Bourke et al., 2008), the consensus prevailing in the mid-2000s was that the winds on Mars only very rarely exceeded the threshold for movement of sand, based in large part on inferences derived from Viking lander meteorological measurements (e.g., Arvidson et al., 1983). The first definitive evidence that ripples showed measurable movement in today's environment came from the Spirit rover, where tens-of-cm-scale ripples moved ~ 2 cm within a five-day period separating navigation images (Fig. 28 of Sullivan et al., 2008). The Opportunity rover documented Aeolian erasure of rover tracks over a period of hundreds of Mars days, likely the result of both gradual processes such as passage of dust devils (e.g., Fig. 9; interested readers should check the expanded caption available for this image on the HiRISE

web site) and short-lived strong wind events associated with seasonal dust storms (Geissler et al., 2008), consistent with earlier observations of track erasure while Opportunity carried out the first in situ investigation of a dark wind streak on Mars (Geissler et al., 2008).

HiRISE images have revealed that, at least in several locations, sand on Mars is moving on time scales of from weeks to years. Widespread ripple migration was documented (averaging ~ 1.7 m is less than 4 Earth months) on several barchan dunes in the Nili Patera region, the first observations to provide strong constraints on the rate of bedform movement derived from orbital data (Silvestro et al., 2010a). Ripple patterns on individual dunes in the Olympia Undae dune field in the north polar region of Mars were used to map out recent transporting wind directions and their effect on dune development at the 100 m scale (Ewing et al., 2010). Chojnacki et al. (2011) used orbital images to document dunes in Endeavor crater (where Opportunity is now operating) that showed both translation and erosion between 2001 and 2009 as derived from images obtained from multiple spacecraft, providing evidence that the wind inside the crater recently exceeded the surface threshold velocity. Measurable dune advance of between 0.4 and 1 m in one Mars year was documented in the Arabia Terra/Meridiani region of Mars, accompanied by consistent changes in the ripple pattern on the dunes (Silvestro et al., 2011). High albedo features associated with the slip face orientations on nearby barchan dunes in an equatorial dune field on Mars are interpreted to represent cemented Aeolian deposits that formed at the base of dune avalanche faces (see Fig. 5 of Gardin et al., 2011, and accompanying text), providing a new feature for determining the orientation of recent dune movement, much like features observed around the barchans dunes at White Sands National Monument in New Mexico (McKee, 1966; Kocurek et al., 2007). Most recently, repeat HiRISE imaging of numerous monitored sites representing diverse areas of Mars have documented planet-wide sand movement of as much as a few meters per year (Bridges et al., 2012). We are now well into the era where detection of movement will give way to documentation of movement rates, which will represent important constraints both for modeling studies and for quantifying the work potential of Aeolian processes under present Martian conditions, and may help to inform future modeling efforts (see Section 5.1).

6.4. Inactive bedforms

At the same time that we have entered the era of documenting current sand movement on Mars, evidence is also growing that certain Aeolian bedforms remain stable at time scales ranging from thousands to perhaps millions of years. The Opportunity rover documented that some ~ 20 -cm-high megaripples (coated with coarse grains) are well indurated (Sullivan et al., 2005), as was also observed by Spirit in Gusev crater (Sullivan et al., 2008), suggesting relatively long stability to maintain such induration. Extrapolation of the rate of movement of granule-coated megaripples on Earth to (Viking-like) Martian conditions indicated that a 25-cm-high megaripple on Mars could take from hundreds to thousands of Earth years to move only 1 cm (Zimbelman et al., 2009). Observations both from orbit and from the Opportunity rover indicate that the megaripples on Meridiani Planum likely had their latest phase of granule ripple migration between ~ 50 and ~ 200 ka, as evidenced by crater ejecta deposits from two fresh-rayed craters that are superposed on, or superposed by, the granule-coated megaripples (Golombek et al., 2010). The stability of megaripples contrasts with sand ripple migration observed on many Martian sand dunes (Section 6.3), but is broadly consistent with recent evidence that some TARs exposed within the eroded Medusae Fossae Formation (discussed in the following section) are substantially cratered

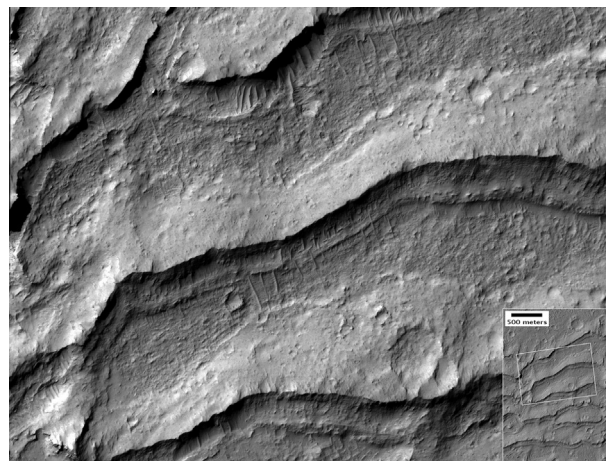


Fig. 10. Lithified dunes with many impact craters superposed on the dune surfaces, indicating considerable time has elapsed since these dunes were last active. Portion of HiRISE PSP_010453_1675. Inset shows context and scale, from portion of browse image. NASA/JPL/U of A.

(Kerber and Head, 2011); cratered Aeolian features (Fig. 10) likely can be interpreted to be fossilized dunes (e.g., Silvestro et al., 2010b) or megaripples. An area ripe for future investigation is the characterization of stabilized Aeolian features so that they can be identified confidently using orbital data, and also contrasted with the documented movement of wind ripples on many sand dune surfaces.

6.5. Wind-related erosional features

The bedforms discussed above all result from Aeolian depositional processes, but erosion by wind-driven sand also produces distinctive landforms. Obstacle marks (crescentic scours) are evident as numerous meter-scale scours around blocks of various sizes scattered within an intracrater dune field located in the Hesperia region of Mars (Bishop, 2011). When combined with wind direction indicators on the nearby dunes, the scour marks provide evidence that the dune field has been subjected to a bimodal wind regime (Bishop, 2011), demonstrating that erosional scour marks can supplement more traditional wind direction indicators associated with sand dunes. Erosion at a scale of hundreds of meters is evident in the form of yardangs, the streamlined ridges shaped by wind-driven sand; yardangs on Mars are particularly well expressed in the friable Medusae Fossae Formation (MFF) deposits located along the equator west of the Tharsis Montes volcanoes (Ward, 1979). HiRISE images of yardangs in the westernmost portion of the MFF deposits show clear evidence of a caprock unit within the MFF materials; the heights of the yardangs suggest that at least $19,000 \text{ km}^3$ of lower member MFF materials have been removed by the wind from just the lower member exposures (Zimbelman and Griffin, 2010). A survey of MOC images in the cratered highlands south of the MFF deposits identified dozens of isolated outliers of MFF, with abundant small yardangs carved into the deposits, suggesting that MFF initially may have covered an area substantially larger than the current enormous extent of the primary MFF exposures (Harrison et al., 2010). Lava flows embayed into MFF exposures suggest that the erosion of the MFF yardangs may date from the Hesperian era, so that some of the Aeolian erosion represented by the yardangs could have taken place more than 3 Ga ago (Kerber and Head, 2010). Some locations within MFF show different yardang orientations on differing layers exposed by the erosion, suggesting wind patterns may have varied greatly with time (see Fig. 29.16 of Wells and Zimbelman, 1997).

6.6. Analogs

Terrestrial studies are shedding light on the formation mechanisms for Aeolian features, especially for megaripples that represent one of the TAR formation alternatives. Rates of movement were measured for 1-cm-high granule ripples at White Sands National Monument (Jerlomack et al., 2006) and 3- and 10-cm-high granule ripples at Great Sand Dunes National Park and Preserve (Zimbelman et al., 2009), both of which produced comparable flux rates for the granular materials, and both of which were applied to understanding megaripples on Mars. Analytical models incorporating nonlinear dynamics are being developed and refined both for normal sand ripples (Yizhaq et al., 2004) and megaripples (Yishaq et al., 2009), constrained by field documentation of the evolution of megaripples derived from repeat stereo photogrammetry (Yizhaq et al., 2009). Recently this work was extended to include documentation of the destruction of megaripples by infrequent strong storm winds, tracing the changes from megaripples back to normal sand ripples (Isenberg et al., 2011). Field measurement of the profile shape of sand ripples, megaripples, and sand dunes led to a method for scaling the measured profiles by the feature width, allowing profile shapes to be compared directly for Aeolian features that span more than three orders of magnitude in physical size (Zimbelman et al., in press). The Mars-like temperatures experienced in the dry valleys of Antarctica led to field studies of slipfaceless 'whaleback' dunes (Bristow et al., 2010b) and frozen reversing dunes (Bristow et al., 2010a), both of which have application to understanding GPR data like that which may eventually be collected during rover missions to Mars. All of the new field-based data should be particularly valuable for constraining models of long-term evolution of Aeolian systems (e.g., Diniaga et al., 2010a) and their potential application to Mars (e.g., Kok, 2010a,b).

Yardangs eroded into ignimbrite (emplaced as flowing volcanic ash) deposits in the high Puna region of western Argentina provide important analog studies for understanding the MFF yardangs on Mars (de Silva et al., 2010). Variations in the degree of welding of the Argentina ignimbrite deposits contribute to erosional attributes that are very similar to the caprock erosion-resistant tops on some MFF yardangs. Near to the location of the Argentina yardang study, are located some of the largest Aeolian megaripples yet to be documented in the literature; these enormous ripples attain heights up to 2.3 m, wavelengths up to 43 m, and a crest maximum grain size up to 19 mm in size (Milana, 2009). There is continuing

debate as to whether or not these very large megaripples require contemporaneous erosion of the bedrock in the inter-ripple troughs (Comment: de Silva, 2010; Reply: Milana et al., 2010). The arid, 4000-m-high Puna region holds great potential for continuing analog studies that will be relevant to both depositional and erosional Aeolian processes on Mars.

7. Modification processes on Mars

Once the sand has been emplaced upon Martian dunes, factors other than only Aeolian processes may come into play. Horvath et al. (2009) described dark (low albedo) features (spots and extended streaks) visible in images of sand dunes (Fig. 11) near the poles of Mars; they investigated origins by dry avalanche, liquid CO₂, liquid H₂O, and gas-phase CO₂, but no single model seemed to adequately address the observations. The big question was whether or not water was required to be involved in the formation of these features, with the implied corollary that should liquid water be directly involved, then perhaps some form of life might take advantage of even short-lived or ephemeral appearances of water at the surface. Further work demonstrated that the temperature in the dark spots is too high for CO₂ to exist in liquid form, but the temperatures were still low enough for H₂O ice to be stable close to the surface (Kereszturi et al., 2009). This constraint led to the development of a model for formation of a liquid interfacial water film (which can remain liquid well below the melting point of bulk ice) through interfacial attractive pressure driven by van der Waals forces and the curvature of the water film surface (Kereszturi et al., 2009). This model was further enhanced by consideration that not only interfacial water, but also bulk brines could form around the sand grains in the dunes under the influence of solar insolation in late winter into early spring (Kereszturi et al., 2010, 2011). The composite result is something termed 'viscous liquid film' flow on and around the grains at the surface of Martian polar sand dunes, a low-temperature rheological phenomenon that can be active today at high polar latitudes on Mars (Mohlmann and Kereszturi, 2010). The flow-like shapes of the dark features have been well documented in many HiRISE images (e.g., Fig. 11), leading to the identification of a modification process on Martian polar dunes not found on Earth: the springtime sublimation of the seasonal CO₂ polar caps (Hansen et al., 2011). However, other studies of the Martian polar dunes suggest that at least some of the features attributed to sublimation may instead result from normal Aeolian processes (Horgan and Bell, 2012). Even the magnificent resolution of the HiRISE images has not yet produced conclusive evidence of the precise mechanism(s) responsible for the defrosting dark spot patterns, and the proportional roles of CO₂ frost and H₂O water film in the growth of dark spots remains an open question. Laboratory experiments (discussed below) suggest additional complexities for whatever the ultimate resolution of the defrosting dune mechanisms turns out to be.

An interesting case that is distinct from, but still possibly related to the polar dune dark spots, are numerous long gullies (see Horgan et al., 2012, for various types of gullies on Martian dunes) that have formed on the slip faces of sand dunes in Russell crater (54.6°S, 12.4°E), which is at a high latitude but is closer to the equator than the polar dunes whose defrosting characteristics were discussed above. Reiss et al. (2010a) documented present day activity within gullies on the Russell crater dunes using HiRISE images from two Mars years; a 2-m-wide gully grew ~50 m in the first year and ~120 m in the second year, with all activity taking place during early spring. Channel morphology and modeled surface temperatures led these researchers to the conclusion that the observed changes can be best explained through transient melting of small quantities of water ice, which triggered slurry

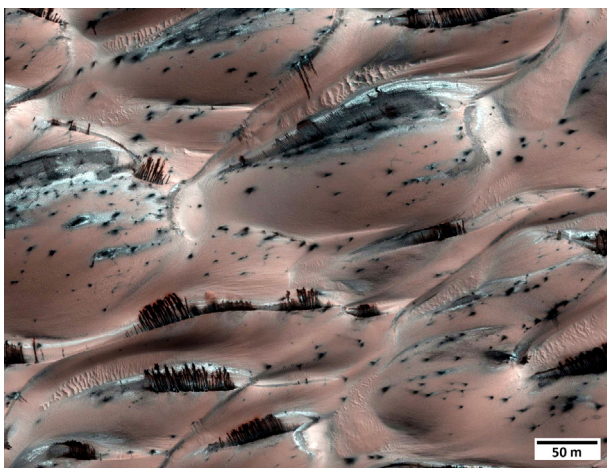


Fig. 11. The seasonal covering of CO₂ frost is sublimating from north polar dunes, revealing dark linear flow features that tend to emanate from dark spots, which represent the first signs of defrosting. Portion of HiRISE PSP_007962_2635; scene width is 500 m. NASA/JPL/U of A.

flows of sand mixed with ephemeral liquid water (Reiss et al., 2010b). A separate study used HiRISE images and hyperspectral data from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM; Murchie et al., 2007) to monitor the defrosting of the Russell dunes, observing a sequence starting with dark spots (similar to those observed during defrosting in the polar regions) from which emanated dark linear flows 1–2 m wide and 50–100 m long (Gardin et al. 2010). Spectra showed that the frost is composed mainly of CO₂ and a small amount of H₂O ice, leading to the conclusion that the dark flows are avalanches of a mixture of sand, dust, and unstable CO₂ gas triggered by eruption of flow materials from the dark spots (Gardin et al., 2010). This role of CO₂ in present-day dune-gully activity is broadly consistent with the study by Diniaga et al. (2010b), where image monitoring over six Martian years revealed activity within 18 gullies on 7 dune fields (all in the southern mid-latitudes, but not including the Russell dunes) mostly during mid-winter, although activity occurred over a broad seasonal range. The gullies monitored by these researchers led them to conclude that the activity occurred when temperatures were too cold for the involvement of liquid water, concluding that the gully modification mechanism is driven by seasonal CO₂ frost (Diniaga et al., 2010b). The volatile involved in the dune gullies is therefore a critical component of the inferences that can be drawn from observations of active gullies on dunes.

Laboratory studies contribute additional constraints to a discussion of the volatiles that modify dune surfaces on Mars. Vedic et al. (2008) used cold-room-based laboratory simulations to evaluate whether dune gullies could result from groundwater seepage from an underground aquifer, concluding that the resulting gully morphology is best reproduced by linear debris flows resulting from the melting of near-surface water ice intermixed with silty materials. However, a subsequent laboratory and modeling study concluded that gully formation in polar regions can be initiated by fluidization of sediment over a subliming seasonal deposit of CO₂ frost, leading to an essentially 'dry' mechanism for the gully modification (Cedillo-Flores et al., 2011). At present, it would appear that diverse origins could be involved in high latitude dune-gully modification; these gullies deserve consideration as a unique complement to on-going investigations of mid-latitude youthful gullies (e.g., see Dickson et al., 2007; Dickson and Head, 2009; Lanza et al., 2010; McEwen et al., 2011).

8. Titan

There has been significant recent progress in studying Titan in general (Lopes et al., 2010) and Titan's dunes in particular, along

with assimilating lessons from Titan on Aeolian processes more generally. The initial impression (Lorenz, 2008) was that the vast majority of Titan's dunes were linear in form and apparently longitudinal in orientation (Fig. 12), indicating net sand transport from west to east, and confined to a belt within 30° of the equator. Subsequent mapping (Radebaugh et al., 2008; Lorenz and Radebaugh, 2009; Radebaugh et al., 2010) has robustly confirmed these early indications.

The latitudinal extent of the dunes appears reassuringly consistent with climate models (e.g., Mitchell, 2008) indicating that Titan's low latitudes should dry out (where the 'moisture' on Titan is liquid methane; Mitchell, 2008). The single equatorial desert belt on slowly-rotating Titan makes an instructive contrast with the Earth's midlatitude desert latitudes, defined largely by the downwelling (dry) branches of the Hadley circulation, the location of which is determined by the balance between solar heating and planetary rotation. Recent studies have thoroughly documented the latitude and elevation distributions of the sand dunes on Titan (e.g., see Le Gall et al., 2011, 2012).

The orientation of the dunes on Titan presented a challenge, in that GCMs appeared to indicate that low-latitude near-surface winds should be predominantly retrograde (i.e. east to west, or 'easterlies' in meteorological parlance). This paradox, which follows from first-principles considerations of overall angular momentum balance in the atmosphere and was not particular to any specific model, even caused modelers to question (Wald, 2009) whether the geomorphological interpretation of sand transport direction (e.g., Radebaugh et al., 2008) was correct. Adjustment of assumed topography (Tokano, 2008) failed to produce the required prograde winds (in fact, linear dunes form in typically bimodal wind regime – that aspect was reproduced in the models, but not the westerly bias). More detailed examination of the wind statistics, however, may have resolved the issue (Tokano, 2010; Lorenz, 2010). Specifically, while easterlies usually occur, for a brief period around the equinoxes there is stronger mixing in the atmosphere, leading to brief but fast westerlies at the surface. If the saltation threshold is such (~1 m/s) that the sand only responds to these faster winds, the geomorphology will reflect that wind direction rather than the prevailing easterlies.

A striking feature of the Titan dunes was their remarkable similarity in size and spacing with large linear dunes on Earth, despite the very different atmospheric density, gravity, etc. (Lancaster, 2006; Lorenz et al., 2006). It appears, however, that the controlling parameter on the ultimate size and spacing of dunes is the thickness of the atmospheric boundary layer, which acts to cap the growth of dunes (Andreotti et al., 2009). The rather uniform spacing of ~3 km of dunes on Titan seems to fit this hypothesis (Lorenz

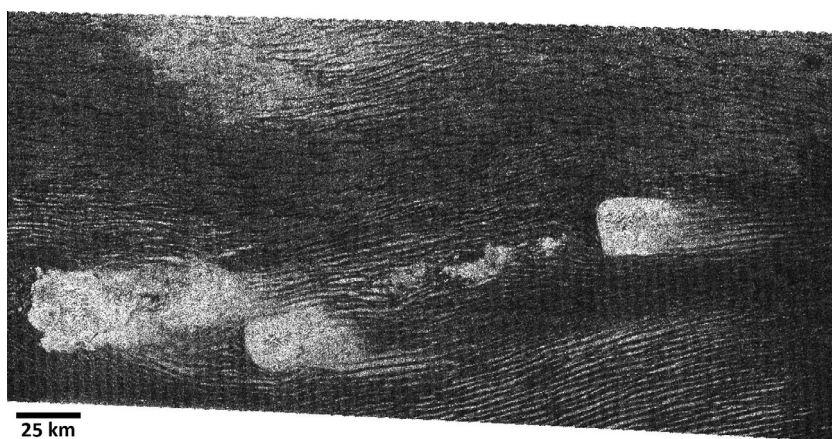


Fig. 12. Example of linear dunes on Titan, as imaged by the Cassini radar system. Scene is 325 km wide, centered on 8°N, 44°W, taken during the Sept. 7, 2006, flyby of Titan. NASA PIA08738.

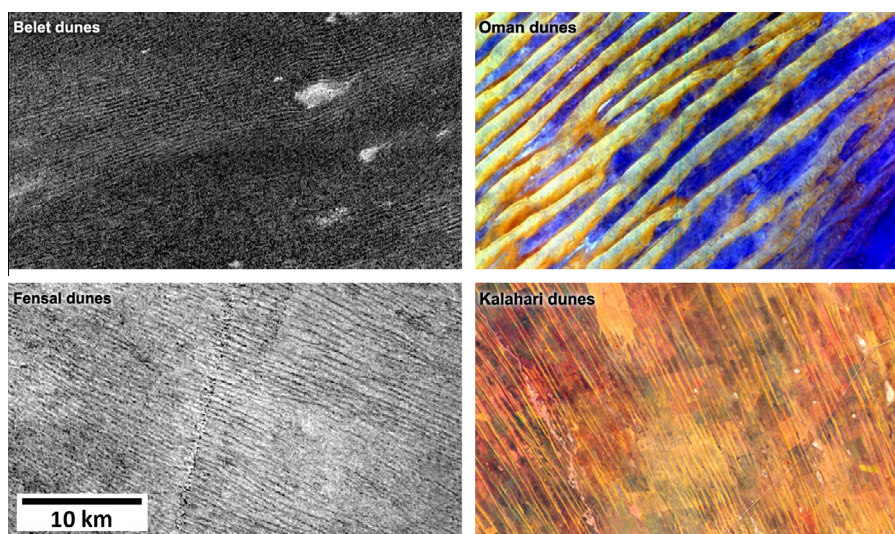


Fig. 13. Comparison of linear dunes on Titan (left) with linear dunes on Earth (right), shown at the same scale. The Belet region of Titan (top left) has dunes that are wider and closer together, with thicker sand in the interdune area, as compared to the Fensal region of Titan (bottom left), where the dunes are 1–2 km wide and spaced further apart. Titan radar views were taken during the Oct 28, 2007 (Belet) and April 10, 2007 (Fensal) flybys. Earth dune scenes are from Rub' al Khali in Oman (top right) and the Kalahari in Namibia (bottom right); both scenes were obtained by the ASTER instrument on the Terra spacecraft. NASA PIA15225.

et al., 2010), and would imply also that Titan's dunes are morphologically mature. The dune height, inferred from radarclinometry (Lorenz et al., 2006; Neish et al., 2010) and photoclinometry (Barnes et al., 2008) appears very consistent with terrestrial dunes of the same horizontal extent (Lancaster, 2006; Radebaugh, 2009).

Titan's dunes have prompted more general discussion of the formation of linear dunes, with the notion that they may progressively extend downwind of obstacles by particles adhering to the growing dune (Rubin and Hesp, 2009; Radebaugh, 2009). In addition to being radar-dark, the dunes are optically dark, and they have a characteristic near-infrared 'color' (e.g., Barnes et al., 2008), supporting the initial suggestion (Lorenz et al., 2006) that the sands are predominantly organic, formed by photochemical processes in the atmosphere (Barnes, 2008; Lunine and Lorenz, 2009). Further evidence of an organic composition follows from the recent identification of the spectral signature of aromatic compounds (e.g., benzene) with the dune-covered areas (Clark et al., 2010). This makes the dune sands the largest known carbon reservoir on Titan (at over 100,000 km³, much more than the atmosphere, and more than the lakes and seas of liquid hydrocarbons, Lorenz et al., 2008). The principal question confronting Titan Aeolian research, is how this material is converted from sub-micron haze particles in the atmosphere into saltatable grains assumed to be 0.25 mm across. The dunes on Titan generally appear to decrease in width and the amount of sand present in the interdune regions, with increasing elevation and/or latitude, comparable to terrestrial linear dunes in sand-rich to sand-poor environments (Fig. 13).

9. Discussion

9.1. Significant developments

Several of the topics discussed above have strong potential to become even more important during the next few years. We anticipate that growing interest in these topics within both the planetary and terrestrial Aeolian communities will lead to increased emphasis on tackling the complex issues associated with each topic.

9.1.1. Martian aeolianites

Recent investigations of Mars have revealed that not only are sand dunes an important part of the current Martian landscape, but they also appear to have played a major role in the deposition of sedimentary rocks evident across the planet. Both rover studies (Fig. 1) and high resolution orbital imaging (Fig. 2) have documented the widely distributed occurrence of cross-bedded sedimentary rocks on Mars (see Section 2), interpreted to be the preserved record of previous dune fields that moved across the planet. It also appears likely that silt or dust-sized materials comprise distinctive landforms observed in the portions of the planet that are locations of dust deposition (Bridges et al., 2010), which suggests that it would not be surprising to find lithified versions of such sediments in the rock record of Mars. It seems reasonable to refer to both of these Aeolian-related sedimentary rocks as 'aeolianites'; it will be important to document the occurrence of aeolianite outcrops whenever and wherever they are encountered in the rock record.

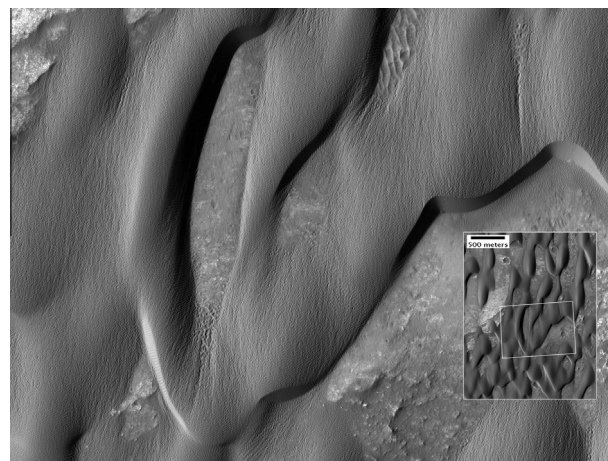


Fig. 14. Grooves are eroded into dunes in Herschel impact basin, Mars. Inset shows context and scale, from portion of browse image. Portion of HiRISE PSP_002860_1650, centered on 14.8°S, 127.9°E. NASA/JPL/University of Arizona.

9.1.2. Sand compositional diversity

Sand-sized sediments hold great potential for sampling both the local and regional bedrock materials that may have served as the source for these materials (see Section 4). High spatial and spectral resolution instruments like CRISM will allow investigators to measure the relative contributions from bedrock outcrops (where mineralogy favors a strong remote sensing signal) to sand accumulations. The ubiquitous Martian dust will always present a challenge to such efforts, but the majority of the Martian surface should be sufficiently dust-free to allow such investigations to progress. The curious organic-related sands of Titan (see Section 8) clearly demonstrate that the wind can mobilize materials other than those derived from silicate rocks alone.

9.1.3. Active versus inactive

For many years, it had been presumed that the Aeolian materials on Mars would not be active under current conditions. Within the last few years, this notion has been shown to be incorrect (see Section 6.3). Not only HiRISE images, but also images from the Thermal Emission Imaging System (THEMIS) visible camera, MRO Context camera, and ESA High Resolution Stereo Camera (HRSC) hold good potential to document dune movement across the planet, particularly when current images can be compared to the vast imaging record that MOC provided from 1997 to 2006 (Malin et al., 2010). Perhaps the most important aspect of monitoring dune and ripple activity is the capability to establish rates of movement, which will provide important new constraints to

atmospheric modeling efforts, which will also facilitate quantitative comparisons with documented rates of sand movement here on Earth. As long as the Cassini spacecraft continues to operate as flawlessly as it has to date, perhaps the radar instrument may eventually document movement of some of the dunes on Titan, providing additional rate information for an environment that is very unlike that of either Earth or Mars.

9.1.4. Deposition versus erosion

High resolution images of dunes on Mars clearly show the influence of recent winds through the pattern of ripples on their surfaces (e.g., Fig. 3), but the new images also show how interpretations change with improving image resolution. MOC images showed that at least some dunes, such as those on the floor of Herschel crater, appeared to have undergone erosion since their emplacement (Edgett and Malin, 2000). For such erosion to take place on the dunes, it would seem that these dunes are somehow more stabilized (if not partially lithified) as compared to nearby active dunes. HiRISE images (Fig. 14) have shown that the “grooved pattern” on the Herschel dunes actually is produced by several sets of ripples (Bridges et al., 2007), and the ripples and dunes in Herschel recently were documented to migrate under current conditions (Cardinale et al., 2012). HiRISE images also are revealing dramatic evidence of both the induration and subsequent erosion of dunes on Mars (Fig. 15). Hopefully continued monitoring of stabilized and eroded dunes may eventually provide some constraints on the current rate of Aeolian abrasion of sedimentary materials on Mars.

9.2. Gale crater

During the summer of 2011, the 150-km-diameter Gale impact basin (4.6°S, 137.2°E) was chosen by NASA as the landing site for the Mars Science Laboratory (MSL) rover Curiosity (Kerr, 2011), achieving a remarkable August 6, 2012, landing. The central mound of Gale crater is buried beneath a 5-km-high pile of sedimentary rocks that have intrigued planetary scientists for many years (e.g., Edgett and Malin, 2001; Pelkey et al., 2004; Malin et al., 2010). When Gale became one of the finalists in the search for the MSL landing site, it (along with the other candidate sites) became the focus of an unprecedented remote sensing campaign, resulting in a wealth of detailed information that has spawned multiple studies of both the crater and the sedimentary rocks of the central mound (Anderson and Bell, 2010; Milliken et al., 2010; Hobbs et al., 2010; Silvestro et al., 2010b; Thomson et al., 2011; Silvestro et al., 2013). The central mound is surrounded by a distributed dune field whose morphology indicates a complex Aeolian history (Hobbs et al., 2010), including new observations that Gale has both active and fossil dunes (Silvestro et al., 2010b, 2013). MSL will investigate the sedimentary rocks on the lower portion of the mound, which have both chemical and morphological indications that clay-bearing strata are intermixed with sulfate-bearing strata, rocks that are distinct from more uniformly layered sediments on the top of the mound (Milliken et al., 2010; Thomson et al., 2011). The uniformly layered sediments at the top of the Gale mound show similarities to uniform layering in nearby exposures of the lower member of MFF (Zimbelman and Scheidt, 2012), so an extended MSL mission may eventually examine rocks that can shed light onto the perplexing history of MFF. The instruments on MSL are designed to search for evidence of any possible biotic activity in the early history of Mars (Kerr, 2011), but they should also provide a wealth of new data on the sediments in Gale crater that contributed to the Aeolian history of the crater.

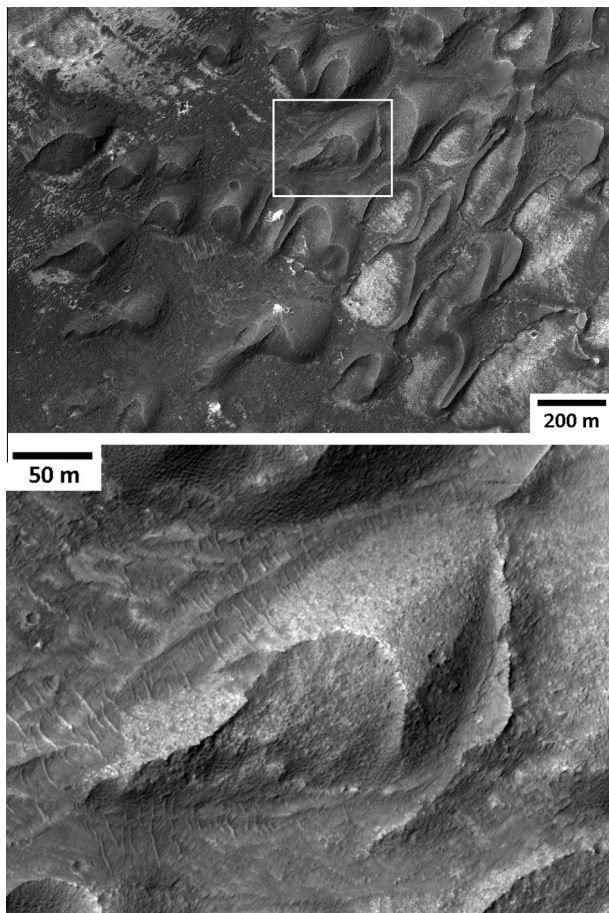


Fig. 15. Weakly lithified barchan dunes being erosion by the wind, superposed on a cratered surface. Top, regional view with box showing location of detailed view. Bottom, full-resolution view of one eroded barchan. Portion of HiRISE image ESP_025389_1690, centered on 11.1°S, 284.9°E. NASA/JPL/U of A.

10. Conclusions

Both orbiter and rover data have shown that cross-bedded sedimentary rocks emplaced by previous migrating dunes are an important part of the rock record on Mars.

Improved understanding of the effects of varying wind regimes is providing insights into how some rather unusual dune shapes have developed.

The composition of Aeolian sediments varies regionally across the Martian surface, and the organic-rich sands of Titan are distinct from the wind-blown sediments commonly found on the terrestrial planets.

Modeling efforts are helping to quantify how sediments are moved by the wind in diverse planetary environments.

Both active and stabilized Aeolian bedforms are wide-spread across Mars; on-going monitoring efforts should continue to improve our understanding of the rates of movement.

Gullies formed on the steep faces of some high-latitude Martian dunes indicate the potential involvement of more than one volatile species.

The linear dunes on Titan are providing evidence that the wind patterns on Titan may be considerably more complex than global models would suggest.

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