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Occurrence and scale of compositional heterogeneity in Martian dune fields: Toward understanding the effects of aeolian sorting on Martian sediment compositions

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ABSTRACT

Aeolian transport and hydrodynamic sorting have been proposed to be a significant influence on Martian sediment bulk compositions, through laboratory experiments, modeling and terrestrial analogies. But to date, few studies have directly examined compositional-grain size relationships within sediment fields on Mars; thus the prevalence of hydrodynamic sorting as well as the scales at which sorting is important remain poorly understood. To that end, we assessed the degree and occurrence of thermophysical and compositional heterogeneity for 25 dune fields within a ~42,000,000 km^2 area on Mars. Among these, only four exhibit spatial heterogeneity in spectral properties and composition. Two of these four sites show a strong positive relationship between particle size and olivine abundance. The rarity of compositional heterogeneity within dune fields in our study region (5–185°E, 45°N–20°S) may indicate phenocryst-poor source rocks; alternatively, sorting within individual bedforms may be present but not at the scale of the full dune field (~10–20 km). Compositional segregation correlated with grain size due to hydrodynamic sorting has been observed by rovers at scales much smaller than THEMIS ground resolution (100 m/pixel); thus these small scales might be the operable, relevant ones of hydrodynamic compositional sorting prevailing most commonly in Martian dune fields.

1. Introduction

Interpretation of sediment compositions from remote measurements requires consideration of a variety of factors, including source rock properties, chemical and mechanical alteration, transport history, and sorting processes. Presently, major questions regarding Martian sediments and aeolian processes relate to the degree to which sediments have been compositionally homogenized by aeolian, impact and other processes, and conversely, the role that physical sorting plays in generating compositional variations with particle size. The similarity in chemical compositions of basaltic sediments at Gale crater, Gusev crater and Meridiani Planum, measured in-situ by landed missions, has prompted the hypothesis of a “global” soil unit (Blake et al., 2013; Yen et al., 2005), in which sand-sized particles have been globally homogenized through aeolian activity (Blake et al., 2013). An alternative model is that basaltic soils are not globally homogenized, but sample a large enough area to approximate average upper crust (Taylor and McLennan, 2009, p.159). This latter idea is more consistent with global measurements of surface compositions from infrared and gamma ray measurements that show significant spatial variability at the regional scale (e.g. Karunatillake et al., 2010; Ody et al., 2012; Rogers and Christensen, 2007; Rogers and Hamilton, 2015; Taylor et al., 2010; Pan et al., 2015), indicating that complete homogenization of the sediment fraction has not occurred (Rogers and Hamilton, 2015). However, it is possible that homogenization occurs within a restricted size range of the saltatable fraction, where smaller sediments are physically separated from larger ones and homogenized at larger scales.

Additional motivation for this work stems from the need to understand the origin(s) of spatially isolated bedrock compositions. For example, numerous ancient craters and basins on Mars, ranging from ~8–130 km diameter (average diameter of ~42 km) (Edwards et al., 2014) contain flat-lying olivine-enriched bedrock plains (Edwards et al., 2009, 2014; McDowell and Hamilton, 2007). Potential origins for these units include effusive volcanism and/or lithified sedimentary fill (McDowell and Hamilton, 2007; Edwards et al., 2009, 2014). If these units are sedimentary, there must be a mechanism to enrich the sedimentary deposits in olivine compared to surrounding terrains (the presumed sediment sources). Aeolian sorting is one potential way to do this.

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Thus, understanding the potential role of physical sorting in controlling bulk sediment composition is an important facet in interpreting observed spatial variability in surface compositions from orbit. Though the processes that result in compositional fractionation from a bulk source during erosion and aeolian transport are generally well understood from the terrestrial literature (Section 2), it is unclear under what scales these processes are important on Mars, as well as how these changes might appear on surfaces dominated by basaltic sources. Dune and ripple fields are natural environments in which to assess the degree to which physical sorting processes have affected Martian sediments. Martian sediments investigated *in-situ* with landed missions show evidence of compositional and grain size sorting over the scale of individual bedforms (e.g.McGlynn et al., 2011; Sullivan et al., 2008). At slightly larger scales, such as within a portion of the informally named "Bagnold" dune field in Gale crater, spatial variability in mineral composition and grain size has been observed remotely (Lapotre et al., 2015; Seelos et al., 2014). Additionally, prior infrared mapping studies of Martian dune fields and nearby bedrock provide evidence that many dune field compositions are at least partially controlled by local inputs (e.g.,Chojnacki et al., 2014a; Tirsch et al., 2011). However, studies across larger areas, such as a whole dune field, have been limited. A comprehensive study of dune fields within Valles Marineris showed significant compositional heterogeneity at multiple scales, with major differences in mineralogy between individual basins within Valles Marineris, as well as compositional differences observed between individual dune fields (Chojnacki et al., 2014a,b). Those authors suggested that the diversity of sand sources within Valles Marineris contributed to the regional differences in dune field composition, whereas aeolian sorting was likely the more dominant factor in the smaller scale variability observed. However, aside from that study, as well as the *in-situ* observations at few landing sites, detailed analyses of heterogeneity (or lack thereof) within other Martian dune fields, as well as an assessment of composition-particle size relationships, are generally lacking (Section 2).

Thermal infrared imaging from the Mars Odyssey Thermal Emission Imaging System (THEMIS) instrument (Christensen et al., 2004) provides a means to assess spatial variability in spectral and thermophysical characteristics that are related to composition and particle size (Section 3). Though the coarse spectral resolution prevents precise determination of mineralogy, the uniform spatial coverage at high spatial resolution (100 m/pixel) uniquely allows assessment of spatial heterogeneity in bulk composition and particle size across regions of interest. This work complements previous studies by using visible and infrared imagery from THEMIS to assess the frequency of thermophysical and spectral heterogeneity within dune fields in an equatorial region of Mars, and then characterizing compositional-particle size relationships in the spectrally heterogeneous dune fields.

2. Background

Variations in composition and particle size distributions within aeolian dune fields on Earth are a function of source rock composition(s), mechanical and chemical weathering, and aeolian sorting mechanisms (Boggs, 2006, p. 145–157, 258–267). The original crystal size and composition of source rock(s) first influence the grain size and composition of sediments derived from those rocks (Pettijohn et al., 1987, p. 252–254). Preferential comminution and chemical alteration can change the composition of those sediments, as a function of grain size, during transport. Finally, aeolian sorting of particles leads to preferential enrichment of specific materials in certain grain-size fractions (e.g. Tolosana-Delgado and von Eynatten, 2009; Weltje and von Eynatten, 2004). Grain size, shape and density are major factors controlling the effectiveness of aeolian sorting (e.g. Anderson and Bunas, 1993; Makse, 2000). Grain sizes are commonly segregated within individual dune fields, with coarse-grained ripple crests and finer-grained troughs (Anderson and Bunas, 1993).

On Earth, the protolith composition of the sand source has been shown to have a major role in affecting compositional sorting trends within sediments derived from that source. Because the common rock-forming minerals in basaltic rocks can have a wide range of densities compared to intermediate and silicic rocks, the effects of hydraulic sorting on compositional trends with particle size in basaltic sediments can differ greatly from those of intermediate-to-silicic sediments (e.g., Kiminami and Fujii, 2007). Unfortunately, studies of aeolian sorting in basaltic terrains are rare. Spatial variations in chemical and mineralogical composition were observed in volcanic sands in Iceland, such that sands showed enrichments in olivine compared to the source rock; and, within the sediments, olivine abundance (by way of Ni abundance as a proxy for olivine abundance) increased with decreasing mean grain size (Mangold et al., 2011). The negative correlation between olivine abundance and particle size was explained by olivine shape, hardness and density leading to longevity as sand-sized particles compared to plagioclase. In the basaltic terrains surrounding Moses Lake, Washington, dune crests were observed to be compositionally dissimilar from the remaining dune field surfaces in remotely sensed infrared data (Bandfield et al., 2002). In this example, however, the differences were due to distinct sand sources, followed by aeolian sorting, rather than preferential comminution from a single sand source. Last, particle size sorting can occur with density variations related to porosity/vesicularity, which is expected for basaltic terrains. Density-related particle size sorting has been observed in granule mega-ripples in Iceland and Mono Crater, where the high density and finer obsidian grains formed the crests and the low density and coarser pumice was concentrated between the crests (e.g. Greeley and Peterfreund, 1981).

Despite the limited number of terrestrial examples of sorting in basaltic terrains (e.g. Edgett and Lancaster, 1993), combined experimental and modeling work on basaltic sediments suggests that physical processes could produce significant compositional changes in Martian sediments from a single protolith (Fedo et al., 2015). In that study, two basalt samples differing in composition and petrographic texture were crushed and pulverized to generate synthetic sediments (Fedo et al., 2015). The two samples were a trachybasalt from Cima volcanic field in Mojave Desert, California and porphyritic vesicular basalt from Kilauea, Hawaii. Samples were sieved into multiple grain-size fractions; particles finer than 62 µm were not further subdivided. The mineral abundance of sieved sediments and source rocks was determined and divided into five groups: lithic fragments, olivine, plagioclase and pyroxene and opaque oxides. The compositions of the sieve fractions differed greatly with starting composition. They concluded that the crystal-size distribution of the parent material had a major influence on the compositional variability between grain size fractions. Next, using aeolian transport models, Fedo et al. (2015) showed that these compositionally distinctive size fractions could then be spatially sorted through hydrodynamic processes under Martian atmospheric conditions. They conclude that physical sorting should be likely on Mars, and that sorting is a process that should not be overlooked when assessing chemical or mineralogical variability in Martian sediments. However, the hydrodynamic effects related to density differences within basaltic sediments, which are expected to vary by nearly a factor of two among common minerals (e.g., plagioclase vs. Fe-oxides), may have been lost or conflated during the processes of sieving, thus the likelihood of physical sorting remains unclear.

Some well-characterized dune or ripple fields on Mars do show evidence for sorting. The "El Dorado" ripple field investigated by