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Aeolian processes on the terrestrial planets: Recent observations and future focus

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Abstract

Aeolian dune fields have been described on Earth, Mars, Venus, and Titan. The amount and fidelity of data being returned from orbiting spacecraft and landers have enabled a new era in aeolian studies. This progress report presents an overview of the latest planetary geomorphic studies characterizing aeolian processes on extraterrestrial surfaces. Our understanding of aeolian processes on other planetary surfaces comes largely from Earth analog studies, along with wind tunnel experiments and theoretical modeling. However, an important difference is that unlike terrestrial dunes most dunes on Venus and Mars are composed primarily of basaltic particles. Additional research is needed to understand how basaltic particles weather both physically and chemically so that it will be possible to apply traditional sedimentological concepts, such as sediment maturity, to understanding aeolian processes on Venus and Mars. It may also be possible to characterize sediment maturity and provenance through remote sensing data once we have a better understanding of basaltic sediments. Although there have been a variety of dune forms identified on the surfaces of the other terrestrial planets, the only dune form found on all of them is linear dunes. Even though linear dunes are the most common dune forms on Earth, we currently have a poor understanding as to how they are formed, and additional work is needed to understand these features.

Keywords

aeolian processes, basaltic particles, dunes, Mars, planetary geomorphology, Titan, Venus

I Introduction

Aeolian processes have significantly modified the surfaces of all the terrestrial planets that have appreciable atmospheres, including the Earth, Mars, Venus, and Saturn's moon Titan. This progress report presents an overview of the latest planetary geomorphic studies characterizing aeolian processes on extraterrestrial surfaces, and builds on a previous progress report presented by Tooth (2009). While these studies are conducted using imagery and remote sensing data returned from orbiting spacecraft and landers, our understanding of planetary aeolian processes is based largely on Earth analogs coupled with theoretical modeling and wind tunnel experiments. In particular, Earth analogs are increasingly important as our knowledge of the similarities and differences between aeolian processes and dune forms on the other planets continues to grow. Thus, researchers who specialize in terrestrial aeolian processes or who investigate terrestrial dune forms can provide valuable

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input into our understanding of extraterrestrial surface processes. Three areas where Earth analogs are extremely relevant are discussed, including studies of basaltic dune fields, laboratory analyses, and the formation of linear dunes. It is hoped that the summary presented here may generate some interest by the terrestrial geoscience community into investigating aeolian processes on the other planets.

II Current understanding

1 Venus

Because of the thick carbon dioxide atmosphere the pressure at the surface of Venus is ~90 atm (9000 kPa), which is equivalent to conditions experienced at a depth of 900 m in sea water on the Earth. Despite the extreme differences compared to typical terrestrial surface conditions, there are theoretical (Iversen et al., 1976) and empirical data indicating that aeolian processes are possible on Venus. In fact, wind tunnel simulations show that the threshold velocity of a 75 mm particle is only ~0.28 cm/sec, indicating that large amounts of material could be easily transported on Venus (Greeley et al., 1984). Basically, the enormous atmospheric pressure at the surface of Venus should allow even large particles to be transported with a slight breeze. However, the direct evidence for aeolian features on Venus is limited.

Basilevsky et al. (1985) suggest that small bedforms and layered rocks imaged by the Venera landers were formed by aeolian processes. Orbital radar data from the Magellan spacecraft indicate that wind streaks are frequently associated with impact craters and some tectonically deformed terrains, both of which may provide the source for fine-grained materials (Greeley et al., 1992). Linear wind streaks having a length to width ratio >20:1 are the most common and widespread aeolian feature on the planet (Greeley et al., 1992, 1995). There are also putative yardangs on Venus, which occur in a field ~40,000 km^2 in size, 300 km southeast of Mead crater (9°N, 60.5°E). These features are 25 km long by 0.5 km wide on average, with a spacing of 0.5–2 km (Greeley et al., 1992, 1995). They appear to differ from linear wind streaks in that they have sharply defined margins and do not originate from any topographic feature. However, the resolution of the Magellan images is limited, and interpretation of these features as yardangs is complicated by the interfingering of bright and dark wind streaks throughout the region (Greeley et al., 1992). It is possible that the spaces between these features, which have been interpreted as erosional grooves (Greeley et al., 1992, 1995), are actually swales separating linear dunes.

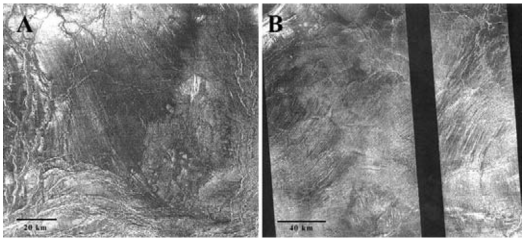

Figure 1. Some examples of linear features on Venus thought to have resulted from aeolian processes. (A) Examples of radar-bright and radar-dark wind streaks centered at 15°N, 60.43°E. Magellan spacecraft radar illumination is from the left at an incidence angle of 46°. (B) The radar-dark linear features in this figure are putative yardangs. Magellan spacecraft radar illumination is from the left at an incidence angle of 46°. Note the scale bars at the bottom left of each image.
Source: From Weitz (1993)

Only two dune fields have been positively identified on Venus (Greeley et al., 1992, 1995; Weitz, 1993). The first is centered at 25°S, 340°E, ~100 km north of the 65 km diameter impact crater Aglaonice, and covers ~1300 km^2. The dunes in this field are 0.5–5 km long, and neighboring wind streaks indicate that the dunes are oriented transverse to the westward flow of the wind (Figure 1). The source of these dunes appears to be sediments from an ejecta outflow channel that was generated by the formation of an impact crater (Greeley et al., 1995). A second, larger dune field is Fortuna-Meshkenet located in a valley beween Ishtar Terra and Meshkenet Tessera and covering $\sim$17,000 km^2. Local wind streaks indicate that the dunes are also oriented transverse to prevailing winds toward the west (Greeley et al., 1995). Comparison of images taken eight months apart reveals that there was no dune movement in the Fortuna-Meshkenet dune field over this timeframe (Weitz, 1993); however, movement may have been below the image resolution of $\sim$120 m.

Given that it may be unlikely that dune movement would occur over spatial scales sufficient to be visible in Magellan radar data (i.e. scales of hundreds of meters), Weitz et al. (1994) compared Magellan radar imagery collected from cycle 1 and 2, with differing viewing geometries. In some areas, differences in bright and dark regions on the surface were apparent when the data from the two cycles were compared. Weitz et al. (1994) concluded that Bragg scattering or subpixel reflections from the slipfaces of microdunes could account for the differences in radar brightness, and suggested that microdunes may be present in parts of the Southern Hemisphere of Venus, including near Stowe, Guan, Daosheng, and Eudocia craters, which could act as sources of fine-grained material.

It is interesting that more aeolian features have not been found on Venus given the capacity of the atmosphere to transport sediments (Greeley et al., 1984). Potentially, surface weathering is slow and does not generate many sand-sized particles. Some other process, such as impact cratering, may be necessary to comminute the necessary particles. This seems logical given the close association many aeolian features have with craters or tectonic features (Greeley et al., 1992, 1995; Weitz, 1993). Additionally, dunes can only be identified in radar data under limited viewing geometries (Blom and Elachi, 1981, 1987), and it is possible that the Magellan viewing geometries and resolution are not capable of identifying all the aeolian features that may exist on Venus (Greeley et al., 1995, Weitz et al., 1994).

2 Mars

For over a century we have had indirect evidence of the importance of aeolian processes on Mars. Historical telescopic observations showed that dark features on the Martian surface waxed and waned with the seasons (e.g. Kahn et al., 1992). Originally this was interpreted to be the result of vegetation undergoing seasonal cycles similar to vegetation in temperate zones on the Earth (Gallant and Hess, 1956). With the advent of spacecraft data, however, it became apparent that dust from global storms, which occur fairly frequently during Southern Hemisphere summer (Hartmann and Raper, 1974; Kahn et al., 1992), were simply hiding dark albedo markings on the surface. Although there is abundant evidence in the form of valley networks, outflow channels and modified impact craters indicating that the early history of Mars supported rainfall and surface runoff (Craddock and Howard, 2002), aeolian processes have been a persistent geologic agent for the last 3–4 billion years (Carr, 2006), and the evidence for aeolian processes is ubiquitous at all scales from orbital data (e.g. Edgett and Christensen, 1994) to lander images (e.g. Greeley et al., 2004).

Mars exhibits many of the same dune forms as seen on the Earth, including barchan, transverse, yardangs, as well as star and climbing dunes (Bourke, 2010; Chojnacki et al., 2010; Fenton et al., 2005; Greeley et al., 1999; Zimbelman and Griffin, 2010). Also, perhaps some of the most interesting images returned by the Mars Exploration Rovers show a series of large dust devils advancing across the surface (Greeley et al., 2006). Although not as common, seif and linear dunes have also been recognized (Edgett and Blumberg, 1994; Lee and Thomas, 1995). Many dunes are located in the floors of impact craters where sediment could accumulate (Figure 2). Perhaps one of the most significant

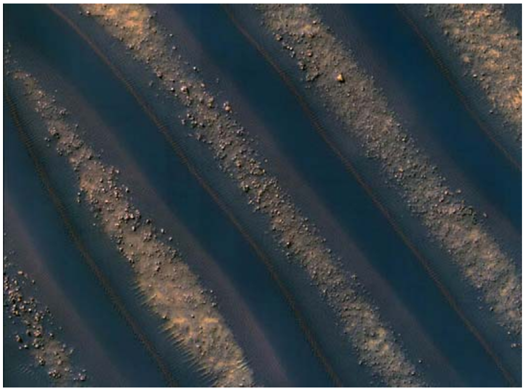

Figure 2. Examples of linear dunes found in an impact crater in Noachis Terra on Mars. The reddish material is probably dust that has concentrated on the northeast-facing slopes. Large boulders can be seen in the dune swales. This image is approximately 500 m across, is centered at 42.66°S, 38.02°E, and has a resolution of 0.25 m/pixel.
Source: HiRISE image ESP_016036_1370

developments to be made recently is the ability to determine sediment provenance and pathways on Mars, which is possible because of the variety of high-resolution images that are available. The High Resolution Stereo Camera (HRSC) with a spatial resolution of ~ 10 m/pixel (Neukum and Jaumann, 2004) and the Mars Context Camera (CTX) with a resolution of ~ 6 m/pixel (Malin et al., 2007) can provide the spatial coverage and resolution necessary to identify and characterize major dune fields along with their potential sources. In addition, the High Resolution Imaging Science Experiment (HiRISE) camera with a spatial scale of 25–32 cm/pixel (McEwen et al., 2007) and the Mars Observer Camera with a resolution of 1.4 m/pixel (Malin et al., 1991) provide the detail necessary to observe small characteristics of individual dunes. Using these data, Silvestro et al. (2010) were able to were able to analyze the nature of complex dune field patterns located in Aonia Terra (52°S, 292.5°E) in the Thaumasia Quadrangle (MC-25) and determine that there were at least two episodes of dune construction, indicating that the local wind regimes changed over time. They also provided some of the first evidence of distant sediment transport on Mars (tens of kilometers) and identified the source areas as layered materials exposed in pits and crater walls.

High-resolution imagery has also provided some of the first evidence for recent dune movement on Mars. Silvestro and Fenton (2011) have begun a systematic search to identify areas of active sand transport outside of the polar regions ($\pm 65°$ latitude) beginning with an analysis of dune fields in the Arabia Terra region of Mars. Using HiRISE images they found four sites where active sand transport appears to be occurring. The evidence is subtle, and most of the areas showing changes are less than a few meters in size. However, such observations are important for understanding physical processes on the surface. Results from such efforts will also lead to a better understanding of the current Martian climate and wind regimes.

3 Titan

Because sunlight is so faint at Saturn, it was originally thought that there would not be enough energy from solar insolation to drive surface winds, and thus Titan would not have any active aeolian processes (Lorenz et al., 2006). However, climatic models suggest that the tidal pull by Saturn generates pressure variations in Titan's atmosphere capable of driving near-surface winds (Tokano and Neubauer, 2002). Titan has a methane-rich atmosphere with a surface pressure of ~ 1.5 atm (146.7 kPa); coupled with a low gravity (0.14 g), this results in a threshold wind-speed of only ~ 10 cm/s necessary to move an average sand-sized particle (Lancaster, 2006). Observations from the Cassini spacecraft's Radio Detection and Ranging (RADAR) instrument, which has a resolution similar to the Magellan spacecraft's radar images of Venus (Lorenz et al., 2001), show radar dark parallel features (Figure 3) that appear to be linear dunes (Lorenz et al., 2006). These features are

Figure 3. Some of the linear dunes on Titan can be seen in this Cassini radar mapper image. The image is centered near 19.2°S, 257.4°W, and covers an area of 220 by 170 km. North is approximately toward the top of the image, the radar illumination is from the right, and the incidence angle is ~25°. The vertical stripe across the image at its center is a processing artifact.
Source: Cassini radar image PIA11802

~100–150 m high, have slopes of 6–10° (Lorenz et al., 2006), are tens of kilometers long (Radebaugh et al., 2008), and resemble terrestrial linear dunes in all respects (Lancaster, 2006; Lorenz et al., 2006; Radebaugh et al., 2008, 2010). However, Titan is an icy satellite, and instead of consisting of quartz-rich sediments, the dunes on Titan are most likely composed of ice particles that were eroded from precipitation and runoff of liquid methane (Lorenz et al., 2006) or they consist of hydrocarbon particles that were generated by photochemistry in Titan's stratosphere and that simply accumulated over time (Wahlund et al., 2009; Yung et al., 1984). Although the radar survey of Titan's surface is not complete, it appears that the linear dunes are ubiquitous in the equatorial region between ±30° latitude (Radebaugh et al., 2008), possibly due to Titan's global atmospheric circulation pattern (Lorenz and Radebaugh, 2009; Radebaugh et al., 2008). Interestingly, the slope orientations of the dunes suggests that they are being driven by westerly winds (Lorenz et al., 2006), which is opposite to the wind directions predicted by global climatic models (Tokano and Neubauer, 2002). However, more recent models of global circulation that were integrated over an entire year on Titan suggests that there may be occasionally fast, turbulent westerlies initiated by the equinoctial passage of the intertropical convergence zone around the equator (Tokano, 2010).

The discovery of linear dunes on Titan has several important implications for understanding aeolian processes in planetary environments. Dunes have now been recognized on all terrestrial planets that have an appreciable atmosphere, and aeolian processes are now known to be literally universal in several meanings of the word. Generation and transport of sediment appears to be a basic geologic process on planetary surfaces. Aeolian processes also adjust to the environment and occur in a range of atmospheric pressures and compositions as well as variations in surface gravities. It is interesting to note, however, that the only dune forms that appear to be ubiquitous are linear dunes.

III Terrestrial analog studies

Terrestrial analogs represent places on the Earth that, in some respect, approximate the geological or environmental conditions thought to occur on another planetary surface either today or sometime in the past. Analog studies are important for providing the ground truth for interpreting data returned by spacecraft. Results from analog studies can often improve our understanding of geologic processes here on the Earth, and they are a useful way to test models developed to explain the formation of terrestrial features or processes. Historically, analog studies have also been used to support astronaut training (El-Baz, 2011), and have been important for developing and testing exploration technologies, such as the Mars Exploration Rovers (Cook, 2005). Léveillé (2010) provides a useful summary of analog studies that have taken place over the last 50 years. In particular, there are three areas of research that promise to increase our understanding of aeolian processes on the terrestrial planets, especially in regard to Mars.

1 Weathering of basaltic materials

Dunes composed of volcaniclastic sediments are found on Venus and Mars. Specifically, the Venusian and Martian dunes are derived from basaltic materials, which consist of olivine, pyroxene, feldspar, and both lithic and vitric fragments. In contract, terrestrial dunes are typically composed of quartz-rich sand, but in some rare instances they may also be composed of gypsum (Szynkiewicz et al., 2010), carbonates (Fletcher et al., 2005), or clay aggregates (Dare-Edwards, 1984). Edgett and Lancaster (1993) recognized that dunes composed of reworked volcaniclastic sediments make up a rare but important additional composition class of terrestrial dunes. There are only a few places on Earth where dunes are also derived from a basaltic provenance, including parts of the western United States, New Zealand, Iceland, and Hawaii (Edgett and Lancaster, 1993). To date, studies of these basaltic dunes have been limited.

Edgett (1994) conducted field studies and an analysis of Thermal Infrared Multispectral Scanner (TIMS) data for the Shifting Sand Dunes of Christmas Valley, Oregon. He showed that differences in thermal emissivity, which relates to the physical characteristics of the sediment, can be useful in differentiating active from inactive dune sand as well as in distinguishing interdune surfaces. He suggests that additional infrared spectra of basaltic materials would be useful in constraining Martian remote sensing data. As discussed below, utilizing multispectral data for determining the provenance of sediments on Mars is promising (e.g. Tirsch, 2009).

More recent work on basaltic dunes has been conducted in Iceland by Baratoux et al. (2007) and Mangold et al. (2010). They show that sediments deposited as the Langjokull glacier retreats are transported by katabatic and prevailing winds downslope to ~ 8 km away. Abrasion of local Eldborgir lava flows by the saltating sand increases the amount of material available for transport. Eventually olivine is preferentially sorted so that it increases in abundance downwind across the sand sheet. These results suggest that similar to quartz-rich sediment variations in the composition of the basaltic material may be used as a way of inferring maturity and transport distances.

One of the largest basaltic dune fields on Earth is in the Ka'u Desert of Hawaii. Gooding (1982) analyzed some of the materials in this area and determined that the sand was derived largely from the Keanakako'i tephra formation, which is a sequence of ash and tephra that has been deposited from periodic phreatic eruptions that Kilauea volcano has experienced over the last 2000 years (Fiske et al., 2009). Gooding (1982) suggested that the material in the dunes he sampled were too well-sorted to have been emplaced directly from a base surge (Christiansen, 1979). This is important because it implies that the dunes in the Ka'u Desert were formed by aeolian processes and not directly by volcanic processes, and is thus one of the few suitable terrestrial analogs for understanding basaltic dunes on the other planets.

Many questions about basaltic sediments remain. For example, how does basaltic material change physically and chemically during transport? What mineralogy can be used to determine provenance or transport distance? In the absence of quartz sand, what are the most reliable mechanisms for age-dating basaltic (volcaniclastic) dunes? How do the characteristics of basaltic sand differ between fluvial, glacial, or aeolian sediment transport? Addressing such questions through terrestrial analog studies of basaltic dunes here on Earth could improve our understanding about aeolian processes on the terrestrial planets as well as the nature of dunes seen on Venus and Mars.

2 Laboratory analyses

Hyperspectral visible and near-infrared (VNIR) data of Mars have been collected by the Thermal Emission Spectrometer (TES) on Mars Global Surveyor (Christensen et al., 2001), the Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité (OMEGA) spectrometer on Mars Express (MEX) (Bibring et al., 2005), and Mars Reconnaissance Orbiter (MRO)/Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) (Murchie et al., 2007). TES collected two types of data, hyperspectral thermal infrared data from 6 to 50 micrometers (μm), and bolometric visible-NIR (0.3 to 2.9 μm) measurements at a spatial resolution of 3 km. OMEGA acquires spectra in 352 contiguous channels covering 0.35–5.1 μm with a spatial resolution of 300 m to 4.8 km (Bibring et al., 2005) while CRISM collects ~10 km wide images from 0.36–3.9 μm at 18 m/pixel in the high-resolution targeted mode (Murchie et al., 2009). Among the many exciting discoveries made by these instruments is the identification of both Al-bearing and Fe-bearing phyllosilicates (Bibring et al., 2006; Poulet et al., 2005) in the older terrain on Mars, suggesting that deep chemical weathering occurred early in that planet's history (Bibring et al., 2006), which could also be an important process for producing fine-grained material suitable for aeolian transport (Craddock and Howard, 2002).

OMEGA/CRISM have also been used to map the distribution of Al- and Ca-bearing pyroxenes and olivine minerals (Mustard et al., 2005). The results from these instruments compare well in general to the mineral maps made using TES over larger footprints (Christensen et al., 2001). There is a great deal of work needed to determine the composition of aeolian sand from these data. Most of the sand is mafic (Fenton et al., 2003; Poulet et al., 2008; Rogers and Christensen, 2003; Stockstill-Cahill et al., 2008; Tirsch, 2009; Tirsch et al., 2011) ranging from a Type 1 surface composition (Bandfield et al., 2000), which has a spectrum similar to basalt, to a Type 2 surface composion, which has been interpreted as basaltic andesite (Bandfield et al., 2000) or a basalt containing clay minerals (Wyatt and McSween, 2002) or amorphous silica (Kraft et al., 2003). Interestingly, OMEGA data have also shown evidence for dunes composed of gypsum in the northern polar erg (Fishbaugh et al., 2007; Langevin et al., 2005; Szynkiewicz et al., 2010).

There are also a number of recent studies that suggest VNIR data can be useful for determining the provenance of aeolian sand on Mars. For example, Stockstill-Cahill et al. (2008) used variations in mineral abundances observed in TES multispectral data to determine the provenance of dark dunes found in Amazonis Planitia craters. They determined that dark deposits probably resulted from aeolian erosion of local basaltic lava flows and were subsequently redistributed within the floors of these craters. Tirsch et al. (2011) used OMEGA and CRISM data to show that dark dune materials located in many Martian craters originated from layered basaltic materials exposed in the walls or floors of these craters. Given that similar spectra were observed in 70 different locations distributed across the planet, they suggest that the source of the dune sand may be from a global layer of ash that may have been deposited from a large explosive eruption sometime in the past.

In terrestrial dune studies the amount of quartz present is often used as a way of determining mineralogical maturity (Blatt et al., 1972; Muhs et al., 1995). As mentioned previously, the study by Mangold et al. (2010) suggests that olivine abundances may be useful for determining mineralogical maturity in volcaniclastic systems. A number of investigators have conducted laboratory analyses to determine how volcaniclastic deposits weather both mechanically and chemically, while acquiring spectra to better understand the remote sensing data we have for Mars.

For example, it has been suggested that palagonitic tephra from Hawaii volcanoes are good spectral analogs for Martian soil and dust because of their general similarities at visible to near-infrared wavelengths (VNIR, ~0.35–2.5 μm) (Adams et al., 1986; Bell et al., 1993; Bishop et al., 1998, 2007; Evans and Adams, 1979; Hamilton et al., 2008; Morris et al., 1990, 1993, 1996; Singer, 1982). Laboratory analyses of the Keanakako'i tephra (Schiffman et al., 2000, 2002) indicate that palagonization occurs in response to hydrothermal alteration and is typically isolated to caldera-boundary faults. During palagonization the tephra develops a quasi- or nano-crystalline rind containing smectite and other clays that eventually results in consolidation of the tephra. Pedogenic weathering also occurs, and the resulting products reflect the local environmental conditions (Schiffman et al., 2000). Under acidic conditions (pH <6.0) the tephra undergoes dissolution and develops opaline crusts on exposed surfaces. Under neutral conditions (pH = 6.5–7.8) the resulting pedogenic product is dominantly smectite in areas where the mean annual rainfall is <50 cm/yr and dominantly kaolinite, allophane and imogolite where the mean rainfall >250 cm/yr. Such analyses are important for characterizing the phyllosilicates found on Mars (Bishop et al., 2008; McKeown et al., 2009).

Analyses of tephra from Haleakala, Maui, indicate that the unaltered tephra are composed of feldspar, glass, pyroxene, and olivine, and alteration products include Fe-oxides, phyllosilicates, and sulfates, as well as amorphous Al-Si-bearing material as shown by selected area electron diffraction (SAED) (Bishop et al., 2007). Hamilton et al. (2008) collected visible to near-infrared (VNIR, 0.35–2.5 μm) and middle-infrared (MIR, 1800–250 cm^{-1}) spectra of basaltic tephras from Mauna Kea volcano that were altered under ambient, hydrothermal, and dry heat conditions. They found that while MIR spectra of altered tephras identified major alteration phases (cristobalite, oxide, phyllosilicate, and sulfate), the comparison of the tephra spectra (<45 μm fraction) to dust spectra retrieved from Mars Global Surveyor and Mars Exploration Rover instruments did not provide good spectral matches. Instead, they found that the best MIR match is a tephra that has a strong plagioclase feldspar transparency feature and was altered under dry, high-temperature, oxidizing conditions. However, this sample was not a good VNIR analog and is not a process analog, but it emphasizes the mineralogical importance of plagioclase feldspar in Martian dust (Bandfield and Smith, 2003).

In fact, to date no single tephra has been found to be a good spectral analog across the VNIR and MIR spectrum, and none of the tephra samples examined are ideal matches to Martian spectra at all wavelengths. However, spectral features have been observed to vary with decreased temperature and pressure and spectral features attributable to H_2O are visible (Bishop et al., 2007; Hamilton et al., 2008). It is possible that basaltic materials collected from other localities may have spectral signatures that more closely match those from Mars. More importantly, studies to date have only analyzed material that has been altered in situ. It is likely that sediment transport would affect the bulk composition of Martian surface materials. For example, the plagioclase feldspar component observed in the Martian dust (Bandfield and Smith, 2003) may reflect the stability or preferential selection of this mineral following aeolian transport. Laboratory analyses of basaltic materials that have been physically transported by aeolian (and fluvial) processes may help us better understand and interpret remote sensing data from the terrestrial planets.

Figure 4. Linear dunes in the Simpson Desert as seen by an aircraft. These dunes are oriented towards the northwest, are 10–40 m in height and can be from one to several hundred kilometers in length (Craddock et al., 2010). Interdune spacing is typically between 100 m and 1.5 km and varies as a function of height (Ambrose et al., 2002).
Source: Photograph by Robert A. Craddock

3 Linear dunes

Linear dunes appear to be the only dune form that occurs on all the terrestrial planets with an atmosphere, including Venus, Mars, and Titan. On Earth they are the most common dune form, accounting for nearly 40% of all dunes (Bristow et al., 2000; Lancaster, 1982). Linear dunes (Figure 4) are characterized by their straight to irregularly sinuous, elongated shape. Typically the width of a linear dune is only a few tens of meters or less, but the length of an individual dune can often exceed many tens to hundreds of kilometers. Generally they are found in semi-arid to arid regions where the regional wind speeds and directions are highly variable. Despite their common occurrence, it is still not clear how they form. Currently there are three possible models for linear dune formation:

a Linear extension. Twidale and Wopfner (1990) suggest that sand is derived from a single source downwind of the dune field and is transported over great distances as the linear dunes grow forward along the snout. The sand located in the swales is either blown off existing dunes or simply has not yet been incorporated into a dune.

b Wind-rift. There are two slightly different wind-rift models, but both imply that the dune sand was derived locally and then transported over short distances. King (1960) suggested that linear dunes accrete vertically and uniformly along the length of the dune. Alternatively, Pell et al. (1999, 2000) suggested that sand is deposited only in the lee of the advancing dune snout. The morphology of the dune advances downwind, but the sand is not transported any great distances.

c Lateral migration. This is the latest theory borne out by studies of dunes in the Namib Desert (Bristow et al., 2007a) and in the Camel Flat basin within the Simpson Desert (Hollands et al., 2006). This theory supports dune formation primarily from vertical accretion of locally derived sand. However, it suggests that linear dunes also migrate laterally over time and smaller dunes eventually coalesce into larger ones.

Linear dunes represent some of the largest dune forms on any planet, which is one of the reasons a unique solution to their formation has not been realized. For example, it is difficult to place any constraints on the age, composition, and stratigraphy of a linear dune over its entire length, which can often exceed a few hundred kilometers. Additionally, ground-penetrating radar studies (Bristow et al., 2000, 2007b) and luminescence age-dating (Hollands et al., 2006; Munyikwa et al., 2000) indicate that linear dunes are composite structures that are probably the result of multiple episodes of aeolian activity. It is not clear how the stratigraphy of linear dunes may relate to past climates or wind regimes. Whether linear dunes form in a bidirectional wind regime (Lancaster, 1982; Parteli et al., 2009) or helical roll vortices (e.g.

Tseo, 1993) will also influence the preservation of stratigraphy and the record of climatic changes (Munyikwa, 2005), and in places such as central Australia vegetation has also perturbed the upper meter of sand, increasing the difficulty of placing age-dates and climatic constraints on linear dune formation (Bristow et al., 2007b). More research is needed to understand the formation process of linear dunes and to provide constraints on their physical properties (e.g. grain size and stratigraphy). Additionally, the effects physical properties have on remote sensing signatures in VNIR, thermal, and microwave wavelengths must also be assessed in order to better relate our understanding of terrestrial linear dunes to the other planets (Titus et al., 2008).

IV Summary

Given the increasing amount of high-resolution imagery for Mars, the fidelity of the data being returned for Titan, and the availability of data for Venus, our understanding of aeolian processes has entered into a new golden age of exploration and discovery. Terrestrial geoscientists have a unique opportunity to apply their knowledge and skills to dune forms and aeolian processes on these other planets. In particular, this progress report discusses three areas of Earth analog studies which could potentially provide important results. For a broader perspective, there are also several recent papers that provide a more community-based consensus of important future research directions (Bourke et al., 2010; Fenton et al., 2010; Titus et al., 2010). Obviously, the aeolian processes discussed here occur in open systems, so the concept of equifinality is an important consideration. However, perhaps the greatest benefit of conducting Earth analog studies is that they offer a mechanism for testing a variety of hypotheses. Simply stated, any hypothesis for explaining the formation of a dune or some aspect of sediment transport on Earth, for example, should also be applicable to the surface of another planet. Results from planetary geological studies will ultimately increase our understanding of terrestrial processes as well.

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