Icarus 256 (2015) 13–21

Contents lists available at ScienceDirect

Icarus

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

Physical abrasion of mafic minerals and basalt grains: Application to martian aeolian deposits

C. Cornwall [a,b,*], J.L. Bandfield [a,c], T.N. Titus [d], B.C. Schreiber [a], D.R. Montgomery [a]

[a] Department of Earth and Space Sciences, University of Washington, Seattle, WA 98195, USA
[b] School of Environmental Science, University of Ulster, Coleraine, UK
[c] Space Science Institute, Boulder, CO 80301, USA
[d] United States Geological Survey, Flagstaff, AZ 86001, USA

ARTICLE INFO

Article history:
Received 26 January 2015
Revised 7 April 2015
Accepted 13 April 2015
Available online 18 April 2015

Keywords:
Aeolian processes
Mars, surface
Mineralogy
Mars

ABSTRACT

Sediment maturity, or the mineralogical and physical characterization of sedimentary deposits, has been used to identify sediment sources, transport medium and distance, weathering processes, and paleoenvironments on Earth. Mature terrestrial sands are dominated by quartz, which is abundant in source lithologies on Earth and is physically and chemically stable under a wide range of conditions. Immature sands, such as those rich in feldspars or mafic minerals, are composed of grains that are easily physically weathered and highly susceptible to chemical weathering. On Mars, which is predominately mafic in composition, terrestrial standards of sediment maturity are not applicable. In addition, the martian climate today is cold and dry and sediments are likely to be heavily influenced by physical weathering rather than chemical weathering. Due to these large differences in weathering processes and composition, martian sediments require an alternate maturity index. This paper reports the results of abrasion tests conducted on a variety of mafic materials and results suggest that mature martian sediments may be composed of well sorted, well rounded, spherical polycrystalline materials, such as basalt. Volcanic glass is also likely to persist in a mechanical weathering environment while more fragile and chemically altered products are likely to be winnowed away. A modified sediment maturity index is proposed that can be used in future studies to constrain sediment source, paleoclimate, mechanisms for sediment production, and surface evolution. This maturity index may also provide insights into erosional and sediment transport systems and preservation processes of layered deposits.

1. Introduction

Mineralogical and physical characterization of sediment grains on Earth has been an important area of study that has significantly increased understanding of sediment source, transport medium and distance, weathering processes, and paleoenvironments (e.g., Bagnold, 1941; Folk, 1951, 1954; Suttner and Dutta, 1986; Weltje and von Eynatten, 2004; Garcia et al., 2004). The term 'sediment maturity' has been commonly applied to clastic deposits on Earth and describes composition as well as grain texture (Folk, 1951; Boggs, 2006). Sediment maturity refers to the degree to which sediment has been modified by physical and chemical processes. In general, "mature" sediment grains are those that are well rounded, well sorted (consisting of similar sizes), and composed of minerals that are resistant to aqueous and physical weathering (Folk, 1951; Pettijohn, 1975). The majority of mature terrestrial sands are dominated by quartz, which is abundant in source lithologies on Earth and is physically and chemically stable under a wide range of conditions.

On Mars, however, terrestrial standards of sediment maturity are not applicable due to the martian surface having a predominantly mafic composition (e.g., Christensen et al., 2000; Bandfield, 2002; Bibring et al., 2005). The presence of mafic minerals indicates sediment immaturity under terrestrial conditions because many common mafic minerals are highly susceptible to chemical weathering, softer than quartz, and may include a wider assemblage of minerals that contain cleavage planes, making them less durable during physical transport. The martian climate today is cold, dry and dominated by wind-blown (aeolian) activity. Significant aqueous activity on the martian surface is thought to have ended early in the planet's history with geologic evidence relating to liquid water on the surface dating to over 3 billion years ago (e.g., Carr and Head, 2010). Thus, modern martian sediments

* Corresponding author at: School of Environmental Science, University of Ulster, Coleraine, UK.

http://dx.doi.org/10.1016/j.icarus.2015.04.020
0019-1035/© 2015 Elsevier Inc. All rights reserved.

are likely to have been largely shaped by physical weathering related to aeolian processes.

Martian sediments require an alternate maturity index that takes into account the absence of significant chemical weathering and the presence of a primarily mafic surface composition (Grotzinger et al., 2011; Titus et al., 2012; Fenton et al., 2013). A modified sediment maturity index can be used to place constraints on sediment source, paleoclimate, mechanisms for sediment production, and surface evolution. A maturity index can also provide insights into erosional and depositional landscapes (sediment transport systems) and preservation processes of layered deposits. This study explores the physical durability of a variety of geologic materials and investigates the changes in grain texture during a series of abrasion tests. The results of these experiments lead to the construction of a maturity index (intended for sand-sized clastic aeolian sediments) more appropriate for the martian environment and climate.

2. Sediment samples

The natural terrestrial samples used for this study are mafic sands collected from South Point Beach, Hawaii; Hilo, Hawaii; and the Moses Lake dune field in Washington. The Hawaiian sediments are predominantly composed of olivine (South Point) and volcanic glass (Hilo; Moberly et al., 1965; Marsaglia, 1993). The Moses Lake sediment is composed of granodiorite and basalt grains with minor smectite alteration products (Bandfield et al., 2002). Natural sediment samples were collected and chosen for analysis based on the composition and environment in which they were weathered and deposited. The Hawaiian beach sand samples range in size from 420 μm (South Point) to 560 μm (Hilo) and originate from a humid environment, where aqueous activity dominates. The olivine grains of South Point are thought to originate from lava phenocrysts or crystal ejecta in tuffs from Mauna Loa lava flows (Moberly et al., 1965) ranging in age from <200 ka to approximately 400 ka (Sharp et al., 1996). These olivine grains were weathered out of basalt and tuff deposits and subsequently transported to the beach primarily by fluvial activity. The volcanic glass grains originate from Mauna Loa lava flows as well but were produced when lava came in contact with the ocean and rapidly cooled (Moberly et al., 1965). The Moses Lake dune field sand grain sizes average 237 μm and originate from a relatively arid environment. The basaltic dune sand originated from the Quincy Basin, where sediment was deposited by one or more of the Missoula or Channeled Scabland flood events that scoured the underlying Columbia Basalts between 17,000 and 12,000 years ago (Bretz et al., 1956; Nummedal, 1978). These sediments were subsequently reworked by aeolian processes. For the purposes of this study, only weathering textures of basaltic grains were analyzed from the Moses Lake sediments. Grains of basalt were manually separated from the granodiorite particles under a microscope.

The abrasion samples were used to determine physical durability of common materials on Mars as well as to provide a comparison to terrestrial quartz-rich sediments. The variety of mafic minerals and volcanic materials were chosen based on remote sensing observations of Mars. The surface of Mars is predominantly basaltic in composition and comprised of minerals rich in magnesium and calcium (e.g., Bandfield, 2002). Therefore, the materials chosen for this study include olivine (forsterite), clinopyroxene (augite), plagioclase (labradorite), volcanic glass and fine-grained basalt from the Columbia River Basalt Group volcanic deposits. The varieties of silica-rich samples that were used to relate abrasion results to familiar terrestrial materials include crystalline quartz, polycrystalline quartz, and microcrystalline chert. Unaltered and compositionally pure mineral samples were ordered from the suppliers Ward's Science and D.J. Minerals Inc. Columbia River Basalt Group rock outcrop samples were collected from localities near Moses Lake, Washington.

3. Analysis techniques

3.1. Natural samples

SEM images were used to investigate differences in grain weathering textures between humid (Hawaiian) and arid (Moses Lake) climates and to determine the amount of influence aqueous processes have on shaping volcanic sediments (Marshall et al., 1987). In addition, to better constrain the effects of aqueous weathering, the basaltic grains from Moses Lake were also compared to the abraded Columbia River basalt sample to investigate differences in grain texture and to see if the physical weathering textures present on the Moses Lake basalt grains could be replicated using a Bond air mill.

3.2. Abrasion tests

In preparation for abrasion, the mafic minerals, silica-rich materials, and Columbia River basalt were crushed, sifted and sorted into approximate equidimensional grain shapes with sizes between 2 and 3 mm. Abrasion tests were conducted using a modified Bond air mill following the design and convention of Nitkiewicz and Sterner (1988). The modified Bond air mill used in this study has similar dimensions to the mill employed by Nitkiewicz and Sterner (1988), Fig. 1, with inner walls composed of 320 μm silicon carbide grit mixed with an epoxy resin and copper tubing employed for the forced-air entrance. Compressed air is connected to the air entrance of the mill through rubber tubing and, when turned on, causes mineral fragments within the chamber to rapidly roll around the interior cylindrical track and quickly become well rounded and spherical.

Each abrasion experiment consisted of 100 grains, following the grain analysis method of Rosenfeld et al. (1953), and was conducted for each mineral and volcanic material separately. These samples are hereafter referred to as the homogenous samples. The final abrasion experiment consisted of a mixture of 50% basalt grains and the remaining 50% consisted of equal parts of other mafic minerals and materials including: olivine, pyroxene, labradorite, volcanic glass, and a Mg-rich phyllosilicate. A basaltic mixture was included in the abrasion tests to investigate potential differences in abrasion rates and durability of minerals as they were abraded together. This sample is hereafter referred to as the heterogeneous sample.

Due to the small size of the Bond air mill, 10 separate batches of 10 grains were run at a time to provide data for 100 grains for each sample composition. To ensure consistency between batches, grains were weighed so that each batch only had a difference of ±0.005 g, as larger differences tended to cause grains to abrade more rapidly or slowly than other batches, thus introducing inconsistences in abrasion rates. Grains were abraded using a constant flow of compressed air at approximately 62 kPa to ensure the grains were not being abraded at different rates than other batches. The airflow used was strong enough to roll the grains rapidly around the cylindrical track inside the air mill, following the convention described in Nitkiewicz and Sterner (1988). A fine mesh was glued over the air exit on the mill and prevented grains larger than 400 μm from escaping. The air exit also ensured that significant amounts of dust did not accumulate in the mill preventing variability in the abrasion effectiveness between samples.