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**Characteristics Of Terrestrial Basaltic Rock Populations: Implications
For Mars Lander And Rover Science And Safety**

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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* [1935] classification system and posit that this is a function of cooling fractures in the basalt. 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]).

75 In this paper, we characterize the morphometry of terrestrial basaltic rock
76 populations found in a variety of geologic settings that are analogous to many past and
77 current martian environments. Our analyses focus primarily on rocks and clasts that are
78 derived from basaltic lava flows. (We define rocks as individual particles, whereas clasts
79 are particles that are in contact with one another or are in a supporting matrix of smaller
80 particles.) Most of the measurements are from Hawaii, which is an ideal location for
81 conducting such analyses because the fairly homogenous basaltic composition of the
82 islands precludes variations in rock morphometry caused by lithology. By limiting our
83 analyses to basaltic rocks, it also makes our results amenable to understanding the
84 emplacement mechanisms for rocks found on the surface of Mars and the other terrestrial
85 planets, which are also composed primarily of basalt [e.g., *Head et al.*, 1981]. Hawaii is
86 volcanically active and, because of its location in the Pacific Ocean and dramatic surface
87 relief, it experiences many different microclimates. Thus, there are basaltic surfaces that
88 have been exposed to a wide variety of different geologic processes. Additionally,
89 because Hawaii is located over a hotspot there is a systematic increase in the ages of the
90 basaltic units towards the northwestern islands [*Clague and Dalrymple*, 1987], which
91 means that it is also possible to characterize changes in rock morphometry within specific
92 geologic environments through time.

93 We characterized the morphometry of over 700 rocks and clasts emplaced or
94 created by a variety of chemical and physical processes, including phreatic eruptions
95 from Kilauea volcano, freeze-thaw processes near the summit of Haleakala, salt erosion
96 on Molokai, as well as several other processes that may be relevant to Mars. For
97 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

121 from only two axial dimensions, which is commonly the case for rocks viewed from
122 landers.

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

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

143 2. Background

144 There is extensive evidence for basaltic volcanism on the surface of Mars [e.g.,
145 *Francis*, 1993]. Geologic features such as the Tharsis volcanoes [*Carr*, 1973], analyses of
146 the SNC meteorites [*McSween*, 1994], hyperspectral data from orbiting spacecraft [e.g.
147 *Bandfield et al.*, 2000; *Christensen et al.*, 2001; *Bibring et al.*, 2005; *Mustard et al.*,
148 2005], and in situ measurements made by Viking [*Kelliher*, 1977], Mars Pathfinder
149 [*Wänke et al.*, 2001], Spirit [*Gellert et al.*, 2004] and Curiosity [*Grotzinger*, 2013]
150 indicate that most martian rocks are basaltic [e.g., *Golombek and McSween*, 2014].
151 Collectively, the results from these investigations suggest that the major elemental
152 composition of the basalts found on Mars are similar to basalts found on the Earth
153 [*Palme*, 2002].

154 INVESTIGATORS HAVE LONG REALIZED THAT THE ROCKS IMAGED BY
155 LANDERS PROVIDE FUNDAMENTAL CLUES ABOUT THE GEOLOGIC HISTORY OF
156 THE SURFACE, YET ARGUMENTS HAVE OFTEN REMAINED QUALITATIVE. THE
157 ROCKS AT THE VIKING 1 LANDING SITE, FOR EXAMPLE, HAVE BEEN EXPLAINED
158 BY IMPACT CRATERING [*Jones et al.*, 1979; *Garvin et al.*, 1981; *Sharp and Malin*,
159 1984; *Arvidson et al.*, 1989], IN SITU WEATHERING [*Mutch et al.*, 1976; *Binder et al.*,
160 1977; *Garvin et al.*, 1981], AND CATASTROPHIC OUTFLOW [*Mutch et al.*, 1976; *Mutch*
161 *and Jones*, 1978]. SUCH INTERPRETATIONS IMPLY VERY DIFFERENT GEOLOGIC
162 HISTORIES FOR CHRYSE PLANITIA [E.G., *Craddock et al.*, 1997], AND THEY
163 ILLUSTRATE THE DIFFICULTIES IN EVALUATING THE GEOLOGIC HISTORY OF A
164 LANDING SITE FROM QUALITATIVE ARGUMENTS ALONE. OUR GOAL IS TO MAKE
165 SUCH ARGUMENTS MORE QUANTITATIVE. THE OBJECTIVE OF OUR STUDY IS TO
166 CHARACTERIZE BASALTIC ROCK POPULATIONS EMPLACED BY A VARIETY OF
167 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,
pg. 110]. Angularity describes the variations in corners, edges and faces on the particle
and is typically more useful for environmental transport interpretations [*Tucker*, 1981, pg.
17]. Surface texture describes fine-scaled morphometric variations on the particle itself
and is also useful for making environmental transport interpretations [*Krinsley and*
Doornkamp, 1973, pg 8].

2.1.1. Particle Form

After almost a full century of investigations, no less than a dozen different parameters have been proposed to estimate a particle's form (Table 1). Each parameter typically involves relating the three principal axes of symmetry (long, intermediate and short) to one another. *Barrett* [1980] noted that form can be efficiently represented by pairing two dependent measures; in particular, the Maximum Projection Sphericity (ψ_p) [*Sneed and Folk*, 1958] and the Oblate-Prolate Index (OPI) [*Dobkins and Folk*, 1970]. From his analyses, he determined that both of these measures show an arithmetic normal distribution when applied to most particle populations. *Dobkins and Folk* [1970] showed the usefulness of such measurements in distinguishing, for example, basaltic beach pebbles modified in low-energy versus high-energy wave environments.

The measure of Maximum Projection Sphericity (ψ) is defined by *Sneed and Folk* [1958] as

$$\psi = \frac{S^2}{L \cdot I} \quad (1)$$

where S is the short axis, L is the long axis, and I is the intermediate axis of a particular rock or particle. *Sneed and Folk* [1958] also defined the Form Factor (F) as

$$F = \frac{L - I}{L - S} \quad (2)$$

Additionally, *Dobkins and Folk* [1970] define the Oblate-Prolate Index as

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$$OPI = \frac{10 \cdot \frac{L - I - 0.50}{L - S}}{S/L} \quad (3)$$

211 The resulting dimensionless values for Equations 1-3 range from 0 to 1. While these
 212 indices have practical applications for determining and distinguishing the form of
 213 individual particles that can be picked up and examined, they cannot be readily applied to
 214 most rocks seen in lander images because typically, at best, only two principal axes can
 215 be seen. Fortunately, there are methods for measuring the form of particles using only
 216 two of the three principal axes that were developed for analyzing particles seen through
 217 an optical microscope. The simplest formula for measuring a particle's form from
 218 measurements of only two axes is the Corey Shape Factor (CSF), which expresses the
 219 ratio of the cross-sectional area of a sphere to the maximum cross-sectional area of an
 220 ellipsoid [Corey, 1949]

221

$$CSF = \frac{S}{\sqrt{I} \cdot L} \quad (4)$$

222 Like Equations 1-2, the resulting dimensionless values for the CSF range from 0 to 1 and
 223 describe the difference between a flat plate and a perfect sphere, respectively. Besides
 224 having a geometric basis, the CSF also relates the particle's shape to its hydraulic
 225 properties [Dietrich, 1982]. When examining particles through an optical microscope the
 226 intermediate and short axes are assumed to be approximately equal to each other [e.g.,
 227 Dietrich, 1982] so that Equation 4 becomes

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$$CSF_{2.Axes} = \sqrt{\frac{I}{L}} \quad (5)$$

Unfortunately, not even Equation 5 can be applied directly to estimating the form of rocks seen in lander images. The most stable position for a rock is when it is resting on its short axis (i.e., the short axis is perpendicular to the surface). When seen in a lander image, the short axis can be estimated by measuring from the surface to the top of the rock. However, the intermediate and long axes are oriented somewhere between 0 and 90° oblique to the viewing direction of the spacecraft, so these cannot be measured easily [e.g., *Golombek and Rapp, 1997*]. For this reason, we use the measurements of the three principal axes of symmetry from our terrestrial rock populations to develop a modified form of Equation 4 for application to lander images. We use the ψ , F , and OPI to describe and compare the form of rocks in our sample sites, but also present measurements of the CSF so that our results can be compared easily to measurements of rocks from lander images.

2.1.2. Particle Angularity

Similar to sphericity, a variety of methods have also been used to quantify angularity (Table 2). To confuse matters, published methods sometimes refer to angularity as “roundness,” but both terms mean the same thing. Unfortunately, many of the methods involve practical or conceptual problems that limit their usefulness for quantifying angularity or comparing values between different rock populations. *Barrett* [1980] determined that for most applications the visual comparison chart proposed by *Krumbein* [1941] for estimating angularity appears to be the most representative. T

Although *Krumbein*’s [1941] charts are easy to use (and most geologist are familiar with them) they are qualitative and subjective. For convenience, we assigned a numeric

value to each of *Krumbein's* [1941] angularity categories where 0 was very angular, 1 was angular, 2 was subangular, 3 was subrounded, 4 was rounded, and 5 was well-rounded. To insure the objectivity of our results, the angularity of each rock population was determined by no less than three individuals to help reduce the bias that may be introduced from a single person. It should be possible to compare our results for angularity to measurements that can be made from lander images because *Waddell* [1932] determined that *Krumbein's* angularity can be estimated from a two-dimensional projection (such as seen from a spacecraft image or an optical microscope) without causing any serious bias. Implicitly, other investigators have agreed with this assertion primarily because of the difficulty in measuring angularity in three dimensions [*Barrett*, 1980]. Because angularity is independent of sphericity or particle form, it can also be estimated independently of the viewing direction. That is to say, the same estimate of angularity will be made regardless of the particle orientation with respect to the lander. The inherent problem with using *Krumbein's* [1941] visualization chart, however, is the fact that an unknown degree of operational bias always remains, and this must be considered when applying the data presented here. Later, we describe an automated method for estimating angularity using *Krumbein's* [1941] charts as a template that is both quantitative and objective that could prove useful for analyzing rock morphometry from digital images.

2.1.3. Particle Texture

For smaller particles (<64 mm), surface texture has been proven to be a useful diagnostic tool alone. *Krinsley and Doornkamp* [1973], for example, showed that beach

sands often contain small V-shaped percussion marks, desert sands possess "upturned plates," and sands from glacial deposits have conchoidal fracture patterns and striations. While there have been successful efforts to understand the applicability of surface texture in interpreting the transport processes associated with larger diameter (>64 mm) particles [Bourke *et al.*, 2005; Ehlmann *et al.* 2008], the usefulness of this characteristic alone would appear to be limited at these scales. Surface texture on smaller particles results primarily from particle-to-particle contact during transport. Fractures and scratches on large particles, however, can exceed the size of individual phenocrysts. It is also less likely larger particles will come in contact with one another during transport, and the texturing that does result is often found only in isolated patches [Bourke *et al.*, 2005]. In addition, the development of texture also requires that the rocks be transported, and many rock populations are either transported very short distances (e.g., debris flow) or created in situ, so it is unlikely that most emplacement processes would result in rock populations with any diagnostic textures. However, Ehlmann *et al.* [2008] demonstrate that the use of surface texture in characterizing rock populations is promising. They analyzed three populations of basalt boulders in the Channeled Scabland, Washington, including talus, flood-transported boulders recently excavated from a quarry, and flood-transported boulders that were weathered in situ on the Ephrata Fan surface. Their textural data show that boulders weathered and exposed at the surface are significantly rougher than those that were buried. However, signatures diagnostic of flood transport were still present on the surface of boulders. Although we remained conscious of surface texture while conducting our analyses, we focused primarily on understanding the variations in form

(sphericity) and angularity (roundness) of rocks, which are first-order characteristics that can be used to describe—and quantify—any type of rock population.

2.2. Previous Morphometric Studies of Terrestrial Basaltic Rock Population

Terrestrial geologists typically have three general views regarding the natural variability often recognized in the shape of rocks: (1) rocks erode to a specific shape based on lithology; (2) rocks erode to a specific shape based on the mechanics of the transport mechanism; and (3) both variables come into play to determine rock shape. *Wentworth* [1922], for example, has argued that the discoidal shape of pebbles found on beaches in New England is inherited from anisotropic parent rock. In this scenario, rocks erode to a flat shape regardless of the environment. Alternatively, *Landon* [1930] suggested that discoidal beach pebbles are simply sorted through wave action. In this scenario, a flat pebble is not necessarily a direct result of the environment; rather, all the other odd-shaped rocks simply roll farther into the surf. Finally, there is the view that discoidal beach pebbles are abraded flat by the surf and finer particles that are washed over them [*Marshall*, 1928, 1930]. In this scenario, rock shape is a product of the environment and reflects those processes.

To test these competing hypotheses for rocks eroded by fluvial action, *Dobkins and Folk* [1970] measured the shape of 961 basaltic rocks located in rivers and beaches on Tahiti. Basalt, as they explain, is isotropic, so shape is not directly inherited from the parent rock. They also measured rocks found in high- and low-wave energy beaches defined by typical wave characteristics, and they collected measurements throughout the surf zone. By combining these measurements to those obtained from rocks found in rivers, they were thus able to eliminate putative sorting effects and identify potential

variations in shape resulting from the environment. They concluded that abrasion is the chief cause of discoidal rocks found on beaches, and that the environment results in distinct variations in rock shape. Unfortunately, however, the environments investigated by *Dobkins and Folk* [1970] were limited and do not correspond directly to most planetary environments. Nevertheless, their study does show that rock morphometry can be a diagnostic tool.

Garvin et al. [1981] recognized the potential usefulness of rock morphology in characterizing the history of a planetary surface. They made measurements of rocks imaged by the Viking Mars and Venera Venus landers, paying particular attention to rock surface texture. Based on their analyses they concluded that the rocks at the Viking landing sites were not emplaced by fluvial processes. The typical sphericity values that they measured were 0.63; *Dobkins and Folk* [1970] found that a sphericity value of >0.65 separated rocks emplaced by beach and fluvial processes. Instead, *Garvin et al.* [1981] suggest that the rocks within the Viking landing site resulted from impact cratering or in situ weathering of a lava flow. A problem with this interpretation, however, is the fact that values for sphericity can change as a function of the method employed (Table 1). Although *Garvin et al.* [1981] correctly state that sphericity can be calculated by measuring only two axes of symmetry from the lander images, the methods used by *Dobkins and Folk* [1970], to which their data were compared, were based on three axes of symmetry. Thus, their results are not consistent or comparable with *Dobkins and Folk* [1970].

The latest study focused on basaltic rocks was conducted by *Ehlmann et al.* [2008]. In addition to using surface texture to distinguish between talus, freshly excavated and

weathered flood transported boulders; they also characterized the sphericity of their rock populations using maximum projection sphericity (ψ), the form factor (F), and deviation from compactness (D), which is the ratio of S/L. They showed that the average values of these morphometric indices were different between the populations of objects they analyzed. In particular, values of ψ (0.69 ± 0.14), F (0.47 ± 0.25) and D (0.51 ± 0.18) are similar to values we derived for the boulders on the Ephrata Fan in Washington State as described below. Our effort expands into basalt rock populations transported and weathered by a range of geologic processes applicable to the past and current martian environment.

3. Particle Shape Analyses

3.1. Sampled Environments

Rocks are created by complex interaction between physical (disintegration), chemical (decomposition) and biological processes, which are collectively referred to as weathering. Physical weathering produces smaller particles from larger ones while chemical weathering breaks down the rock by changing the composition of minerals within it. Typically these processes work simultaneously and can often affect the rate of the other. However, here we distinguish between primary and secondary weathering processes for the purpose of clarity. Basically, a primary process is responsible for creating the actual rock population. In certain instances the rock may have been transported great distances by the primary process, such as a catastrophic flood or phreatic eruption. In other instances the rock population was created in situ, such as by frost shattering or chemical weathering of a lava flow. Secondary weathering processes

are defined as processes that occurred after the rock population was emplaced or are simply ancillary to the primary process. In the environments that we sampled, in situ chemical weathering and perhaps some physical weathering due to sand abrasion were the most important secondary processes. Excluding the cases where chemical weathering was actually the primary process, subsequent chemical weathering following emplacement could be demonstrated to be minimal and would not affect rock morphometry at the scales that we measured. Obviously, this approach assumes that rock morphology is a function of the environment as indicated by *Dobkins and Folk* [1970]. That is, we are assuming that the primary weathering process is reflective of a geologic transport process or environment and that other potential influences, such as preferential sorting [*London*, 1930], are not pervasive.

In order to conduct our analyses, it was also necessary to identify and characterize an unmodified population of basaltic rocks. In their study, *Ehlmann et al.* [2008] used talus broken from columnar joints as the unmodified baseline population of rocks. Although practical, even in this type of deposit the rocks have been transported a certain extent and have had the opportunity to bounce and break, and the size and shape are partially controlled by the thickness of the flow, which controls columnar jointing [*Aydin and Degraff*, 1988]. It was challenging to find a similar population of rocks in Hawaii. However, we were able to find a population of rocks that had broken off from young historic pahoehoe flows found in the Southwest Rift Zone of Kilauea. In this area, modern flows cover portions of the older Keanakako'i Tephra. Periodic storm events have removed the tephra in places [*Craddock et al.*, 2012] creating cantilevers in the younger lava flows. Rocks formed when these cantilevers failed and the flows broke

apart following cooling fractures in the pahoehoe. We were able to measure 101 rocks >64 mm that formed this way. These rocks formed our baseline for an unmodified population of basaltic rocks. The tacit assumptions that we made were that (1) this population of rocks represents a starting unmodified basaltic rock shape, (2) rocks that might result from the interior of a ponded or aa flow would have the same general shape, and (3) compositionally different flows would also create rocks with the same general shape. We also assumed that at the rock diameters of >64 mm phenocrysts that may be found in other lava flows would not dramatically alter the starting shape of the rocks. Basically, it is possible that there are variations in the starting shapes of unmodified basaltic rocks, but this was not explored. Our baseline population was designated as Southwest Rift Zone (SWRZ) in the analyses.

3.2. Rocks Resulting from Physical Weathering

The dominant process for creating rocks on planetary surfaces would appear to be physical weathering, especially if one considers impact cratering to be a type of physical weathering process. In the case of Mars, catastrophic flooding [e.g., *Baker et al.*, 1992] and wind abrasion [e.g., *Gooding et al.*, 1992] are two other types of physical weathering processes that occur. Wind abrasion is the more important and longer-term process [Gooding et al., 1992; Armstrong and Leovy, 2005; Greeley et al., 2006, 2008; Bridges et al., 2014]. Other suggested types of physical weathering processes that may have occurred on Mars include frost shattering [Rodriguez-Navarr, 1998], salt weathering [Malin, 1974; Jagoutz, 2006], beach erosion [Parker et al., 1989, 1993; Carr and Head, 2003; Moscardelli, 2014], and thermal stress [Eppes et al., 2015]. Where it was possible,

we include measurements of rock populations affected by these additional processes in an effort to be thorough as well as to determine the uniqueness of any particular morphometric characteristic for distinguishing the emplacement mechanism and interpreting the geologic history of a landing site.

3.2.1. Impact Cratering

Impact cratering may be the primary process for creating rocks at the Viking 1 [Jones *et al.*, 1979], Viking 2 [Mutch *et al.*, 1977] and Spirit [Squyres *et al.*, 2004; Yingst *et al.*, 2008] landing sites on Mars. Unfortunately, with the exception of the Lonar crater in India, impacts into basaltic material on Earth are rare. Additionally, most terrestrial impact structures on Earth have been subjected to substantial amounts of subsequent erosion [Grant, 1999], which is likely to have affected the morphology of the corresponding rock populations. However, the rocks near the rim of the Halema`uma`u pit crater on Kilauea offer a potential proxy.

The evidence from interpretations of the tephra deposits is that Kilauea has experienced periodic phreatomagmatic eruptions for at least the last 2,000-3,000 years [Dzurisin *et al.*, 1995; Swanson *et al.*, 2012] with the most recent explosive eruption occurring in 1924. Although the amount of tephra produced by the 1924 eruption was relatively minor compared to other eruptions, particularly THE THICK TEPHRA DEPOSITED AS THE Keanakako`i, Decker and Christiansen [1984] report that rocks weighing as much as 8,000 kg (8 tons) are found 500 m (1,600 feet) from the rim of Halema`uma`u crater. In fact, rocks from this eruption are scattered across the summit of Kilauea. Although one can argue that the scale and dynamics of phreatic eruptions are

much different than the formation of an impact crater, the rocks near Halema`uma`u offer a chance to investigate the morphology of fragmented basaltic rocks emplaced ballistically from explosive processes. To understand how rock morphology may change due to transport distance during such an event, we investigated three sites ranging from ~20 m (65 feet; PE1 and PE2) to 500 m (1,600 feet; PE3) away from the rim of Halema`uma`u crater.

3.2.2. Catastrophic Flooding

The Viking 1 landing site was chosen to provide the lander with access to potential materials deposited by the circum-Chryse outflow channels [Masursky and Crabill, 1981]. Similarly, the Mars Pathfinder landing site was selected with the idea that Sojourner would have access to a “grab bag” selection of rocks transported by Ares Vallis from the martian highlands [Golombek *et al.*, 1997b]. The Spirit landing site was selected because of the potential that flooding from Ma`adim Vallis had debouched and ponded in Gusev crater [Cabrol *et al.*, 1998]. Obviously deposits associated with catastrophic flooding are and will continue to be of great scientific interest and importance in our exploration of Mars. There are no catastrophic floods in Hawaii that are at the same scale as those proposed for Mars [Baker *et al.*, 1992]; however, catastrophic floods released from Pleistocene glacial Lake Missoula are analogous [Baker and Nummedal, 1978]. These floods created a series of large channels, including the Grand Coulee in Washington State. Water from this channel flowed into the Quincy Basin through Soap Lake building a subfluvial bar that resulted in a 40-km long by 40-km wide fan near Ephrata, Washington [Baker and Nummedal, 1978]. Known as the

“Ephrata Fan,” *Golombek et al.* [1997] suggested that the geologic setting of Grand Coulee and the fan deposit is analogous to Ares Vallis and the Mars Pathfinder landing site. Late-stage drainage of the Quincy Basin removed fines from portions of the Ephrata Fan near Soap Lake resulting in an extensive lag surface of coarse rocks. We collected measurements from three separate sites near a large boulder (18 m by 11 m by 8 m) informally referred to as “monster rock” [*Golombek and Rapp*, 1997]. These boulders were the same as those measured by *Ehlmann et al.* [2008] in their study, and they were also used by *Golombek and Rapp* [1997] for their size-frequency counts. Data for these sites are abbreviated EF1, EF2, and EF3.

Additional rocks were measured in the Eden Channel of Idaho, which resulted when flooding from Lake Bonneville poured through the Snake River during the Pleistocene [*O’Conner*, 1993]. Rocks and boulders stripped from the Sand Springs Basalt collected into several large scour holes that formed during flooding of the channel. We measured rocks found in the largest of these “East of Eden potholes,” which is 40-m deep and 200-m wide [*O’Connor*, 1993]. Rocks at this site are comparable in scale to some of the larger rocks and boulders imaged by Viking 1 at Chryse Planitia and Mars Pathfinder at Ares Valles, and provide an additional assessment of rocks emplaced by catastrophic flooding. This site is denoted as EC1 in our analyses.

3.2.3. Frost Shattering

The High Energy Neutron Detector (HEND) on board Mars Odyssey has mapped the distribution of subsurface hydrogen on Mars, indicating that water ice-rich layers are concentrated at high latitudes [*Mitrofanov et al.*, 2002]. Interestingly, the distribution of

ground ice as mapped by HEND corresponds well to pre-Mars Odyssey models predicting where ground ice should be stable [Mellon and Jakosky, 1993]. The presence of ground ice is also supported by a variety of geologic features, including fluidized ejecta craters [Kuzmin *et al.*, 1988], “softened terrain” [Squyres and Carr, 1986], thermokarst [Carr and Schaber, 1977], patterned ground [Rossbacher and Judson, 1981], and putative pingos [Rossbacher and Judson, 1981]. In addition, the troughs observed at the Viking 2 [Mutch *et al.*, 1976] and Phoenix [Mellon *et al.*, 2008] landing sites have been interpreted as polygonal fractures due to ground ice [Mellon *et al.*, 2009]. On Earth, the formation of many of these geologic features is produced by cyclic freezing and thawing, but thermal contraction mechanisms in permanently frozen ground due to large and sudden temperature changes can explain their presence on Mars [Mellon *et al.*, 2009]. In terrestrial environments such processes produce rock populations through frost shattering.

Matsuoka [1991] has developed a semi-empirical model from field observations that predicts the rate of frost shattering. He explains that frost shattering is a function of temperature, moisture content, and rock properties. Although moisture content is the most significant parameter in *Matsuoka*’s [1991] model, *Hall* [1992] observed that weathering rates due to frost shattering were greater in the dry interior regions of Antarctica than in moist maritime environments, so the relative importance of moisture content is not clear, and this would be important for determining the likelihood and frequency of frost shattering on Mars. Although several experiments have discounted thermal expansion in the absence of water [Rice, 1977, p. 116], the need for at least some moisture appears to be equivocal on Mars. *Eppes et al.* [2015], for example, provide observational evidence

for numerous fractures in rocks at the Spirit landing site that are preferentially oriented with respect to the sun. They present a numerical model for how insolation-related thermal stresses may induce fracturing in the rocks.

We found a population of rocks created by frost shattering on the summit of Haleakala on the island of Maui. The flows that we investigated were mapped by *Macdonald* [1978] as “kl,” which is a combination of lava flows composed mainly of picritic basalt and hawaiite that are Pleistocene in age. Although it was not clear if frost shattering was a currently active process, the lack of vegetation on most of the affected surfaces and the absence of any patina or evidence for subsequent chemical alteration of the fractured surfaces suggested that it had occurred relatively recently. At an elevation of 10,023 ft (3,055 m), Haleakala experiences frequent diurnal fluctuations in below-freezing temperatures and seasonal accumulations in snow and ice (<http://www.ifa.hawaii.edu/haleakalanew/weather.shtml>). We analyzed two sites ~50 m apart from one another in an upslope direction. The data for the Maui sites are abbreviated MS1 and MS2.

3.2.4. Salt Weathering

Salt weathering behaves similar to frost shattering in terms of how it disintegrates a rock; however, instead of ice crystals it involves the growth and thermal expansion of salt crystals in rock. Salt refers not only to standard NaCl but a variety of compounds that form crystals from supersaturated aqueous solutions, including HF, HCl, and H₂SO₄, which are often associated from volcanic outgassing, MgSO₄, NaF, and KCl, which are additional compounds typically precipitated by evaporating sea water, and CaCl₂ and

CaSO₄, which are often associated with hydrothermal alteration. Salt weathering is a rare process on Earth and is typically isolated to coastal zones [Wellman and Wilson, 1965] where salt precipitated by sea spray concentrates along the shore, and in dry climates such as Antarctica [Selby and Wilson, 1971] or Death Valley [Goudie and Day, 1981] where salt weathering becomes an important process for rock disintegration primarily because the climatic conditions reduce the efficiency of other weathering processes.

Because of certain climatic similarities to Antarctica, Malin [1974] suggested that salt weathering could also be an important process on Mars as well. Given the amount of volcanism [e.g., Mouginis-Mark *et al.*, 1992], arguments for past hydrothermal activity [Squyres and Kasting, 1994], and the evidence for an ancient ocean [Parker *et al.*, 1993], it is not unreasonable to suggest that salts may actually be widespread on Mars. In fact, chemical analyses of the martian soils [Hurowitz *et al.*, 2006] as well as subsurface regolith in Gusev crater [Wang *et al.*, 2006] show high concentrations of S and Cl indicating that a salt component is a ubiquitous feature of all soils and rocks on Mars. Chemical precipitation of salts was probably widespread in the past on Mars as Opportunity documented widespread sulfate evaporites deposited at Meridiani Planum in the Late Noachian [Squyres *et al.*, 2004]. Although liquid water is not stable on Mars today, Malin [1974] argues that the presence of salt would reduce the melting point of water [Ingersoll, 1970]. He points out morphologic similarities between the Labyrinth region of the Wright Valley in Antarctica and fretted terrain on Mars as possible evidence that salt weathering may occur on Mars. It has also been proposed that groundwater exfiltration and evaporation generate salt weathering, which subsequently leads to focused undermining and alcove development in terrestrial sapping channels [Laity,

1983], so potentially the alcoves in theater-headed valley networks on Mars may be another place where salt weathering has occurred [*Laity and Malin, 1985*].

Jagoutz [2006] suggests that several fragmented rocks seen at the Mars Pathfinder and Spirit landing sites may be the result of in situ salt weathering. He acknowledges, however, that transportation and concentration of salt on Mars would require the presence of liquid water, and large deposits of sufficient salts are also absent. He argues for “aeolian salt and ice particulate transport.” In this model, small particles of salt and ice eventually collect in rock cracks where concentrations of salt depress the freezing point of water. Seemingly, such a process would quickly become choked by inert dust particles, so salt weathering may possibly be best explained as a process that occurred during more favorable climatic conditions. Alternatively, shattered rocks may have undergone acidic alteration [*Ming et al., 2006*]. We analyzed rocks affected by salt weathering along the sea coast of Kephui Bay on Molakai in an effort to identify such processes on Mars. The evidence for salt weathering is apparent, because the rocks are covered in a coating of salt ~1 mm thick that has accumulated from evaporation of sea spray from the beach below. These rock populations are denoted by MB1.

3.2.5. Alluvial Fan and Debris Flow Deposits

Alluvial fans represent some of the best evidence for past liquid water on the surface of Mars. Although alluvial deposits were first identified in Viking images [*Cabrol and Grin, 2001*], alluvial fans and deltas were not identified until the advent of high-resolution imagery. To date, dozens of large alluvial fans have been identified [*Moore and Howard, 2005*] and many more continue to be discovered [e.g., *Wilson et al., 2012*].

Typically they are found at the base of alcoves in impact craters where valley networks have breached the crater rim [Wilson *et al.*, 2012]. In addition, Curiosity landed on an alluvial fan in Gale crater [Williams *et al.*, 2013].

We measured large clasts found in an alluvial fan off the Hilina Pali fault scarp in the Ka'u Desert on the Big Island of Hawaii. This fan deposit is only one of several found at the base of the pali. It is located at the base of an alcove where ephemeral streams breach the fault scarp in a fashion similar to valley networks that have breached impact crater walls to form the alluvial fans found on Mars. While the clasts measured in our analyses were >64 mm in size, and thus too big to be compared to the conglomerates found at Gale crater [Williams *et al.*, 2013], they are comparable to some of the boulders imaged on the Eberswalde delta [Howard *et al.*, 2007].

Debris flows have also been suggested as a mechanism for forming a range of fluvial features on Mars, including outflow channels [Nummedal and Prior, 1981] and young gullies in mid-latitude craters on Mars [Johnsson *et al.*, 2014]. Debris flows are a formative process for alluvial fans and represent an end-member flow type characterized as a slurry of mud and rock that is both laminar and viscous, resulting in minimal grain-size sorting [e.g., Nummedal and Prior, 1981]. We analyzed debris flow deposits in Virginia that resulted from large magnitude storm events that occur on a 2,000-4,000 year interval [Eaton *et al.*, 2003]. The deposits we analyzed were associated with the June 1995 storm event in the Rapidan basin near the village of Graves Mill [Eaton, 1999]. We focused on identifying and measuring clasts of metabasalts derived from the Catoctin Formation, which is upper Precambrian in age [Badger and Sinha, 1988]. Individual clasts were removed from the debris flow deposits and measured. The clasts were

subsequently broken to confirm their lithology. The difference between the Hilina Pali alluvial fan and the Graves Mill debris flow is the amount of water entrained in the flow as well as the size and sorting of the particles. The two deposits were analyzed to provide a range of possible rock/clast morphologies. The Hilina Pali clasts are designated as AF1 and the Graves Mill clasts are designated GM1.

3.3. Rocks Resulting from Chemical Weathering

All the Venera and Vega landers are thought to have landed on a weathered basalt flow [Barsukov, 1992, Surkov, 1997]. It has been suggested that rocks at the Viking 1 landing site result from in situ weathering of a basaltic pyroclastic flow [Sharp and Malin, 1984]. Also, Backstay class rocks examined by the Spirit rover at the Columbia Hills may have resulted from chemical weathering of basalt flows [Squyres et al., 2006]. Chemical weathering, or decomposition, involves the chemical reactions of dissolution, oxidation and reduction, and hydrolysis, all of which occur simultaneously in the weathering zone within the ground.

While there are always the odd xenoliths, phenocryst (e.g., leucite), or less common quartz amygdules found in basalt, the three primary minerals are typically olivine, pyroxene, and feldspars. Olivine weathers into iddingsite, which is a pseudomorphic mixture of remnant olivine, iron oxides, ferrihydrites, and clay minerals. Iddingsite continually alters in the presence of water until it has weather primarily into clay minerals. Pyroxenes and feldspars also weather into clay minerals. Gislason et al. [1994] found that the chemical weathering of primary minerals in Icelandic basalts was selective and depended on the local weathering environment [Stefansson and Gislason, 2001].

The rate of chemical weathering is temperature and moisture dependent [Gislason *et al.* 1994; White *et al.*, 1999]. Although basalt typically weathers chemically faster than felsic rocks it is still a slow process. For example, Hawaiian basaltic lava flows that have erupted during post-contact times (i.e., since 1778) have typically developed only thin (<1 mm) weathering rinds [Jackson and Keller, 1970]. Similarly rocks deposited in glacial moraines that are several thousand years older have weathering rinds that are not much thicker (<1 cm) [Locke, 1986]. The process of weathering a lava flow to the point where it is broken into a loose pile of rock could potentially take hundreds of thousands of years. Rates should be orders of magnitudes slower on Mars than Earth given the current climate. Results on weathering rinds developed on Gusev crater basalts as well as older Columbia Hills rocks indicate slow chemical weathering in the current climate [e.g., Hurowitz *et al.*, 2006]. An additional caveat arguing against the importance of in situ weathering on Mars is the fact that there must be an efficient mechanism for transporting fine particles away as they are created. Obviously, runoff would be more efficient at removing fine particles from the tight spaces between rocks during the early stages of disintegration than aeolian processes. Thus, the tacit assumptions that can be made are that in situ weathering on Mars may have been more efficient in the past when the climate was more favorable.

In characterizing the morphometry of rocks created by chemical weathering, we attempted to quantify rocks created from lava flows in various stages of disintegration. An important requirement was that the surfaces be devoid of all vegetation. Jackson and Keller [1970] showed that while the unvegetated chemical weathering rind of a 1907 lava flow was only 0.002 mm thick, rocks from the same flow had rinds 0.142 mm thick

642 where lichen was present. There are several environments in Hawaii where the effects
643 from vegetation are minimal, such as the Ka'u Desert on the western flank of Kilauea.
644 We also restricted our analyses to pahoehoe flows, which are the most common flows in
645 Hawaii [e.g., *Stearns*, 1946]. There are also physical differences between pahoehoe and
646 aa flows that would affect the morphometric characteristics of the rocks resulting from
647 disintegration. Arguably, rocks from pahoehoe flows are the easiest to apply to
648 understanding rock populations on the other terrestrial planets. Aa flows are composed of
649 extremely angular clinkers that form a rubble pile several meters deep at the surface, and
650 if a rock were to come from this part of the flow, it would be obvious and easily
651 recognized. Pahoehoe flows, on the other hand, have a smooth surface that is also
652 distinguishable. However, the nature of both aa and pahoehoe flows change with depth.
653 We assume that rocks derived from the interior of both types of flows would break apart
654 similarly.

655 Because the crust of a pahoehoe flow cools quickly, the upper few centimeters is
656 typically glassy. Volatiles continue to exsolve from the flow as it is moving and cooling,
657 so the upper layer is also highly vesiculated. We noticed that the upper glassy layer was
658 quickly broken down and removed on flows only a few decades old. The removal of this
659 layer was especially pronounced on flow surfaces with slopes of 5° or more. The
660 underlying surface contains fewer vesicles. Of particular importance is the presence of
661 polygonal cooling cracks that are typically a few centimeters apart. These cracks permit
662 water to penetrate the rock and create a weathering front, which *Mignon and Bergstrom*
663 [2001, p. 288] describe as the three-dimensional boundary surface that separates altered
664 (decomposed or disintegrated) rock from fresh rock.

Chemical weathering appears to be the primary process modifying lava flows in Hawaii, and the progressive stages of this process can be observed from one island to the next. Usually within a few decades, lava flows near Kilauea on the Big Island show signs of weathering on the upper glassy layer. Flows that are subsequently buried are weathered by chemical processes resulting from shallow groundwater flow. This process, known as spheroidal weathering, eventually rounds the edges off blocks comprising individual flow units, resulting in core stones that are frequently concentrated in gullies when processes such as overgrazing, which we observed in western Molokai, allow the supporting matrix to be removed. Rocks measured in Molokai at the former Molokai Ranch in such a setting are designated MR1 and MRR1.

3.4. Sampling Methods

We made efforts to identify rock populations that were representative of each general environment and large enough to be statistically meaningful. Thus, the size of our sampling sites ranged anywhere from 0.37 m² (4 ft²) to 9.29 m² (100 ft²). Because most of the environments we investigated were located within Hawai'i Volcanoes National Park, we also remained cognizant of the fact that some rock populations could have been disturbed by anthropogenic processes, so our sampling sites were often in remote locations or far away from any roads or trails. The boundaries of each site were measured and marked with flags. Each rock ~4 cm (~1.5 inches) in diameter or larger was picked up and the three principal axes were measured using a tape measure. The measurements were recorded to the nearest 0.5 cm (0.2 inch) resulting in a margin of error of ~0.2-0.3 cm (~0.1 inch). Each investigator used *Krumbein's* [1941] angularity

chart to assess the angularity of each particle. To reduce bias, a minimum of three people made measurements at each site, which typically included a rotation of two people making measurements while a third person recorded the results. To prevent resampling, each rock was marked with chalk after the corresponding measurements were recorded. Any surface texture that may have resulted from the emplacement process (e.g., percussion marks) or subsequent erosion (e.g., ventifacts) were also noted and often photographed.

Because the morphometric analyses were often made of representative rock populations within these environments, it was apparent that we did not always sample the largest rock within a given population. However, we did sample the largest rock in each of the plots. To increase the sampling size for the larger rocks, we measured a larger area around the primary sampling site. Then, using a folding rule, we recorded the number of rocks larger than a given size. The rule was folded out to a specified length, and an investigator would determine if the long axis of a particular rock was longer than this specified length. The number of rocks longer than this specified length was recorded, the length was shortened by 6 inches (or the standard length of one fold in the rule), and the rock population was measured again. This resulted in a count of each rock within a particular 6 inch-sized bin or larger, or the cumulative number of rocks at a particular size.

4. Results

4.1. Particle Shape

To understand the influence of basalt texture on the shape of rocks, we plotted each individual rock on a Zingg diagram (I/L vs S/T) (Figure 2). From these plots we calculated the average proportions of discs, spheres, blades and rods for each of the environments (Table 4). *Drake* [1970] found that bedrock with aphanitic textures such as basalt often produced a greater proportion of blades. However, as Figure 2 and Table 4 show, most basalt rocks are either discs or spheres regardless of the environment we sampled. This suggests that basaltic rock shape in pahoehoe is influenced primarily by fractures that form in the lava flows as they cool. The rocks sampled in the Southwest Rift Zone, for example were the obvious result of cooling fractures as they were so close to one another that the part of the flow from where they had detached from was obvious. Typically, these rocks often had a tetragonal shape. In contrast, the columnar jointing observed in basalt flows of the Snake River Plain in Idaho are often hexagonal in plan view [*Ehlmann et al.*, 2008; *Kattenhorn and Schafer*, 2008]. The difference in jointing between the Hawaiian and the Snake River flows is likely a function of the thickness as *Aydin and Degraff* [1988] showed joints evolve systematically inward from tetragonal to hexagonal networks as lava cools. The Hawaiian flows that we examined were simply not thick enough to develop columnar jointing or hexagonal fracturing. However, the difference in cooling joint fractures does not appear to influence the overall Zingg shape class of the rocks (Figure 2).

We randomly sampled between 1-5 rocks from each of the environments and tested for a goodness-to-fit to a normal distribution using the χ^2 TEST, WHICH WAS NECESSARY TO DETERMINE BEFORE PROCEEDING TO OTHER STATISTICAL ANALYSES. FEWER THAN 5% OF THE SAMPLES WERE FOUND TO DIFFER

SIGNIFICANTLY FROM NORMALITY. WE THEREFORE WERE ABLE TO
STATISTICALLY COMPARE EACH OF THE morphometric indices determined for the
different environments to the morphology of rocks from the Southwest Rift Zone. Both
differences in the means (Student's t -test) and variances (F -test) were analyzed using
standard statistical methods described in *Davis* [1986].

Student's t -test is often used to determine if a given sample could be a member of a
population with specified characteristics. We applied this test to determine if the mean of
the different morphometric indices for rocks from the Southwest Rift Zone and the rocks
from the sampled environments were significantly different from one another. Basically,
our null hypothesis was that morphometric indices from the sampled environments were
different from the morphometric indices of rocks from the Southwest Rift Zone. To pass
the null hypothesis, there are critical values of t that must be met that are a function of
the number of degrees of freedom (i.e., the number of rocks sampled in each population)
as well as the significance level. We analyzed significance levels of 10%, 5%, 2.5%, 1%,
0.5%, and 0.1%. (A significance level of 5% is the typical standard.) Table 5 shows that
angularity is by far the most reliable index for distinguishing between the means of a
modified and unmodified basaltic rock population. For example, the angularity of rocks
at Ephrata Fan, Site 3 (EF3) have a t -value of 5.26 with a significance level of 0.1%.
This means that there is a 99.9% probability that the angularity of the rocks we measured
at the EF3 site were different from the rocks measured at the Southwest Rift Zone
(SWRZ). In several instances, values for rock populations in certain environments also
passed t -tests for D , OPI and CSF . In general, however, the results from the Student's t -
test show that many of the morphometric indices are not significantly different.
Essentially, even after what appears to be extensive weathering and transport, many

basaltic rock populations are morphometrically similar to rock populations that have not been moved or modified at all.

Of the environments we sampled, the morphometric indices related to catastrophic flood deposits, particularly EF1 and EF2, passed more of the t -tests. This probably reflects the fact that the EF1 and EF2 rock populations are more disc shaped than the baseline SWRZ rocks (Figure 2). Although *Ehlmann et al.* [2008] suggest that they may not have always accurately measured the short axes of rocks on the Ephrata fan because of partial burial, we did make an effort to compensate for this by tilting or digging around the rocks to more precisely measure their short axes, so we believe that the percentage of disc shaped rocks (Table 4) accurately reflects the EF1 and EF2 populations. It is not clear why there is a lower percentage of discs in the EF3 population (Figure 1C), which was measured ~200 m away from EF1 and EF2. Potentially flow around “monster rock” helped to stall subsequent flow and deposit disc shaped rocks locally while more spherical rocks were transported farther out into the Ephrata fan.

F -tests can evaluate the statistical differences between sample populations. F -tests determine the equality of variances between different sample populations, and evaluate the probability of obtaining the same variance between two normal populations. These tests were also performed at different levels of significance (2% and 10%). ,

To be truly useful and diagnostic, the morphometric indices should pass both the t -test and the F -test. However, the F -test results (Table 6) were often different from the t -test results. For example, while the angularity values at the Ephrata Fan, Site 1 (EF1) passed the t -test, it did not pass the F -test. This implies that although the mean angularity values are statistically different (Table 3 and 4), the variances in these populations were not

(Table 6). The OPI index for the Phreatic Eruption, Site 2 (PE2) failed the t -test, but passed the F -test, including at a significance level of 2%. This means that the mean OPI value of the PE2 population is not statistically different from the SWRZ population, but the difference in the variance between these two populations is. In general, however, the F -tests indicate that differences in angularity are more likely to be statistically significant. Combined with the t -test results, the F -tests also indicate that OPI and D can be useful for separating basaltic rocks emplaced by catastrophic outflow.

Application of Student's t -test is predicated on the assumption that two populations have normal distributions with equal variances. However, results from the F -tests suggest that the variances are often not equal, and in these instances the results from the Student's t -tests may also not be valid. An additional test that can be applied is Welch's t -test, otherwise known as the "unequal variance t -test." Although Welch's t -test is not applied to population analyses as frequently as Student's t -test, some scientific researchers have advocated its primary use because it performs better than Student's t -test whenever sample sizes and variances are unequal between groups [e.g., *Ruxton*, 2006]. In applying Welch's t -test, the null hypothesis we used was that differences between means of the Southwest Rift Zone rocks and the other rock populations was 0. Because we were applying Welch's t -test to verify the results from Student's t -test and the F -test, we only evaluated for the standard significance level (α) of 5% (0.05). In cases where the p -levels were equal to or greater than the significance level, the null hypothesis was accepted (Table 7). In other words, where the p -level was ≥ 0.05 the differences in the means between the two rock populations was 0; basically, the populations were statistically similar. Where the p -level was < 0.05 , the differences between the means was

not 0, and the populations were statistically different from one another. Because Table 3 shows that the mean values for the morphometric indices could be less than or greater than the corresponding means for the Southwest Rift Zone rock populations, we evaluated “two-tailed p-values,” which analyzed for variations on either side of the normal distribution. Basically, we considered the possibility that the distribution of morphometric indices could be shifted right or left when compared to the Southwest Rift Zone rock populations. The degrees of freedom (ν) were calculated using the Welch–Satterthwaite equation, which is a different approach than Student’s t -test in that the denominator is the difference between the two sample means and is not based on the pooled variances. The degrees of freedom are also reported in Table 7.

In general, the results from Welch’s t -test (Table 7) support the results from Student’s t -test. However, these results indicate that potentially more morphometric indices may be useful depending on the rock population. For example, Welch’s t -test indicate that rocks emplaced by phreatic eruptions (PE1 and PE2), catastrophic flooding (EF1, EF2, and EC1), and on the alluvial fan (AF1) can be shown to be morphometrically different using a number of indices. What is interesting is that rock populations resulting from frost shattering (MS1 and MS2), salt weathering (MB1), and chemical weathering (MR1 and MRR1) show no morphometric differences with the exception of angularity. This may be due to the possibility that such weathering processes affect the fine-scale surface texture of the rocks faster. Essentially, the surface features that ascribe a rock’s angularity are broken down quickly, but the three axes of symmetry are all eroded at the same general rate, so the rock retains its general form. Again, Welch’s t -test indicates

that angularity is the most diagnostic morphometric indices for separating rock populations.

Using the mean values for the morphometric indices for each of the sampled environments (Table 3), we constructed a series of scatter plots to help identify any consistency between processes and environments (Figure 3). Relationships between S/L (D) vs F ($L-I/L-S$), D vs ψ (MPS), and OPI vs ψ , for example, have shown to be useful for distinguishing between clasts deposited in different fluvial environments [Dobkins and Folk, 1970; Howard, 1992]. We also plotted angularity against OPI and S/L because our data indicates that differences in these values are often statistically significant. Essentially, these scatter plots represent a way of visualizing some of the information presented in the tables.

It is interesting to see how mean values for the catastrophic flood and explosive deposits plot towards the high and low values of D , ψ , and OPI (Figure 3a, b, c and d). The mean values for the remaining environments plot within the ranges defined by the catastrophic flood and explosive deposits. Although it is possible that additional sample sites within these environments could help better identify some trends, in general, the scatter plots show how similar the morphometric indices for sphericity are among the rock populations we sampled. However, some clear groupings can be observed by plotting D and OPI against angularity (Figure 3e, f). Separation in sphericity between the populations appears to be a function of how many rocks were discs versus spheres within the populations. However, angularity appears to be the most diagnostic. Figures 3e and f show that frost shattering makes rocks more angular and disc-shaped, explosive eruptions make rocks slightly more rounded and more disc-shaped, and processes such as chemical

and salt weathering as well as alluvial fans and debris flows make rocks that are rounded. Not surprisingly, Figures 3e and f show that catastrophic flooding produces the most well-rounded rocks, and some populations become more disc-shaped, which could be a function of local transport as we discussed earlier.

4.2. Size-Frequency Distributions

Plots of the cumulative fractional area versus diameter (Figure 4) of the basalt rocks in this study show the same general exponential shape as shown for a wide variety of rocky surfaces on the Earth as well as all of the landing sites on Mars [Malin, 1989; Golombek and Rapp, 1997; Golombek *et al.*, 2003, 2008, 2012]. Note that although power laws have been used to describe the size-frequency distribution of rocks and smaller particles over a limited range of diameters (straight line on a log-log plot) [e.g., Shoemaker and Morris, 1969; Hartmann, 1969; Moore *et al.*, 1987; Moore and Jakosky, 1989; Moore and Keller, 1990; Turcotte, 1997], fracture and fragmentation theory clearly shows that over a larger range of particle diameters that the size-frequency distribution instead follows an exponential shape (e.g., Weibull distribution) for both fragmentation and subsequent fracture during transport with far fewer rocks at large diameter than predicted by a power law [Rossin and Rammler, 1933; Gilvarry, 1961; Gilvarry and Bergstrom, 1961; Wohletz *et al.*, 1989; Brown and Wohletz, 1989; Charalambous, 2015]. In contrast, log-normal rock size-frequency distributions, which also have a convex up shape on log-log plots, but have shallower slopes at small diameter and steeper slopes at large diameter than exponential models, have also been proposed for Mars [Hebrard *et al.*, 2012]. However, these log-normal models [Hebrard *et al.*, 2012] severely under predict the area

covered by (i.e., the total number of) rocks with a diameter greater than 1.5 m, when compared to measurements made from 25 cm/pixel HiRISE (High Resolution Science Experiment) images and verified by the landers [Golombek *et al.*, 2008, 2012].

The data in Figure 4 generally resemble the convex up exponential model curves for Mars developed from the Viking 1 and 2 landing sites by Golombek and Rapp [1997] and show a similar range of total area covered by rocks from a few percent to around 50% for rock diameters >6 cm as characterized for rocky locations on Earth [Malin, 1989; Golombek and Rapp, 1997]. Sites with the greatest area covered by rocks are proximal to a catastrophic outflow channel (Ephrata Fan, EF1), near the rim of Halema'uma'u crater emplaced by phreatomagmatic explosions (PE3), and frost shattered rocks on Haleakala (MS1).

Similarly, plots of the cumulative number versus diameter (Figure 5) of the basalt rocks show the same general trends as those presented for a variety of rocky locations on Earth in Malin [1989] and Golombek and Rapp [1997], with 0.1 to 2 rocks per m^2 at diameters >6 cm. Also plotted for reference are the model rock curves for Mars, which capture the rock distributions measured at the Mars landing sites [e.g., Golombek *et al.*, 2003, 2012]. Note that these curves are not true exponentials because of the inability to analytically integrate an exponential, defined by cumulative fractional area, to get the cumulative number [Golombek and Rapp, 1997]; instead the curves were derived by numerical integration [Golombek *et al.*, 2003]. As a result, the cumulative number of rocks per m^2 versus diameter on a log-log plot have a fairly constant slope at small diameters (i.e., more like a power law), before becoming steeper at large diameters. Most of the cumulative number per m^2 curves generally resemble the model curves, with the

possible exception of the Ephrata Fan sites that have flatter slopes at smaller diameters, which is caused by the preponderance of fines (sand and silt) that bury the smaller rocks at these sites (also observed by *Golombek and Rapp*, 1997). The same flattening of slope at small diameter is evident in the cumulative fractional area plot for other sites (Figure 4b), but sites with fewer fines have steeper slopes similar to the exponential curves (and not consistent with log-normal distributions [*Hebrard et al.*, 2012]).

The observation that most of the basalt rock size-frequency distributions are generally similar to Mars model rock curves, which are defined by exponential distributions that result from fracture and fragmentation theory indicates that these terrestrial distributions are also being dominantly controlled by the initial fracture and fragmentation of the basalt. Further, Earth rock size-frequency distributions produced by alluvial fan evulsions, in situ basalt weathering, and coarse rockfall talus [*Malin*, 1989; *Golombek and Rapp*, 1997] are also similar, which also supports the conclusion that the overall shape of the distributions is dominantly controlled by fracture and fragmentation. However, the observation that the observed size-frequency distributions steepen at different large rock diameters and the total area covered or the cumulative number differs suggests that additional work might be able to determine the “fingerprints” of the specific process that produces and/or modifies the size-frequency distributions [e.g., *Malin*, 1989].

5. Implications for Future Lander Science and Safety

5.1. Application to Lander Images

Quantifying the sphericity and angularity of rock populations imaged on other planetary surfaces is not straightforward. A lander will image most rocks sitting in an oblique position to the spacecraft or camera and at varying resolutions. This makes it difficult to directly apply terrestrial field data to understanding Mars rock populations. As an example, *Golombek and Rapp* [1997] estimated the diameter of rocks in the far field of VL1 by measuring their apparent width and multiplying by 0.75. Fortunately, however, form can also be estimated from independent measurements of only two of the three principal axes.

5.1.1. Estimating Sphericity

Recalling Equation 4, one of the simplest formulas for measuring a particle's sphericity from measurements of only two axes is the Corey Shape Factor (CSF), which expresses the ratio of the cross-sectional area of a sphere to the maximum cross-sectional area of an ellipsoid [*Corey*, 1949]. The *CSF* for the optical microscope particles is estimated by assuming that the intermediate and short axes are approximately equal to each other (Equation 5) [e.g., *Dietrich*, 1982]. Equation 5 is essentially a modified version of the “projection sphericity” developed by *Riley* [1941], which is defined as

$$F = \sqrt{\frac{i}{D_c}} \quad (6)$$

where i is the diameter of the inscribed circle that is the largest circle that fits fully inside the boundaries of the particle, which when seen in plan view is equivalent to I , and D_c is the diameter of the circumscribing circle that is the smallest circle that fully envelops all of the particle, which is equivalent to L in plan view. The sphericity values calculated from Equations 5 and 6 would be identical. This is important, because Equation 6 has been applied to estimating the sphericity of Mars rocks [Yingst *et al.*, 2007; 2008; 2013], and those sphericity values should be similar to our CSF_{2Axes} values.

While both Equations 5 and 6 are applicable to small particles seen in plan view, it is not directly applicable to larger rocks seen from the side, which is the perspective of most lander or rover images. Instead, rocks sit with their short axis pointing up. The short axis is the height of the rock, which can easily be measured. However, the long and intermediate axes are turned away from the lander by some unknown amount. Also, because we found that most basaltic rocks tend to be either discs or spheres, meaning that their I and L axes are often similar, we found that measurements made by Equations 5 and 6 were not diagnostic of the geologic environment (Tables 3, 5 and 6). Measuring the short axis (S) and relating that to sphericity is crucial. We used our rock morphometric measurements of all three axial dimensions and calculated CSF_{Mars} as

$$CSF_{Mars} = \frac{S}{(L - I) * 0.5} \quad (7)$$

Plotting the calculated CSF_{Mars} to the corresponding CSF, we determined that CSF_{Mars} can be expressed as

958

959
$$CSF_{Mars} = 0.989 \frac{S}{Y}^{1.006} \quad (8)$$

960

961 where Y is the average value of I and L. When seen by a lander, the shortest axis that
962 could be measured would be I, and the longest axis that could be measured would be L.
963 When applying Equation to lander images, Y is assumed to be equivalent to the length of
964 horizontal axis that can be measured (i.e., the axis parallel to the ground), which is a
965 value somewhere between I and L. The correlation coefficient of Equation 8 is 0.999. It
966 is important to note that the CSF and CSF_{2axes} values we measured for many of our
967 environments were not statistically significant, and thus measurements of CSF or
968 CSF_{2axes} in and of themselves may not be particularly diagnostic. However, Equation 8
969 could be useful in making a general assessment of the sphericity of particles at a landing
970 site and identifying areas that appear to be more physically diverse or different from
971 others. From a monoscopic spacecraft image, a form of Equation 8 would be a quick
972 method for estimating basaltic particle sphericity.

973

974

975 **6. Implications for Previous Studies**

976 *6.1. Viking*

977 Although *Garvin et al.* [1981] made the most comprehensive study of rock shapes
978 at the Viking landing sites that was possible at the time, they were limited by several
979 factors. (1) Terrestrial data on rock shape were not available from a wide range of

geologic processes that may be applicable to Mars. They mention the need for additional fieldwork and measurements of rocks from impact cratering and pebbles from desert environments as being particularly useful. (2) It was not clear how angularity was assessed, and our analyses suggest that this parameter is the most useful in separating geologic processes. (3) They included particle sizes (<64 mm) that are probably too small to be diagnostic of the primary emplacement process. Finally, (4) *Garvin et al's* [1981] sphericity values were not comparable to the sphericity values given by *Dobkins and Folk* [1970]. Although they correctly state that sphericity can be estimated by measuring two dimensions, they did not adjust for the differences between estimating sphericity from two axial measurements to those made by *Dobkins and Folk* [1970] using three axes (and a different formula), which resulted in incorrect sphericity values (Table 1). Regardless, our analyses show that many morphometric indices to quantify sphericity are not statistically reliable when applied to basaltic rock populations. While their principal interpretation that rocks at the Viking 1 landing site were emplaced predominately by impact cratering is certainly plausible, it is difficult to determine from the data that are presented.

6.2. Mars Pathfinder

Basilevsky et al., [1999a] quantified the general shape (L and Y) and angularity of several larger rocks at the MPF landing site while comparing their general surface texture (e.g., pits and flutes) to look for potential relationships and found none. *Golombek et al.* [2003] evaluated the shape (round, square or triangular) and burial (perched, partially buried, and deeply buried) of rocks of different height at the Mars Pathfinder, Viking 1

and 2 landing sites for comparison to rocks used in Mars Exploration Rover full-scale airbag drop tests in vacuum chamber.

The analysis conducted by *Yingst et al.*, [2007] was more comprehensive and included measurements of 575 rocks 16 to 256 mm in diameter. Individual particles were digitized as two-dimensional polygons, and sphericity was calculated using *Riley's* [1941] projection sphericity method (Equation 6). Elongation was measured using a two-dimensional method proposed by *Dapples and Rominger* [1945], and angularity (roundness) was calculated using the method proposed by *Dobkins and Folk* [1970] (Table 2). Angularity was also calculated qualitatively using a method identical to ours. Values calculated for the Mars rocks were compared to a table of values they compiled from published terrestrial data for a variety of environments, including basaltic rock data from *Dobkins and Folk* [1970].

Of the measurements presented by *Yingst et al.*, [2007], sphericity can be compared directly to our calculations for CSF_{2Axes} . They found that sphericity was unimodal with an average value of 0.75, which is lower than the average values we measured for terrestrial basaltic rocks that ranged from 0.83 to 0.89 (Table 3). The difference may be related to how they applied the technique for estimating sphericity from two dimensions. *Yingst et al.*, [2007] provide an example where the short axis of Pancake rock can be seen, and they suggest that using this axis presents “a more accurate measurement of sphericity for this rock profile.” However, including the short axis in the measurement would artificially reduce the sphericity value of the rock.

Similar to our study, *Yingst et al.*, [2007] observed that the greatest variations in

rock morphometry were in measurements of angularity (i.e., roundness). Most of their rocks were sub-angular (values of 2-3 in our scale). A second population of rocks were observed to be subrounded (values of 3-4 on our scale). Our analyses of terrestrial rock populations support their conclusion that there are two rock populations at the Mars Pathfinder landing site. The rock population they suggest were emplaced by catastrophic flooding have angularity values similar to ours (EF1, EF2, EF3, and EC1, Table 3). However, if terrestrial rocks emplaced by explosive eruptions are a valid proxy (PE1, PE2, and PE3, Table 3) to impact cratering, then the second rock population at the Mars Pathfinder landing site may be too rounded. Potentially, this second rock population at the Mars Pathfinder landing site has also been modified by chemical weathering.

6.3. Mars Exploration Rovers

Yingst et al. [2010] analyzed 333 particles located at “Home Plate” area in Gusev crater that were imaged by the Spirit Mars Exploration Rover. They used quantitative techniques for sphericity and angularity (roundness) and qualitative techniques for angularity identical to those applied to the Mars Pathfinder landing site [*Yingst et al.*, 2007], so their results are comparable to those presented here. They found that sphericity was unimodal with an average of 0.73. Qualitative angularity was also unimodal with most of the rocks being subangular (our angularity values of 2-3). They suggest that these rocks were emplaced either by volcanism or impact cratering and that they had undergone some weathering process following emplacement. Again, their sphericity values were less than the average values we measured for basaltic rocks, which ranged

from 0.83 to 0.89 (Table 3), but it is unclear if the difference is a result of how they applied the *Riley* [1941] technique to rocks viewed at different angles. The rocks that they observed were generally more rounded than would be expected from either volcanism or impact cratering, and our angularity measurements (Table 3) agree with their interpretation that the rocks have experienced some degree of weathering regardless of the primary emplacement mechanism.

6.4. Curiosity

Rocks and clasts >64 mm in diameter are relatively rare at the Curiosity landing site in Gale crater [*Yingst et al.*, 2013]. However, the larger rocks and clasts that have been observed from Bradbury to Rocknest have an average sphericity of 0.76 and are angular to subangular (our angularity values of 1-3) [*Yingst et al.*, 2013]. *Yingst et al.*, [2013] explain that on Earth sphericity values of 0.70–0.77 are commonly associated with environments dominated by intermittent, high-energy transport citing *Howard* [1992]. This may be a fair analogy as the lithology of some of the particles examined by *Howard* [1992] were metavolcanic; however, he did not measure sphericity using *Riley* [1941] (Equation 6), which is the technique employed by *Yingst et al.* [2013]. Using *Howard*'s [1992] values for I/L metavolcanic clasts (his Table 1), an equivalent sphericity value would be ~0.88. Nevertheless, the interpretation by *Yingst et al.* [2013] that impact cratering emplaced the larger clasts in Gale crater is consistent with our angularity measurements of rocks emplaced by explosive processes.

6. Future Work: Quantifying Angularity

Wadell [1932] argued that angularity could be estimated from a two-dimensional projection without causing any serious bias. Implicitly, other investigators have agreed primarily because of the difficulty in measuring angularity in three dimensions [*Barrett*, 1980]. Because angularity is independent of sphericity or particle form, it can be estimated independently of the viewing angle. That is to say, the same estimate of angularity will be made regardless of the particle orientation with respect to the spacecraft. However, although the angularity measurements presented here were made with at least three different investigators, an unknown degree of subjectiveness remains. This should be considered when applying our angularity results.

A promising alternative involves a Fourier grain shape analysis of the rock angularity. Fourier analysis of particle shapes was introduced to sedimentology by *Szwarcz and Shane* [1969]. Since then, several attempts have been made to derive the angularity values of particles using the Fourier series [*Ehrlich and Weinberg*, 1970; *Czarnecka and Gillott*, 1980]. These authors, however, avoided using the term 'roundness' or 'angularity' and used the term 'roughness,' primarily because single, higher order harmonics were incapable of providing reliable equivalents for angularity. More recently, programs capable of describing a rock's angularity in terms of both higher and lower harmonic amplitudes have become available [*Full and Ehrlich*, 1982; *Diepenbroek et al.*, 1992; *Torley*, 1996]. This "closed-form" technique uses the radial distance from the particle's outlined centroid to equi-angularity spaced sample points on the perimeter to describe the particle's outlined shape. The resulting Fourier transformed data are re-expressed as a shape spectrum representing the contribution of ideal shapes (e.g., a

figure-eight, trefoil, quatrefoil, etc.), which when added back together, reproduce the original particle outline. This technique makes the notion of particle shape decomposition easily understandable, intuitively perceptible, and lends itself to subsequent multi-variant statistical analysis.

Diepenbroek et al. [1992] recognized three criteria for evaluating angularity through Fourier analysis. (1) All curvatures must be considered, including convex and concave plane elements. (2) Because the protuberances and invaginations of a particle erode differently, the curvatures have to be weighted by their relative positions on the particle. (3) Positions and curvatures of morphometric elements have to be compared to the particle's ultimate shape: an ellipsoid, which reflects the aspect of form or sphericity. Angularity is measured by taking a digital image and processing it so that an outline of the particle is generated. The outline of the particle's maximum projection plane is then transformed to a Fourier series (Figure 6), and angularity data are derived from the complete amplitude spectrum. Sphericity is calculated by fitting an ellipsoid to the spectrum of the empirical shape, which is then subtracted. The residual amplitudes are normalized and summed. The final step is to rescale the resulting values to digitized shapes from *Krumbein's* [1941] visual comparison chart. The major weakness in this closed-form technique is that protuberances and invaginations, which cause the perimeter to cross over a radius more than once, compromise the integrity of the computer algorithm. As a result, the algorithm rejects such irregularly shaped outlines. This technique also requires an outline of the entire rock for accurate determination of the sphericity and angularity. However, an alternate technique, the "perimeter-walk," does not require an entire outline.

1115 The perimeter walk technique describes the changes in angular bend of equi-distant
1116 sampling points around the grain perimeter. Angular details on the perimeter are
1117 transformed based on their position on the perimeter and the degree of change in angle of
1118 curvature from sample point to sample point. This technique is not dependent on the
1119 radius connecting the centroid to a sample point on the perimeter, thus making it a more
1120 versatile technique. The resulting transformed data are very similar to that of the closed
1121 form technique with the positive exception that protuberances and invaginations pose no
1122 problem. *Torley* [pers. comm., 1996] has recently developed, tested, and calibrated this
1123 technique using the comparison chart of *Krumbein* [1941]. The Q-mode factor analysis to
1124 look for patterns of similarities in the resulting harmonic number and amplitude values is
1125 a separate process.

1126 The value of this procedure is that it is automated, thus eliminating the
1127 subjectiveness of angularity measurements, and it is quick. Because the measurements
1128 are based on the outline of the rocks, phase angle and viewing geometry (i.e., particle
1129 orientation with respect to the spacecraft) are not important [e.g., *Tillman*, 1973],
1130 although a viewing azimuth parallel to the solar illumination is helpful. In addition, the
1131 perimeter-walk technique makes it unnecessary to have an outline of the entire rock for
1132 analysis so partially buried rocks (i.e., less than ~50% burial) can still provide useful data.
1133 However, the actual amount of rock outline needed to obtain reliable information also
1134 needs to be tested.

1135

1136 **7. Conclusions**

1137 Basaltic rocks from a wide variety of geologic settings and dominant geologic
1138 processes applicable to Mars and >64 mm in diameter show only a small range of
1139 sphericity values regardless of the morphometric index or technique employed. Based on
1140 the Zingg [1935] classification system, most basaltic rocks can be classified as either
1141 discs or spheres regardless of their emplacement process or geologic environment.
1142 Basaltic rock sphericity appears to be controlled primarily by cooling fractures in the
1143 rock. The exponential shape of the size-frequency distributions of these sites are similar
1144 to those predicted by fracture and fragmentation theory, which further argues that these
1145 distributions are being dominantly controlled by the initial fracture and fragmentation of
1146 the basalt. Angularity (roundness) is potentially the most useful morphometric index for
1147 diagnosing emplacement mechanism and weathering environment. Similar to sphericity,
1148 however, there are many ways of quantifying angularity, but few of them can be applied
1149 to landed digital surface images easily. Evaluating angularity qualitatively remains easy,
1150 but there may be ways to reliably quantify this parameter, and these should be explored.
1151 To date, the interpretation of quantitative assessments of rock populations at the Mars
1152 Pathfinder [Yingst *et al.*, 2007], Spirit MER Rover [Yingst *et al.*, 2008; 2010] and
1153 Curiosity [Yingst *et al.*, 2013] landing sites are consistent with our observations of
1154 terrestrial basaltic rock populations. The data presented here could prove to be useful for
1155 determining the geologic histories of Mars landing sites. Theses data could also allow us
1156 to assess the potential geologic processes that have operated within rover-scale areas,

1157 which will help in planning efficient rover traverses and selecting the widest possible
1158 range of sampling locations for future experiments.

1159
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Figure 1. Examples of some of the rock populations that were sampled. A) Rocks that had broken off several flows near the rim of Halema`uma`u in the Southwest Rift Zone (SWRZ) were used as the basis for our unmodified rock populations. B) Rocks emplaced by phreatic explosions (PE1) located near the eastern rim of Halema`uma`u crater. C) Rocks emplaced by catastrophic flooding located on the Ephrata Fan in Washington State (EF1). D) Core stones that were subjected to chemical weathering (MR1, MRR1) exposed in a gulley on Molokai. E) Alluvial fan located on Hilina Pali (AF1). F) Rocks broken apart by salt weathering on the eastern shore of Molokai (MB1).

Figure 2. Zingg plots that show I/L versus S/I that distinguishes disc-, sphere-, blade- and rods-shaped rocks of basaltic rocks emplaced or affected by a variety of geologic processes. Unmodified rocks from the Southwest Rift Zone are shown in grey in all the diagrams for comparison. Because most rocks, regardless of their weathering process are disc- and sphere-shaped, as are the unweathered rocks, this shape is likely inherited from cooling joints.

Figure 2 cont.

Figure 3. Scatter plots comparing average shape values of the different rock populations we analyzed. A) D (S/L) versus F ($L-I/L-S$). B) OPI versus MPS (ψ). C) D (S/L) versus MPS (ψ). D) D (S/L) versus OPI . E) OPI versus angularity. F) D (S/L) versus angularity.

Figure 4. Plot of the cumulative fractional area covered by rocks larger than a given size versus diameter for basalt rock populations in this paper. Also included are exponential model rock size-frequency curves for Mars for 10%, 20%, 30% and 40% total area covered by rocks [Golombek and Rapp, 1997]. Note that most of the distributions have a convex up shape similar to exponentials, indicating that the dominant control on the distributions is due to initial fracture and fragmentation.

Figure 5. Plot of the cumulative number per m^2 of rocks larger than a given size versus diameter for basalt rock populations in this paper. Also included are numerically integrated model rock size-frequency curves for Mars derived from the cumulative fractional area exponentials for 10%, 20%, 30% and 40% total area covered by rocks shown in Figure 4 [Golombek et al., 2003]. These curves are not actually exponentials, because they have a more linear slope at smaller rock diameters. Note that the small sample area of some of the sites is probably contributing to the un-smooth nature of some of the distributions and/or the lack of larger rocks.

Figure 6. Rock shape and resulting shape spectrum. This is a greenstone deposited during a debris flow in Madison Co., Virginia. Note that the harmonic numbers 2 and 5 are high. These numbers correspond to shapes represented by an ellipse (harmonic 2) and a pentagon (harmonic 5), which can be seen in an intuitive way from the digitized shape. Chi-squared results of this sample indicate that it has an Krumbein angularity of 0.15.

Table 1. Methods for evaluating sphericity. (Modified after *Barrett*, 1980).

Reference	Method	Characteristics	Problems
<i>Indices of Flatness</i>			
Wentworth [1922] [i.e., Cailleux, 1945]	$L+I/2S$	Flatness index $(1-\infty)$.	Kurtosis values of results are generally positively skewed.
Zingg [1935]	$I/L, S/I$	Ordinate and abscissa for a plot to characterize shape (0-1).	Cannot be compared directly to angularity.
Sneed & Folk [1958]	S/L $L-I/L-S$	Flatness (0-1). Flatness I_r to the long axis (0-1).	Cannot be compared directly to angularity.
Luttig [in Sames, 1966]	$I \cdot 100/L$	Elongation (0-100). Two-dimensional expression of flatness.	
<i>Indices of Sphericity</i>			
Wadell [1932]	$(V_p/V_s)^{1/3}$	Volume of a particle to volume of a sphere.	Requires precise measurements.
Krumbein [1941]	$((I \cdot S)/L^2)^{1/3}$	Intercept sphericity.	
Aschenbrenner [1956]		Working Sphericity.	Complicated.
Sneed & Folk [1958]	$(S^2/L \cdot I)^{1/3}$	Maximum projection sphericity. Results show an arithmetic normal distribution.	
<i>Other Shape Factors</i>			
Riley [1941]	$(i/D_i)^{0.5}$	Projection sphericity.	Easy to use.
Corey [1949]	$S/(I \cdot L)^{0.5}$	Corey shape factor CSF (0-1). Geometric basis and represents hydraulic properties of particle extremely well [Dietrich, 1982].	Has been applied to particles in seen in plan view (i.e., two dimensions).
Aschenbrenner [1956]	$L \cdot S/I^2$	Shape factor F (0- ∞). Geometric basis.	Does not relate well to hydraulic properties.
Williams [1965]	$I-(L \cdot S/I^2)$ if $I^2 > L \cdot S$ $I^2/L \cdot S$ if $L^2 < L \cdot S$	Williams shape factor (0 $\pm$ 1).	Not directly applicable to 2-dimensional data.
Dobkins & Folk [1970]		Oblate-prolate index (OPI).	Extremely complicated
Garvin et al. [1981]	W/L	Two-dimensional sphericity.	Unclear how W relates to I or S or field data.

Abbreviations: L = long axis, I = intermediate axis, S = short axis, W = minor or width axis, V_p = volume of particle, V_s = volume of circumscribing sphere, $P = I/L$, and $Q = S/I$, i = inscribed circle, D_i = circumscribing circle.

Table 2. Methods for evaluating angularity/roundness. (Modified after *Diepenbroek et al.*, 1992).

Reference	Method	Characteristics	Problems
<i>Geometric Methods</i>			
Wentworth [1919] [i.e., Cailleux, 1947]	d_s/L_s	Regards position of measured corner on the particle to the 'definite ultimate shape (sphere).	Considers only one corner, influenced by sphericity, and very labor intensive.
Wentworth [1922]	$d_s/[(L+I)/2]$	Reduction to maximum projection plane measurement.	Considers only one corner, influenced by sphericity, and very labor intensive.
Wadell [1932]	$[(\sum d_i)/n]/D_i$	Curvature of all corners averaged, influence of sphericity reduced.	Considers only convex parts, no definite ultimate shape, labor intensive.
Szadeczky-Kardoss [1933]	Relation: %Cp, %Cv, %Cc	Curvatures of the complete outline are evaluated.	Semi-quantitative, no single roundness value, very laborious.
Kuenen [1956]	d_s/I	[Wentworth], influence of sphericity reduced.	Considers only one corner, laborious.
Dobkins and Folk [1970]	d_s/D_i	[Wentworth] & [Wadell], influence of sphericity is reduced.	Considers only one corner, laborious.
Swan [1974]	$(d_{s1}+d_{s2})/(D_i/2)$	[Wentworth] & [Wadell], influence of sphericity is reduced.	Considers only two corner, laborious.

Abbreviations: n = number of corners, d_s = diameter of sharpest corner, d_i = diameter of i th corner, D_i = diameter of the largest inscribed circle, L_s = longest diameter through measured corner, L = long axis, I = intermediate axis, Cp = curvature of plane parts, Cv = curvature of convex parts, Cc = curvature of concave parts, [Wadell] = based on Wadell's concept, [Wentworth] = based on Wentworth's concept.

Table 3. Average values for the mophometric indices.

PROCESS AND LOCATION		<i>n</i>	Angularity	CSF	CSF _{2-Axes}	MPS (<i>ψρ</i>)	F (L-I/L-S)	OPI	D (S/L)	I/L	S/I
IN SITU FLOW											
Southwest Rift Zone (SWRZ)		101									
	Mean		1.22	0.63	0.88	0.73	0.51	-0.14	0.56	0.78	0.72
	Standard Deviation		1.26	0.60	0.88	0.70	0.63	6.09	0.52	0.74	0.71
EXPLOSIVE DEPOSITS											
Phreatic Eruption,Site 1 (PE1)		111									
	Mean		1.76	0.56	0.86	0.67	0.50	-0.82	0.48	0.75	0.67
	Standard Deviation		1.96	0.59	0.87	0.68	0.56	6.22	0.51	0.76	0.68
Phreatic Eruption, Site 2 (PE2)		68									
	Mean		1.84	0.54	0.86	0.65	0.50	-0.69	0.46	0.74	0.63
	Standard Deviation		2.02	0.57	0.86	0.67	0.57	6.88	0.50	0.75	0.67
Phreatic Eruption, Kau Desert Rocks (PE3)		42									
	Mean		1.40	0.66	0.88	0.75	0.58	1.18	0.59	0.77	0.76
	Standard Deviation		1.51	0.69	0.88	0.77	0.64	4.76	0.61	0.78	0.78
CATASTROPHIC FLOODING											
Ephrata Fan, Site 1 (EF1)		61									
	Mean		3.61	0.47	0.86	0.60	0.46	-2.03	0.49	0.74	0.56
	Standard Deviation		3.66	0.50	0.86	0.62	0.54	7.67	0.44	0.76	0.60
Ephrata Fan, Site 2 (EF2)		49									
	Mean		3.83	0.44	0.86	0.57	0.43	-3.14	0.38	0.75	0.52
	Standard Deviation		3.84	0.48	0.86	0.59	0.50	8.31	0.41	0.76	0.57
Ephrata Fan, Site 3 (EF3)		60									
	Mean		3.82	0.64	0.88	0.74	0.50	0.08	0.57	0.78	0.73
	Standard Deviation		3.83	0.66	0.88	0.75	0.59	5.12	0.58	0.79	0.75
Eden Channel Deposit, Idaho (EC1)		30									
	Mean		3.52	0.60	0.84	0.77	0.66	2.96	0.57	0.71	0.81
	Standard Deviation		3.52	0.68	0.85	0.77	0.70	5.46	0.58	0.73	0.82
FROST SHATTERING											
Haleakala Flow 1 (MS1)		14									
	Mean		0.71	0.58	0.88	0.69	0.45	-1.41	0.51	0.79	0.65
	Standard Deviation		0.86	0.61	0.88	0.71	0.54	4.83	0.54	0.78	0.69
Haleakala Flow 2 (MS2)		7									
	Mean		0.57	0.62	0.86	0.72	0.57	0.70	0.54	0.75	0.72
	Standard Deviation		0.79	0.64	0.86	0.73	0.61	4.83	0.56	0.76	0.74
SALT WEATHERING											
Molokai Beach (MB1)		25									
	Mean		3.50	0.61	0.85	0.71	0.58	1.02	0.52	0.74	0.72
	Standard Deviation		3.56	0.62	0.86	0.72	0.63	5.30	0.54	0.75	0.74
ALLUVIAL FAN											
Hilina Pali, Hawaii (AF1)		42									
	Mean		1.43	0.55	0.83	0.66	0.54	0.21	0.46	0.72	0.66
	Standard Deviation		1.57	0.58	0.83	0.68	0.67	8.16	0.49	0.74	0.71
DEBRIS FLOW											
Graves Mill, Virginia (GM1)		9									
	Mean		3.50	0.61	0.87	0.71	0.56	0.70	0.53	0.75	0.69
	Standard Deviation		3.53	0.64	0.87	0.73	0.60	2.81	0.57	0.76	0.73
CHEMICAL WEATHERING											
Molokai Ranch (MR1)		74									
	Mean		2.63	0.67	0.89	0.76	0.52	0.04	0.60	0.80	0.75
	Standard Deviation		2.78	0.68	0.89	0.77	0.58	4.45	0.61	0.81	0.77
Molokai Ranch Random (MRR1)		30									
	Mean		3.07	0.63	0.89	0.74	0.47	-0.28	0.56	0.79	0.72
	Standard Deviation		3.10	0.64	0.89	0.74	0.53	4.67	0.57	0.80	0.73

Table 4. Average Zingg Shape Distribution For Basaltic Rock Populations

LOCATION	Discs (%)	Sphere (%)	Blades (%)	Rods (%)	<i>n</i>
IN SITU ROCK					
Southwest Rift Zone (SWRZ)	28	47	8	18	<i>101</i>
EXPLOSIVE DEPOSITS					
Phreatic Eruption, Site 1 (PE1)	39	35	13	14	<i>111</i>
Phreatic Eruption, Site 2 (PE2)	40	28	13	19	<i>68</i>
Phreatic Eruption, Kau Desert Rocks (PE3)	24	55	7	14	<i>42</i>
CATASTROPHIC FLOODING					
Ephrata Fan, Site 1 (EF1)	67	11	8	13	<i>61</i>
Ephrata Fan, Site 2 (EF2)	57	6	27	10	<i>49</i>
Ephrata Fan, Site 3 (EF3)	28	52	4	13	<i>60</i>
Eden Channel Deposit, Idaho (EC1)	10	50	3	37	<i>30</i>
FROST SHATTERING					
Haleakala Flow 1 (MS1)	50	36	0	14	<i>14</i>
Haleakala Flow 2 (MS2)	43	29	14	14	<i>7</i>
SALT WEATHERING					
Molokai Beach (MB1)	40	28	8	24	<i>25</i>
ALLUVIAL FAN					
Hilina Pali, Hawaii (AF1)	29	14	19	38	<i>42</i>
DEBRIS FLOW					
Graves Mill, Virginia (GM1)	44	44	11	0	<i>9</i>
CHEMICAL WEATHERING					
Molokai Ranch 1 (MR1)	28	55	7	9	<i>74</i>
Molokai Ranch Random (MRR1)	30	43	7	20	<i>30</i>

Table 5. T-test results. Vaules that passed the t-test are in bold. Numbers highlightd in yellow also passed the F-tests.

PROCESS AND LOCATION	<i>n</i>	Angularity	CSF	CSF _{2Axis}	MPS (<i>ψρ</i>)	F (L-I/L-S)	OPI	D (S/L)	I/L	S/I	
EXPLOSIVE DEPOSITS											
Phreatic Eruption, Site 1 (PE1)	111										
		<i>T-Value</i>	2.90	-1.25	-0.24	-0.93	-0.19	-1.15	-1.65	-0.42	-0.77
		<i>Significance Level (%)</i>	0.50	-		-	-	-	5.00	-	-
Phreatic Eruption, Site 2 (PE2)	68										
		<i>T-Value</i>	2.53	-1.30	-0.19	-0.98	-0.01	-0.66	-1.65	-0.44	-1.11
		<i>Significance Level (%)</i>	1.00	10.00		-	-	-	10.00	-	-
Phreatic Eruption, Kau Desert Rocks (PE3)	42										
		<i>T-Value</i>	0.77	0.28	0.00	0.17	0.09	1.80	0.32	-0.08	0.33
		<i>Significance Level (%)</i>	-	-	-	-	-	-	-	-	-
CATASTROPHIC FLOODING											
Ephrata Fan, Site 1 (EF1)	61										
		<i>T-Value</i>	5.10	-2.50	-0.18	-1.64	-0.72	-1.92	-1.24	-0.41	-2.08
		<i>Significance Level (%)</i>	0.10	1.00		10.00	-	5.00	-	-	2.50
Ephrata Fan, Site 2 (EF2)	49										
		<i>T-Value</i>	4.76	-2.77	-0.16	-1.90	-1.12	-2.53	-3.07	-0.28	-2.46
		<i>Significance Level (%)</i>	0.10	0.50		5.00	-	2.50	0.10	-	1.00
Ephrata Fan, Site 3 (EF3)	60										
		<i>T-Value</i>	5.26	0.12	0.00	0.10	-0.13	0.33	0.13	0.00	0.10
		<i>Significance Level (%)</i>	0.10	-		-	-	-	-	-	-
Eden Channel Deposit, Idaho (EC1)	30										
		<i>T-Value</i>	3.58	-0.24	-0.26	0.28	1.17	3.11	0.09	-0.53	0.60
		<i>Significance Level (%)</i>	0.10	-		-	5.00	0.50	-	-	-
FROST SHATTERING											
Haleakala Flow 1 (MS1)	14										
		<i>T-Value</i>	-2.22	-0.31	0.00	-0.21	-0.42	-0.98	-0.35	0.05	-0.38
		<i>Significance Level (%)</i>	2.50	-		-	-	-	-	-	-
Haleakala Flow 2 (MS2)	7										
		<i>T-Value</i>	-2.18	-0.04	-0.06	-0.04	0.26	0.46	-0.09	-0.10	0.00
		<i>Significance Level (%)</i>	5.00	-		-	-	-	-	-	-
SALT WEATHERING											
Molokai Beach (MB1)	25										
		<i>T-Value</i>	3.20	-0.16	-0.17	-0.14	0.56	1.09	-0.37	-0.27	0.00
		<i>Significance Level (%)</i>	0.50	-		-	-	-	-	-	-
ALLUVIAL FAN											
Hilina Pali, Hawaii (AF1)	42										
		<i>T-Value</i>	0.87	-0.89	-0.39	-0.67	0.29	0.28	-1.32	-0.53	-0.55
		<i>Significance Level (%)</i>	-	-		-	-	-	10.00	-	-
DEBRIS FLOW											
Graves Mill, Virginia (GM1)	9										
		<i>T-Value</i>	1.94	-0.09	-0.03	-0.08	0.25	0.90	-0.16	-0.12	-0.12
		<i>Significance Level</i>	5.00	-		-	-	-	-	-	-
CHEMICAL WEATHERING											
Molokai Ranch (MR1)	74										
		<i>T-Value</i>	4.36	0.51	0.10	0.34	0.15	0.35	0.56	0.21	0.34
		<i>Significance Level</i>	0.10	-		-	-	-	-	-	-
Molokai Ranch Random (MRR1)	30										
		<i>T-Value</i>	3.27	0.00	0.06	0.07	-0.41	-0.16	0.00	0.07	0.00
		<i>Significance Level</i>	0.10	-		-	-	-	-	-	-

Figure 1

Figure 2 Part 1

Figure 2 Part 2

Figure 3

Figure 4

Cumulative Fractional Area

0.1

0.01

Diameter m

1

Figure 5

Figure 6