Icarus 274 (2016) 50–72

Contents lists available at ScienceDirect

Icarus

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

Characteristics of terrestrial basaltic rock populations: Implications for Mars lander and rover science and safety

Robert A. Craddock[a],*, Matthew P. Golombek[b]

[a] Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560, United States
[b] Earth and Space Sciences Division, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, United States

ARTICLE INFO

Article history:
Received 24 July 2015
Revised 18 February 2016
Accepted 22 February 2016
Available online 14 March 2016

Keywords:
Mars
Mars, surface
Terrestrial planets

ABSTRACT

We analyzed the morphometry of basaltic rock populations that have been emplaced or affected by a variety of geologic processes, including explosive volcanic eruptions (as a proxy for impact cratering), catastrophic flooding, frost shattering, salt weathering, alluvial deposition, and chemical weathering. Morphometric indices for these rock populations were compared to an unmodified population of rocks that had broken off a solidified lava flow to understand how different geologic processes change rock shape. We found that a majority of rocks have an sphericity described as either a disc or sphere in the Zingg classification system and posit that this is a function of cooling fractures in the basalt (Zingg [1935] Schweiz. Miner. Petrogr. Mitt., 15, 39–140). Angularity (roundness) is the most diagnostic morphometric index, but the Corey Shape Factor (*CSF*), Oblate–Prolate Index (*OPI*) and deviation from compactness (*D*) also sometimes distinguished weathering processes. Comparison of our results to prior analyses of rock populations found at the Mars Pathfinder, Spirit, and Curiosity landing sites support previous conclusions. The observation that the size-frequency distribution of terrestrial rock populations follow exponential functions similar to lander and orbital measurements of rocks on Mars, which is expected from fracture and fragmentation theory, indicates that these distributions are being dominantly controlled by the initial fracture and fragmentation of the basalt.

1. Introduction

Geologic outcrops and fragmented particles are commonly characterized by their fabric and composition, which are critical pieces of information for determining their provenance. However, the fragmented particles can be subjected to a variety of transport and erosional processes prior to and subsequent to their emplacement. The provenance of these particles is different than the geologic processes that have transported or weathered them, and for over a century, sedimentologists have known that morphometry, or shape, can reveal important clues about the nature of the geologic processes that have affected individual particles. For example, it is well known that a grain of sand will become rounder with increasing transport distances (e.g., Folk, 1974). Such analyses are used routinely to evaluate the history and origin of a sedimentary deposit. The morphometry of larger rocks and clasts (>32 mm) can also provide important clues regarding transport, emplacement, and erosional processes (e.g., Folk, 1974). Results from studies of terrestrial rock morphometry could be applied to the local geology of a landing site on a planetary surface, help evaluate the safety at prospective landing sites (Golombek et al., 2003, 2008, 2012), and even help future rovers make autonomous decisions regarding safety and scientific objectives. Unfortunately, our knowledge about the relationship between rock shape and the geologic transport/erosion processes is somewhat limited due to a general lack of data. Rock shape is also a function of its composition (e.g., Folk, 1974), and our knowledge becomes even more limited in this regard. In particular, there have only been a handful of studies that have focused on understanding the relationship between basaltic rocks and geologic processes (e.g., Dobkins and Folk, 1970; Ehlmann et al., 2008).

In this paper, we characterize the morphometry of terrestrial basaltic rock populations found in a variety of geologic settings that are analogous to many past and current martian environments. Our analyses focus primarily on rocks and clasts that are derived from basaltic lava flows. (We define rocks as individual particles, whereas clasts are particles that are in contact with one another or are in a supporting matrix of smaller particles.) Most of the measurements are from Hawaii, which is an ideal location for conducting such analyses because the fairly homogenous basaltic composition of the islands precludes variations in rock morphometry caused by lithology. By limiting our analyses to basaltic rocks,

---

* Corresponding author. Tel.: +1 202 633 2473.
E-mail address: craddockb@si.edu (R.A. Craddock).

http://dx.doi.org/10.1016/j.icarus.2016.02.042
0019-1035/Published by Elsevier Inc.

it also makes our results amenable to understanding the emplacement mechanisms for rocks found on the surface of Mars and the other terrestrial planets, which are also composed primarily of basalt (e.g., Head et al., 1981). Hawaii is volcanically active and, because of its location in the Pacific Ocean and dramatic surface relief, it experiences many different microclimates. Thus, there are basaltic surfaces that have been exposed to a wide variety of different geologic processes. Additionally, because Hawaii is located over a hotspot there is a systematic increase in the ages of the basaltic units towards the northwestern islands (Clague and Dalrymple, 1987), which means that it is also possible to characterize changes in rock morphometry within specific geologic environments through time.

We characterized the morphometry of over 700 rocks and clasts emplaced or created by a variety of chemical and physical processes, including phreatic eruptions from Kilauea volcano, freeze-thaw processes near the summit of Haleakala, salt erosion on Molokai, as well as several other processes that may be relevant to Mars. For comparison, we also collected additional morphometric data from basaltic rocks emplaced by catastrophic outflow processes on the Ephrata Fan in Washington State, which is an analog to the Mars Pathfinder landing site (Golombek et al., 1997). We included basaltic rocks from catastrophic outflow deposits located in Idaho (O'Connor, 1993), and metabasaltic clasts from debris flows in Virginia (Eaton et al., 2003), because these sites are relevant and became available as we conducted the analyses. Although our sampling strategy initially included all rocks and clasts >5 mm, the analyses presented here focuses on particles with short axes >64 mm. We concentrated on these larger rocks and clasts because they are more easily seen and measured at a distance away from a lander (e.g., Yingst et al., 2008), so our results would be more generally applicable to assessing landing site geology. Also, rocks of this size are large enough to be directly analyzed by most lander instruments. Additionally, rock shape becomes more influenced by grain size at smaller sizes (Sneed and Folk, 1958), texture (e.g., vesicularity; Drake, 1970), lithology (Sneed and Folk, 1958) and secondary processes (e.g., insolation weathering; Morris et al., 1972). Focusing on the larger rocks and clasts can thus help avoid the possibility of including smaller fragments that were weathered from the primary rock population following transport and emplacement.

The rocks were characterized using a variety of morphometric indices, including the Oblate–Prolate Index (OPI) (Dobkins and Folk, 1970), Form Factor (F), and the Maximum Projection Sphericity (ψ_p) (Sneed and Folk, 1958) (Table 1). Axial ratios were calculated according to Zingg (1935) and measured using the long (L), intermediate (I) and short (S) axes as defined by Krumbein (1941). In order to provide a basis for comparing our data to lander images, we also characterized the rock shapes using the Corey Shape Factor (Corey, 1949) that may be applicable to assessing rock populations from only two axial dimensions, which is commonly the case for rocks viewed from landers.

A natural consequence of our analyses is to see if the size-frequency distributions of rock populations vary with a particular geologic setting. While size-frequency distributions of rocks emplaced by a variety of geologic processes on the Earth generally follow an exponential curve, there is a great deal of variability in exactly what the largest particle might be in a particular setting or environment, which has an large effect on standard cumulative size-frequency distributions (Golombek and Rapp, 1997). Our results also provide constraints on the potential hazards future landers may encounter from large surface rocks (Golombek et al., 2003, 2008, 2012).

The results presented here represent the most comprehensive analysis of the morphology associated with basaltic rock populations to date. Our results indicate that cooling fractures in the original lava flows controls the general shape of most basaltic particles >64 mm. We find that the most diagnostic morphometric index is angularity. However, assessment of angularity is subjective, and we discuss some existing methods for quantifying angularity that could be applied to digital lander images. Potentially the information presented here can be of help to Mars landers as a way to evaluate the transport and emplacement history of individual rocks prior to in situ analyses. Future landers could also use rock morphometry to determine the local geologic history and to evaluate the potential diversity of entire rock populations. This type of quantitative analysis could also prove invaluable when selecting samples for return to Earth.

2. Background

There is extensive evidence for basaltic volcanism on the surface of Mars (e.g., Francis, 1993). Geologic features such as the Tharsis volcanoes (Carr, 1973), analyses of the SNC meteorites (McSween, 1994), hyperspectral data from orbiting spacecraft (e.g. Bandfield et al., 2000; Christensen et al., 2001; Bibring et al., 2005; Mustard et al., 2005), and in situ measurements made by Viking (Kelliher, 1977), Mars Pathfinder (Wänke et al., 2001), Spirit (Gellert et al., 2004) and Curiosity (Grotzinger, 2013) indicate that most martian rocks are basaltic (e.g., Golombek and McSween, 2014). Collectively, the results from these investigations suggest that the major elemental composition of the basalts found on Mars are similar to basalts found on the Earth (Palme, 2002).

Investigators have long realized that the rocks imaged by landers provide fundamental clues about the geologic history of the surface, yet arguments have often remained qualitative. The rocks at the Viking 1 landing site, for example, have been explained by impact cratering (Jones et al., 1979; Garvin et al., 1981; Sharp and Malin, 1984; Arvidson et al., 1989), in situ weathering (Mutch et al., 1976; Binder et al., 1977; Garvin et al., 1981), and catastrophic outflow (Mutch et al., 1976; Mutch and Jones, 1978). Such interpretations imply very different geologic histories for Chryse Planitia (e.g., Craddock et al., 1997), and they illustrate the difficulties in evaluating the geologic history of a landing site from qualitative arguments alone. Our goal is to make such arguments more quantitative. The objective of our study is to characterize basaltic rock populations emplaced by a variety of processes to see if any physical criteria can be established that will allow us to diagnose the geologic history of individual rocks or rock populations. To do this properly, however, we must also consider the special problems that are inherent when applying terrestrial observations to two-dimensional digital images obtained by lander cameras. We therefore also show how comparable shape measurements can be obtained from digital data and how our results can be applied to interpreting lander images.

2.1. Particle shape

The shape of a particle can be used in a general way to infer the duration of transport and the amount of reworking the particle has undergone. The term "shape," however, has been used in a variety of ways in the geological literature. Typically it is used to describe the entire morphology of a particle, which, as Barrett (1980) explained, includes form, angularity (i.e., roundness), and surface texture. Form is related to the three principal axes of symmetry and is usually quantified in terms of sphericity, which can be used to estimate the relative distance a particle travels (Krumbein and Sloss, 1963, p. 110). Angularity describes the variations in corners, edges and faces on the particle and is typically more useful for environmental transport interpretations (Tucker, 1981, p. 17). Surface texture describes fine-scaled morphometric variations on the particle