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Grain size and hydrodynamic sorting controls on the composition of basaltic sediments: Implications for interpreting martian soils

Christopher M. Fedo *, Ian O. McGlynn, Harry Y. McSween Jr.

Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN 37996, USA

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ABSTRACT

Impact shattering of bedrock and wind-driven sorting have been identified as primary processes modifying the size, shape, and roundness of basalt-derived sediments at the Spirit rover landing site in Gusev Crater, Mars. We experimentally explore how physical sorting can cause significant compositional modification of sediment relative to bedrock in the absence of chemical weathering. Two basalt samples, chosen to provide a range of source rock compositions and textures, were crushed and sieved. We quantify variations in sediment mineral proportions as a function of grain size, as well as accompanying changes in major- and trace-element geochemistry. Redistribution of phenocrysts imposes the primary compositional control on basalt-derived sediments, although minor mineral fractionations affect trace-element concentrations. Olivine accumulation pairs with increasing MgO, Fe_2O_3(T), Ni, and Co, and Al_2O_3 depletion. The observed chemical changes in physically sorted sediments in our experiments mimic those measured in martian soils. Aeolian transport models demonstrate that sorting of mineral components of basalts under martian conditions is likely. Given the potential for sorting by winds on Mars we argue that sorting must be considered, in addition to chemical weathering, when interpreting the geochemical changes in martian sediments.

1. Introduction

Interpretations of sediment compositions on Mars commonly focus on abundance of olivine to identify source rocks (Stockstill-Cahill et al., 2009) or as an indication of the extent of chemical weathering of basalt (e.g., Koeppen and Hamilton, 2008). The low *chemical index of alteration* values for sediment at the Mars Pathfinder (McSween and Keil, 2000), Mars Exploration Rovers (MER; Hurowitz and McLennan, 2007), and Mars Science Laboratory Rover (MSL; McLennan et al., 2014) landing sites suggest only limited chemical weathering and clay production through hydrolysis from phases such as plagioclase and volcanic glass. Consequently, clay and sulfate minerals present in martian soils likely represent physical admixtures of material (McSween et al., 2010; McGlynn et al., 2012) that formed during earlier, perhaps wetter, sedimentary cycles.

Johnsson (1993) detailed key factors that control how sediments acquire their compositions, including original provenance variability, chemical weathering, and physical sorting. With all other controlling factors held constant, source terranes with little compositional and textural variation will ultimately produce sediment of equally limited variability. However, in diverse provenances, derived sediment has the potential to be quite heterogeneous as a result of both mixing and unmixing of detrital grains. Where chemical weathering is effective, hydrolysis plays a significant role in altering bedrock composition (e.g., Nesbitt and Wilson, 1992), and therefore, any sediment derived from it. Because physical weathering does not involve compositional change, effects associated with mechanical processes are commonly neglected when interpreting sediment compositions. However, important changes to sediment mineral composition relative to source rocks can occur through the effects of physical sorting during transport (Young and Nesbitt, 1998; Fralick, 2003; Mangold et al., 2011). Here, *physical* (*hydrodynamic*) *sorting*, or the separation of minerals by transport in sedimentary systems, is referred to simply as *sorting*.

On the martian surface, transported and sorted sedimentary particles occur as dunes (Greeley and Iverson, 1985), some presently active (Chojnacki et al., 2011), as aeolian ripples (Sullivan et al., 2008), and as fluvial bedload (Williams et al., 2013). Therefore, possible compositional changes derived from physical processes may have occurred, and be accounted for when interpreting the sedimentology of Mars (e.g., Mangold et al., 2011; McGlynn et al., 2012).

Lack of evidence for pervasive chemical weathering (Hurowitz and McLennan, 2007; McLennan et al., 2014) coupled with a

* Corresponding author.
E-mail address: cfedo@utk.edu (C.M. Fedo).

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growing interest in the important role of physical processes in sediment formation on Mars (McGlynn et al., 2011, 2012) leads us to consider how we might address the extent to which such processes could impact sediment mineralogy and geochemistry in Mars-relevant source rocks. This paper uses experiments to explore the extent of compositional variation within sieved sediment populations derived from two texturally and compositionally different crushed basaltic analogs. The analog experiment, though imperfectly, simulates impact-generated sediment and provides a starting point to consider redistribution of mineral grains from a basaltic source. After evaluating the compositional data from sieving, we model initial threshold velocity (u_{*t}) and grain-size relationships of relevant detrital phases with a range of densities to demonstrate that significant chemical changes in sediment may result from the redistribution of mineral species by sorting. The experiment and modeling investigate the possible extent to which physical fractionations in artificially crushed and sieved sediments mimic impact shattering of bedrock followed by aeolian transport of sediment on Mars could account for its surface composition (McGlynn et al., 2011, 2012).

2. Importance of sorting on sediment compositions

Physical breakdown of bedrock alone is generally insufficient to impose compositional changes on the resultant sediments, which indicates that additional processes leading to mineral segregation must be operative. For example in the Guys Bight Basin in Arctic Canada (Nesbitt and Young, 1996), glacially comminuted sediment, derived from feldspar–quartz–biotite gneiss, underwent sorting during short-distance (<5 km) fluvial transport from glaciers to the ocean. The resulting sediment compositions concentrate quartz and feldspars in coarse sands, and biotite, garnet, and hornblende in fine sands and mud (Young and Nesbitt, 1998).

In addition to sorting of primary minerals, accessory mineral sorting has also been investigated. A case study from Fralick (2003) documented geochemical differences from dense mineral separation controlled by grain size, shape, specific gravity, and flow conditions in Matinenda Formation placer deposits, where smaller dense grains resist erosion compared to light mineral grains. Preferential segregation of accessory minerals was reported with increasing distance from the sedimentary source.

Lastly, in an example from the Eldborgir volcano, Iceland, aeolian-transported, minimally altered volcanic sand provides a basaltic comparison for mineral segregation (Baratoux et al., 2011). Wind concentrated sand enriched in Mg and Ni from an increased proportion of olivine grains relative to the source rocks, but depleted in a number of other trace elements (Mangold et al., 2011). In this study, results are complicated by potential mixing from multiple sources.

3. Physical weathering and dynamic sediment transport on Mars

The surface of Mars is strongly influenced by wind, with aeolian features including ripples and dunes observed at the MER (Greeley et al., 2004; Sullivan et al., 2008) and MSL (Silvestro et al., 2013) landing sites, and elsewhere (Zimbelman, 2010). Entrainment and movement of silt-sized grains (<100 μm) was observed at the Pathfinder (Smith and Lemmon, 1999) landing site; cameras on the Spirit rover in Gusev Crater captured images of active dust devils (Greeley et al., 2010). While dust is easily entrained and suspended on a local and global scale on Mars, the magnitude frequency, and threshold stresses of winds capable of transporting sand is still being investigated (Ayoub et al., 2014).

The lack of observed sediment mobility during the extended Viking and MER missions (Greeley et al., 2004), and modeling of sediment entrainment using the low atmospheric pressure conditions (Greeley et al., 1993) suggested that the transport of sand might be uncommon. However, the El Dorado ripple field in Gusev Crater demonstrates that aeolian transport has been active (Sullivan et al., 2008). In addition, recent observations of active sand dunes (Chojnacki et al., 2011) support the notion that conditions permissible for sorting occur on Mars.

Prior attempts to quantify possible effects of sorting on Mars have used mobile/immobile element ratios as a proxy for documenting mineralogic changes. For example, the Fe/Ti ratio in Viking, Pathfinder (McSween and Keil, 2000; McLennan, 2000) and MER sediments indicated the possibility of aeolian-driven mineral fractionation, where separation of dense accessory phases, including ilmenite, titanomagnetite, magnetite, and chromite from less dense phases might be expected in mafic sediments. However, caution is warranted for extending element-ratio interpretations too far. In Gusev Crater, and elsewhere, while the compositions of sediments must be partly controlled by selective sorting of dense mineral phases from basaltic lithic fragments, the physical mixing of compositionally different materials from multiple bedrock sources may play a role in bulk sediment composition (McGlynn et al., 2012).

4. Rationale and experimental design

4.1. Basaltic bedrock

Global surface compositions indicate a basaltic composition for the crust of Mars (McSween et al., 2009), with basalts having been found at every landing site (e.g., McSween et al., 2006; Schmidt et al., 2014). Most sediment “soils” in Gusev Crater and Meridiani Planum analyzed by the MER Alpha Particle X-ray Spectrometer (APXS) have chemical and mineralogical compositions (McSween et al., 2010; McGlynn et al., 2012) indicating basaltic sources. Accordingly, we selected two basalts with varying textures (aphyric and porphyritic) and compositions, one from the Cima volcanic field, Mojave Desert, CA and the other from Kilauea, HI, to conduct this study. Discussion of these samples, in the context of martian analogs, is described in McGlynn et al. (2012).

4.2. Physical comminution and sieving

Bedrock pulverized by impacts produces sediment with a Rosin grain-size distribution similar to what is generated from comminution experiments (Kittleman, 1964; McGlynn et al., 2011). In our study, two basalt samples were broken into cm-scale pieces with a rock press, and pulverized in a single pass using a jaw crusher. Sediment generated from each basalt sample was sieved into 14 grain-size fractions using a conventional dry sieving procedure (e.g., McManus, 1988) at 0.5 ϕ increments from −2.0 to 4.0 ϕ (4 to 1/16 mm; 4000 to 62 μm), where $\phi = -\log_2$(grain size in mm) and all textural parameters described (Friday et al., 2013). Sediment retained at −2.0 ϕ was manually separated into −2.0, −2.5, and −3.0 ϕ fractions. Constraints in the crushing procedure eliminate the production of boulder- and cobble-sized grains expected from impacts, which results in coarse-skewed distribution. The lack of cobble- and boulder-sized clasts, however, does not matter in this exercise because once the particle size exceeds a volume capable of fully describing the protolith, the composition of sediment cannot change relative to the source.

The mass of sediment retained at each successive sieve was recorded with a maximum loss from sieving at <0.5% for each sample. Resultant grain-size distributions resemble those observed in images taken by the MER Microscopic Imager (MI), with examples provided in McGlynn et al. (2011). Sediments finer than 4.0 ϕ lie outside MI resolution and were not further subdivided.