Aeolian Research 26 (2017) 117–136

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Sedimentary differentiation of aeolian grains at the White Sands National Monument, New Mexico, USA

Lori K. Fenton [a,*], Janice L. Bishop [a], Sara King [a], Barbara Lafuente [b], Briony Horgan [c], David Bustos [d], Philippe Sarrazin [a]

[a] *SETI Institute, 189 Bernardo Ave., Ste. #100, Mountain View, CA 94043, USA*
[b] *University of Arizona, Tucson, AZ, USA*
[c] *Purdue University, West Lafayette, IN, USA*
[d] *White Sands National Monument, NM, USA*

ARTICLE INFO

Article history:
Received 2 February 2016
Revised 9 May 2016
Accepted 10 May 2016
Available online 26 May 2016

Keywords:
White Sands
Gypsum
Saltation
Aeolian transport
Mars
Mars, polar geology

ABSTRACT

Gypsum ($CaSO_4 \cdot 2H_2O$) has been identified as a major component of part of Olympia Undae in the northern polar region of Mars, along with the mafic minerals more typical of Martian dune fields. The source and age of the gypsum is disputed, with the proposed explanations having vastly different implications for Mars' geological history. Furthermore, the transport of low density gypsum grains relative to and concurrently with denser grains has yet to be investigated in an aeolian setting. To address this knowledge gap, we performed a field study at White Sands National Monument (WSNM) in New Mexico, USA. Although gypsum dominates the bulk of the dune field, a dolomite-rich [$CaMg(CO_3)_2$] transport pathway along the northern border of WSNM provides a suitable analog site to study the transport of gypsum grains relative to the somewhat harder and denser carbonate grains. We collected samples along the stoss slope of a dune and on two coarse-grained ripples at the upwind margin of the dune field where minerals other than gypsum were most common. For comparison, additional samples were taken along the stoss slope of a dune outside the dolomite transport pathway, in the center of the dune field. Visible and near-infrared (VNIR), X-ray powder diffraction (XRD), and Raman analyses of different sample size fractions reveal that dolomite is only prevalent in grains larger than ~1 mm. Other minerals, most notably calcite, are also present in smaller quantities among the coarse grains. The abundance of these coarse grains, relative to gypsum grains of the same size, drops off sharply at the upwind margin of the dune field. In contrast, gypsum dominated the finer fraction (<~1 mm) at all sample sites, displaying no spatial variation. Estimates of sediment fluxes indicate that, although mineralogical differentiation of wind-transported grains occurs gradually in creep, the process is much more rapid when winds are strong enough to saltate the $\geqslant$1 mm grains. The observed grain segregation is consistent with the WSNM dune field formative friction velocity (0.39 m/s) proposed by Jerolmack et al. (2011): winds significantly weaker than this value would not lift the large grains into differentiation-inducing saltation, whereas the observed differentiated trend would be obliterated by significantly stronger winds. When applied to Olympia Undae, a similar sediment flux analysis suggests that the strongest winds modeled by the Mars Climate Database (MCD) are consistent with the observed concentration of gypsum at dune crests. Density-driven differentiation in transport should not influence sediment fluxes of finer grains (<1 mm) as strongly on Earth, suggesting that the high ratio of fine gypsum grains to other minerals at WSNM is caused by a relatively high production and/or abrasion rate of gypsum sand. The observed preferential transport of coarse-grained gypsum in the dune field conceals a broader range of coarse-grained minerals present on Alkali Flat, contributing to the problem that mineralogy determined through both remote sensing of dune fields and analysis of dune foresets does not fully represent that of the source regions. Unlike quartz, the concentration of gypsum in WSNM occurs not because it is more resistant to weathering and erosion than other minerals, but rather because it is more readily produced (in the case of finer grains) and transported (in the case of coarser grains) than other minerals present in the region.

---

* Corresponding author.

http://dx.doi.org/10.1016/j.aeolia.2016.05.001

1. Introduction

Olympia Undae is Mars' largest dune field, spanning more than 200,000 km^2. The composition of the dune sand appears to be dominated by mafic materials (e.g., Bell et al., 1997; Bandfield et al., 2000), with the most recent spectral study suggesting a mixture of iron-bearing glass and high-calcium pyroxene (Horgan and Bell, 2012). In 2005, a large quantity of the mineral gypsum was unexpectedly identified on Mars in the high-latitude dune sands of Olympia Undae using OMEGA (Observatoire pour la Mineralogie, l'Eau, le Glace e l'Activité) near-infrared data (Langevin et al., 2005). Because gypsum crystallizes from liquid water, the discovery of this extensive deposit has important implications for the climatic and sedimentary history of the currently cold and dry north polar regions of Mars. CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) data (e.g., Murchie et al., 2009) indicate that gypsum sand grains appear to concentrate at the crests of the large dunes, although the increasing band depth used for gypsum detection could instead indicate an increase in gypsum grain size rather than grain abundance (Roach et al., 2007; Calvin et al., 2009; Horgan et al., 2009; Murchie et al., 2009). Horgan et al. (2009) argued that because coarse grains do not typically accumulate on dune crests, and because the dune crests coincide with a higher albedo more typical of gypsum than of mafic materials, the CRISM data indicate an increase in gypsum abundance rather than an increase in grain size with elevation on the dunes. That study found gypsum abundances on dune crests to be as high as 42 wt.%, with abundances in interdunes as low as 13 wt.%. Gypsum is also present, but not in such high concentrations, on the crests of lower, secondary dunes that are found on the slopes of the larger dunes (Szumila et al., 2013).

The presence of such an extensive deposit of young (Amazonian, <~3.3 Ga) hydrated minerals contrasts sharply with the view that sulfate minerals formed in abundance on Mars much earlier in the planet's history, during the Hesperian (~3.3 to ~3.6 Ga) or Theiikian Epochs (~3.5 to ~4 Ga; Bibring et al., 2006). The various hypotheses explaining the presence of gypsum within Olympia Undae have very different implications for the formation of sulfates at high northern latitudes. Fishbaugh et al. (2007) proposed that gypsum formed from (1) precipitation of gypsum crystals as sulfate-rich brines evaporated and (2) direct aqueous alteration of high-calcium, iron-rich pyroxene and sulfide sand grains already present in the dunes. A field study of the polar sulfur cycle in Svalbard, Norway, supports this hypothesis, suggesting that gypsum on Mars could form from basalt and sulfide weathering during episodic thawing and melting events (Szynkiewicz et al., 2013). Other proposed gypsum formation mechanisms involve abrasion of older strata containing sulfates, such as a "veneer-forming" sedimentary unit exposed within the spiral troughs of Planum Boreum (Horgan et al., 2009) and deposits underlying the sand sea that may have formed from precipitation in hydrothermal groundwater (Tanaka, 2006).

There is no consensus yet on the origin of the sulfates in the dune field. It is possible that the concentration of gypsum on the dune crests may provide some hint of its origin: could this concentration have occurred as a result of preferential aeolian redistribution of grains by size or density, or did it form *in situ* by alteration of other minerals or from precipitation? There is little understanding of how aeolian transport might rework grains of varying mineralogy across a dune or through a dune field. A laboratory study of the compositional maturity of mafic aeolian sand grains indicated that basalt grains are as durable in aeolian transport as polycrystalline quartz, and that volcanic glass grains are nearly as durable, but that monocrystalline grains of plagioclase, pyroxene, and (especially) olivine abrade easily (Cornwall et al., 2015). Gypsum grains (~1 mm diameter) have been found to abrade quickly to smaller (~500 μm diameter) and rounder particles in simulated aeolian transport (Marsland and Woodruff, 1937). However, smaller gypsum grains (ranging in size from ~125 to 1000 μm) were found to abrade much more slowly than quartz grains, suggesting that despite their softness, gypsum sand grains can be transported for long distances under arid conditions (Szynkiewicz et al., 2013).

The intent of the present study is to investigate how aeolian processes spatially segregate sand grains of gypsum and other mineralogies across active dunes. We performed a field investigation of four barchan/barchanoid dunes at White Sands National Monument (WSNM) in New Mexico, USA, selected for their likely "contamination" by non-gypsum grains. Field samples from these dunes have been separated by grain size and, in some cases by apparent color, and mineralogical analyses were performed with the combined use of X-ray powder diffraction (XRD), visible and near-infrared (VNIR) spectroscopy, Raman spectroscopy, and Fourier transform infrared (FTIR) spectroscopy. The study site was located at the upwind margin of the WSNM dune field, along a transport pathway including a secondary population of dolomite grains in addition to the predominant gypsum grains. Although not as hard or dense as the mafic sands of Olympia Undae, dolomite is significantly harder and denser than gypsum (with hardnesses of 3.5–4 and 2, and densities of ~2.84 and ~2.31 g cm^{-3}, respectively), potentially interacting with gypsum in ways that may be analogous to that of the iron-bearing glass and high-calcium pyroxene common to Olympia Undae (with hardnesses of 5.5 and 6, and densities of ~2.75 and ~3.4 g cm^{-3}, respectively).

Spectroscopic analysis from the dolomite-rich study area in WSNM (labeled "Dolomite Dune" in Fig. 1) shows that, although sand grains finer than ~500 μm (>~1φ) were predominantly made of gypsum grains (similar to the rest of the dune field), the coarsest grains (>1 mm, or <0φ) were mostly dolomite. In addition, a small but significant portion of the coarser grains were composed of other minerals, including (in decreasing order of abundance) calcite, quartz, hematite, microcline, the clay prehnite and clay assemblage beidellite–illite–chlorite, albite, rutile, titanite, and possible mafic minerals. There is a marked drop in mineralogical diversity from windward base of the Dolomite Dune stoss slope (i.e., the upwind margin of the dunefield) to the Dolomite Dune crest, with gypsum growing increasingly prevalent in the coarsest size fraction with proximity to the crest. A comparison of potential fluxes from creep and saltation indicates that the mineralogical segregation of coarse grains is caused by saltation, because wind events that are strong enough to saltate >1 mm grains are much more effective at entraining low density gypsum grains than the denser minerals. This process helps to produce the nearly pure gypsum of the main WSNM dune field, which under-represents the mineralogical diversity found upwind. All spectral and XRD data described in this study have been archived at http://odr.io/SETI_WhiteSands01.

2. Background

The White Sands Dune Field is located in the Tularosa Basin in New Mexico, USA. The southern portion of the dune field is contained within the boundary of WSNM (see Fig. 1). The dune sand is derived from gypsum sediment eroded from lake beds located immediately upwind on Alkali Flat, to the west. These beds were formed by evaporation of Lake Otero (located where Alkali Flat and the dune field are today), which formed during the Pleistocene (e.g., Seager et al., 1987; Allen et al., 2009). Beginning ~7000 years ago, the lakebed surface was deflated as much as 20 m, as Lake