Re-Evaluation of Large Martian Ripples in Gale Crater: Granulometric Evidence for an Impact Mechanism and Terrestrial Analogues

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Abstract Mars hosts three scales of superimposed aeolian bedforms: small decimeter-scale impact ripples, large meter-scale ripples, and dunes. The formation mechanism for large meter-scale ripples is enigmatic and debated. This debate is largely informed by two questions: (a) Are large ripples similar to any features on Earth? and (b) Do they have the same grain size distribution as dunes and impact ripples? We address these questions using a novel digitizing approach to produce the largest known data set of Mars ripple sand grain size to date. We find a distinction between the grain size distributions of small ripples and large ripples and suggest that analogous bedforms are found on Earth. Despite an inability to perform rigorous sedimentology on Mars, results help resolve outstanding questions in bedform physics and support a hypothesis that aeolian ripples on Mars develop by a terrestrially analogous impact mechanism.

Plain Language Summary Mars and Earth have many different sizes of sand ripples and sand dunes. The Curiosity rover took pictures of large sand ripples with one meter spacing between crests. On Earth these large ripples are often called “megaripples”. However, it is hard to know if the meter-scale ripples observed by Curiosity form in the same way as Earth’s megaripples. To help solve this problem, we measured more than twenty thousand sand grains from close-up images of the ripples taken by the Mars Hand Lens Imager on Curiosity. The method we used to measure the imaged grains simulates the measurement method used for real sand samples on Earth. Using a method like this is important because it allows for direct comparison between Earth sand and Mars sand. With this method, we find that the large ripples observed by Curiosity have larger sand grains than the smaller ripples. Earth’s megaripples also have larger grains than smaller ripples. The difference in sand grain size we measured provides evidence that large Martian ripples form in a way that is similar to Earth’s “megaripples”.

1. Introduction

Aeolian ripples and dunes are ubiquitous and familiar surface features across the solar system. Importantly, these bedforms provide a natural test environment for theories of fluid-sediment interactions. Extraterrestrial environments, most commonly Mars, have been studied for several decades to validate theories of bedform formation and sediment transport in multiple environments (e.g., Claudin & Andreotti, 2006; Duran Vincent et al., 2019; Greeley et al., 1974; Sagan & Bagnold, 1975; Shao & Lu, 2000). To be considered correct, theories must fit observations across diverse environments. Of recent and particular importance to the study of fluid-sediment systems is the observation of three superimposed bedform scales on Mars, which has challenged our theoretical understanding of fluid-sediment interactions and prompted considerable debate. In all theories, the manner in which sediment is mobilized depends on its properties. Sediment transport on Mars is acknowledged to be the result of both direct fluid entrainment forces and the imparted kinetic energy of saltating grains impacting the bed. This distinction is particularly relevant for Mars, where an impact mechanism is thought to be more vigorous than on Earth. The lower gravity and thinner atmosphere allow a lower impact threshold of transport (Kok, 2010; Sullivan & Kok, 2017). Importantly, impact-driven sediment transport results in distinct sorting patterns of finer and coarser grains in ripple troughs and crests, respectively (Anderson & Bunas, 1993; Jerolmack et al., 2006; Makse, 2000; McKenna Neuman & Bedard, 2017). It follows that the formation processes leave evidence in the surface grain size distribution (GSD).

The GSD of a ripple is easy to measure on Earth where physical samples can be acquired, but very difficult on Mars. For most of the Martian surface, the properties of surface grains must be estimated from orbit (e.g., Lane & Christensen, 2013; Rogers & Bandfield, 2009). However, rover traverses from the Mars Exploration Rovers
Opportunity (e.g., Jerolmack et al., 2006) and Spirit (e.g., Cabrol et al., 2014; Sullivan et al., 2008), and from the Mars Science Laboratory Curiosity (e.g., Sullivan & Kok, 2017; Weitz et al., 2018) have provided images of granular surfaces with sufficient resolution to measure individual grains. The Mars Hand Lens Imager (MAHLI) (Edgett et al., 2012) used during Curiosity’s Bagnold Dunes campaign at Gale crater (Bridges & Ehlmann, 2018; Lapôtre & Rampe, 2018) has provided the highest resolution images (down to 16 μm per pixel) from which grain size metrics of active aeolian ripples have been acquired. Because precise measurement of grains from Martian ripples is only possible from images, these rover images have been an invaluable data source. In recent years, these images have facilitated research and debate about the properties and processes of the three superimposed bedform scales and “large Martian ripples” in Gale crater (Banham et al., 2018; Duran Vincent et al., 2019; Ewing et al., 2017; Lapôtre et al., 2016, 2018; Lorenz, 2020; Sullivan et al., 2020; Sullivan & Kok, 2017; Yizhaq et al., 2021). The research to date has largely, though not exclusively (e.g., Sullivan et al., 2020 for active ripples and Banham et al., 2018 for preserved ripples), concluded that most of these large ripples consist of well-sorted, fine (monodisperse) sand. If this is the case, then large and multi-scale ripples formed from fine well-sorted sand present a paradox: it should not be possible for dunes with a monodisperse GSD to be superimposed with large ripples and for those ripples to also be superimposed with smaller ripples. If an impact mechanism were in place, then a poorer sorting and accumulation of coarse grains at the crest of these larger bedforms would be expected. Further, no wind tunnel experiments or field data from fine, unimodal distributions in mature ripples are known that show multiple scales of ripples. To resolve this ostensible paradox, hypotheses have been developed in which the scaling of large Martian ripples is proposed as analogous to the hydrodynamic mechanisms in subaqueous ripples (Duran Vincent et al., 2019; Lapôtre et al., 2016, 2018). This has been contrasted by work that assumes a more typical aeolian ballistic mechanism and uses the lower dynamic pressure of Martian wind to explain the larger size of Martian ripples and the superimposition of multiple ripple scales (Sullivan et al., 2020).

All theories of bedform development rest on data, and the GSD is of particular importance in this case. A number of methods exist for extracting GSDs from images, including manual digitizing (e.g., Ibbeken & Schleyer, 1986), automated pixel-based methods (e.g., Buscombe, 2013), and automated segmentation methods (e.g., Butler et al., 2001; Kozakiewicz, 2018). Methods for extracting grain size data from rover images used to date have been some form of grid-by-numbers (e.g., Jerolmack et al., 2006 or Ewing et al., 2017 methodology adapted from Kellerhals & Bray, 1971) or clustered/targeted sampling strategy (Banham et al., 2018; Weitz et al., 2018) paired with a manually digitized line of the user-estimated short and/or long axis of grains as they appear in the image. Crucially, presenting the grain count results of a grid-by-numbers approach, where a grid is overlain on an image and grains at the grid intersections are measured, can directly produce volumetrically equivalent data because the increased probability of a larger area grain falling on a grid point proxies volume (Kellerhals & Bray, 1971). However, doing the same grain count procedure for targeted areas of adjacent grains will not (Bunte & Abt, 2001; Johnson, 1994). Because volume scales cubically with grain size (e.g., a 500 μm spherical grain occupies 125 times the volume of a 100 μm spherical grain), some estimation of grain volume must be performed for clustered/targeted sampling from images to reach methodological and interpretive equivalence with conventional methods. Previous workers have used a diversity of grid-by-numbers and clustered/targeted approaches in measuring grain size from MAHLI images. The largest data set of grain size for Mars was published by Weitz et al. (2018), who digitized 15,123 grains using a grain count methodology with targeted/clustered sampling on 16 MAHLI images from Curiosity’s Bagnold Dunes campaign. This data set has been the foundation for the large ripple formation hypotheses of Lapôtre et al. (2016, 2018) and Duran Vincent et al. (2019). Other smaller data sets of MAHLI images have been produced by Banham et al. (2018), Cousin et al. (2017), Edwards et al. (2018), Ehlmann et al. (2017), Ewing et al. (2017), Minitti et al. (2013), Sullivan and Kok (2017), and Sullivan et al. (2020). Importantly, several previous presentations and interpretations of grain size data acquired from MAHLI images have used non-dimensional grain counts acquired with sampling strategies that do not produce volumetrically equivalent data. While presenting a GSD in this way serves a useful descriptive and exploratory purpose, these methods do not relate to conventional sedimentology metrics and limit process interpretations. GSDs are conventionally represented in terms of mass or volume fraction, not a non-dimensional grain count.

Here, we investigate MAHLI images of ripples in Gale crater and re-interpret existing work to present, to our knowledge, the most comprehensive study of Mars bedform GSDs. We reanalyze the images associated with assumed-active ripples taken during the Bagnold Dunes campaign using a polygon-based method of digitizing adapted from Ibbeken and Schleyer (1986). Our method is more labor intensive but automates axis determination and generates a wealth of data for each grain (a-axis, b-axis, perimeter, area, etc.). Importantly, we also use our
data set (Gough, 2021) to generate volumetric estimates of GSDs to facilitate comparison to terrestrial data and calculations of GSD properties. We performed a grain size analysis of 18 MAHLI images from the Bagnold Dunes and the “Sands of Forvie” ripple field. We have produced the largest known data set of Mars grains, totaling 25,093 grains. In this study, we examine the impact of grain size measurement and its influence on process interpretations. Our results show that by interpreting the GSDs of large Martian ripples volumetrically, the interpretations of their formation mechanism change.

2. Materials and Methods

2.1. Evaluation and Acquisition of Previous MAHLI Grain Size Data

To understand the accessibility and reproducibility of Mars grain size data from active bedforms in Gale crater, we searched the literature for available grain size data. We found MAHLI-extracted grain size data sets in Banham et al. (2018), Cousin et al. (2017), Edwards et al. (2018), Ehlmann et al. (2017), Ewing et al. (2017), Minitti et al. (2013), Sullivan and Kok (2017), Sullivan et al. (2020), and Weitz et al. (2018). Each of these studies present and measure grain size data differently. Banham et al. (2018) provide the size of individual grains in tabular format in their Supporting Information S1. However, this study does not consider any active bedforms. Edwards et al. (2018) present relatively small samples for targets Barby (404 grains over 2 images), Gobabeb (74 grains), and Otavi (95 grains), and make the individual grain data available in a repository. Sullivan et al. (2020) have also made individual measurements available, but only a single target is measured (Enchanted Island). For Ehlmann et al. (2017), Minitti et al. (2013) and Weitz et al. (2018) sample data are presented only in histograms or curves from which the number of individual grains in each bin can be estimated via plot extraction. WebPlotDigitizer was used for this extraction. Sullivan and Kok (2017) also present a histogram, but sample sizes for each bin are provided and no plot extraction was needed. In the case of Weitz et al. (2018), a subset of only 600 grains is presented for each of the images. However, the total sample size of each image is presented in Supporting Information S1. In our data extraction, we assumed that the subset of 600 grains was representative and multiplied the sample extracted from the subset by the reported sample size when performing a volumetric conversion for each bin. Cousin et al. (2017) and Ewing et al. (2017) do not disclose their precise sample sizes, but do mention that they made “several hundred” measurements. Further, figures presenting the grain size data in Cousin et al. (2017) and Ewing et al. (2017) use relative proportion on their y-axes, making the determination of sample size using WebPlotDigitizer more difficult. For these figures, we assumed a sample size of 300 for each image and used the relative proportion to estimate the number of grains in each size bin. Finally, we note that Lapôtre et al. (2018) present kernel density plots of grain size from three images, but parameters such as bandwidth and sample size are not disclosed; however, these are the same data that are presented in an easier-to-extract format by Weitz et al. (2018).

In total, we found an estimated 21,273 digitized grains from MAHLI images of bedforms in Gale crater presented in nine previous publications. Uncertainty with this estimate is caused by the unknown sample size of Cousin et al. (2017) and Ewing et al. (2017). The majority of these grains (15,123) were measured by Weitz et al. (2018). We estimate that the volume represented by these 21,273 grains is equivalent to approximately 1.87 cm³ or 38% of a 5 mL teaspoon. Further, most of the estimated volume is from the relatively coarse sand at the Rocknest and Barker targets measured by Minitti et al. (2013) and Weitz et al. (2018) and the targets of Banham et al. (2018), which do not show signs of recent activity. Of images measured in these studies from bedforms that are likely active, we estimate a total equivalent volume of 0.44 cm³ or 9% of a teaspoon. In this work, we attempt to supplement this existing sample of measurements from active bedforms in Gale crater, replicate findings, analyze previously unstudied images, and produce a publicly available data set of every grain measured (Gough, 2021).

2.2. Digitizing and Sampling

To identify MAHLI targets that can be used to acquire grain size data and inform discussions of active bedforms on Mars, we relied primarily on those already measured in the studies mentioned above. For all target images used (Table 1), we use the same images by Weitz et al. (2018) and for Enchanted Island, Sullivan et al. (2020). We have also included some targets (The Forks, Shin Brook, Traquair, and Ratharsair) that provide additional context or were not available at the time of publication for previous studies. The targets identified are from different locations (Figure S1 in Supporting Information S1) and taken from different bedform types. The sample is obviously...
restricted to areas where Curiosity could safely navigate and where use of the MAHLI was feasible and within the scope of mission objectives and timelines.

For our measurements of each image, we used a cluster sampling approach using ArcGIS Pro (Figure 1). Sample preparation occurred in five steps. First, a polygon was drawn over the image to delineate the focused areas. Second, random points were generated within this polygon. Third, buffers with a radius of 50–100 pixels were created around each of these points. Fourth, all grains resolvable by eye with any portion of their surface in the buffer area were digitized. Digitizing involved the user drawing polygons around the visible outline of the grains. As all grains are in contact, polygons are drawn so that they share vertices with no overlap. Fifth, the “minimum bounding geometry” tool with “rectangle by area” setting was used to produce the smallest area rectangle that could contain each digitized polygon. The minimum size, in a two-dimensional context, of the grain is estimated by the short side ($b$-axis) of this rectangle and the maximum size of the grain by the long side ($a$-axis). In this work, we have presented the $b$-axis as “grain size” because this conforms to the typical gravimetric definition of grain size (i.e., sieve diameter). Finally, these geometric properties were converted from pixel values into real dimensions based on the motor count value of MAHLI (Edgett et al., 2012). Resolutions in the images used ranged from 16 to 38 μm per pixel.

### 2.3. Volumetric Conversion and Grain Size Distribution

We converted the extracted $a$- and $b$-axes of grains into estimates of volume for all individual digitized grains. Only the $b$-axis data are presented in this manuscript. The volume of a digitized grain can be estimated by the volume of a sphere with a radius of one half the $b$-axis. This was also done for the $a$-axis and for a combination of these (i.e., an ellipsoid). To replicate gravimetric approaches, the total volume of the grains in an individual bin is taken as the sum of all individual estimated grain volumes within that bin range (e.g., the sum of the volume of all grains with 100–125 μm $b$-axes). Because the digitized grains are discrete observations, they can be binned however the user chooses. Previous publications of Mars GSDs have commonly used linear bins of 15–50 μm. In this study, we performed the sieving operation for bins of 25 μm and 1/4 φ intervals. The latter better replicates

### Table 1

| Target name                  | Image ID                  | Paired with       | Scale (μm/pixel) | Grains digitized |
|------------------------------|---------------------------|-------------------|------------------|-----------------|
| Warsaw                      | 1182MH00036500010402637  | N/A               | 18.9             | 1,205           |
| Kibnas                      | 1184MH0005390030402943    | Barby             | 25.9             | 1,178           |
| Barby                       | 1184MH00054800010402897   | Kibnas            | 22.3             | 1,072           |
| Gobabeb scoop B             | 1231MH0001630000403553    | Otavi, Gob. scoop A | 21.7             | 1,025           |
| Otavi                       | 1242MH0005620020403685    | Gob. Scoop A, Gob. scoop B | 16.0             | 1,159           |
| Gobabeb scoop A             | 1242MH0005740000403723    | Otavi, Gob. scoop B | 17.6             | 1,035           |
| The Forks                   | 1602MH0006750010601969    | Flume Ridge       | 25.4             | 1,100           |
| Flume Ridge                 | 1603MH0005620010602049    | The Forks         | 16.8             | 1,119           |
| Shin Brook                  | 1637MH0006940010602765    | Ripogenus         | 29.7             | 1,100           |
| Ripogenus                   | 1638MH0006970010602838    | Shin Brook        | 20.4             | 1,025           |
| Flanders Bay                | 1651MH0006580010603219    | Avery Peak        | 16.1             | 1,425           |
| Avery Peak                  | 1651MH0005810010603230    | Flanders Bay      | 16.2             | 1,049           |
| Thomas Little Toes          | 1749MH0007110010700498    | Enchanted Island  | 22.3             | 1,100           |
| Enchanted Island            | 1751MH0007220000700516    | Thomas Little Toes | 38.3             | 6,200           |
| The Shivers                 | 1793MH0007110010700799    | Trumpet           | 23               | 1,090           |
| Trumpet                     | 1793MH0006560010700835    | The Shivers       | 23               | 1,057           |
| Ratharsair                  | 2992MH0007070000604820    | Traquair          | 31.4             | 1,100           |
| Traquair                    | 2998MH0001630001100044    | Ratharsair        | 17.5             | 1,054           |

*Note. Target names given by the Mars Science Laboratory (MSL) team. Image ID can be used to find the images using the MSL Analyst’s Notebook at [https://an.rsl.wustl.edu/msl/mslbrowser/an3.aspx](https://an.rsl.wustl.edu/msl/mslbrowser/an3.aspx).*
the conventional logarithmic measurements of grain size in gravimetric methods. Once binning was complete and the data were volumetrically equivalent, GRADISTAT software (Blott & Pye, 2001) was used to calculate grain size parameters for each of the targets (Tables 2 and 3). We note that as with most gravimetric approaches, density differences in the grains cannot be captured with this method. While this may not be a significant concern for the particular targets addressed in this work despite the polymineralic sediment (Lapôtre et al., 2017), density differences are an important consideration where some transported material are of significantly higher (e.g., hematite concretions Sullivan et al., 2005) or lower (e.g., ignimbrite Favaro et al., 2020) density. For simplicity of presentation of results, only the volumetric data and results for the $b$-axis sphere using $1/4 \phi$ bins are shown in this work. However, we found that all major conclusions of this work regarding relative sorting and GSD distinction between ripple classes are the same regardless of whether the large sphere, small sphere, or prolate ellipsoid volume conversions are used and whether $1/4 \phi$ or 0.025 mm bins are used.

2.4. Sample Acquisition at the Oceano Dunes, California, USA

Physical samples were acquired at the Oceano Dunes, California, USA. Two samples of 10–50 g each were acquired at each of the locations denoted by the arrows in Figure 6 (eight samples total). These samples were analyzed using a Malvern Mastersizer laser particle size analyzer with $1/4 \phi$ bins to be equivalent to those presented from the image-based analysis. Grain size parameters were also calculated using GRADISTAT (Blott & Pye, 2001).
3. Results

3.1. Image Pairings and Site Descriptions

MAHLI images were paired to compare samples in the same locations; pairs include the crest and troughs of larger ripples or the crests of larger ripples and directly adjacent smaller ripples. These image pairs facilitate the comparison of whether the GSDs of small superimposed ripples are the same as those of larger ripples, and if the individual or combined GSDs are well sorted (see 1 cm² portion of each image in Figure 2, context and GSDs in Figures 3 and 4, and parameters in Table 2).

3.2. Target Classification

We use a simple relative classification scheme to evaluate if there is a granulometric distinction between ripple sizes. The categories are “small ripples and troughs”, “medium ripples”, and “large ripples”. Small ripples and troughs are any target associated with bedforms that resemble typical impact ripples with wavelengths on the order of 10–20 cm. These ripples are climbing larger ripples or in their troughs. Large ripples are any target taken on or near the crest of bedforms with larger wavelengths (>0.8 m) and heights (>2 cm). Medium ripples are those targets that do not fit neatly into either “large” or “small” categories; these are the Flume Ridge, Avery Peak, and The Shivers targets. Some targets, such as wheel scuffs and scoops, do not fit into this classification scheme. Previous works have used the terms “impact ripples”, “transverse large ripples”, “longitudinal large ripples”, and “coarse-grained ripples” (Lapôtre et al., 2018; Sullivan et al., 2020) to describe these targets. We note that all targets previously called “impact ripples” are classified as “small ripples” here.

| Target            | Geometric mean (μm) | D90 (μm) | D10 (μm) | Modes    | Sorting (φ) | D90-D10 (φ) |
|-------------------|---------------------|----------|----------|----------|-------------|-------------|
| Barby             | 345.1               | 497.5    | 239.0    | Unimodal | 0.414       | 1.058       |
| Kibnas            | 166.2               | 277.3    | 102.1    | Bimodal  | 0.556       | 1.443       |
| Enchanted Island  | 520.2               | 929.8    | 337.9    | Bimodal  | 0.543       | 1.460       |
| T. Little Toes    | 212.8               | 395.7    | 114.2    | Bimodal  | 0.694       | 1.793       |
| Ripogenus         | 212.8               | 330.4    | 114.6    | Bimodal  | 0.582       | 1.528       |
| Shin Brook        | 172.7               | 264.7    | 113.0    | Unimodal | 0.466       | 1.228       |
| Traquair          | 332.5               | 656.7    | 211.3    | Bimodal  | 0.611       | 1.636       |
| Ratharsair        | 200.5               | 312.3    | 129.0    | Bimodal  | 0.493       | 1.276       |
| Flume Ridge       | 164.4               | 287.6    | 91.73    | Bimodal  | 0.666       | 1.649       |
| The Forks         | 171.7               | 341.4    | 106.2    | Bimodal  | 0.662       | 1.684       |
| Avery Peak        | 168.4               | 270.7    | 96.99    | Bimodal  | 0.565       | 1.481       |
| Flanders Bay      | 180.9               | 276.5    | 105.2    | Bimodal  | 0.541       | 1.394       |
| The Shivers       | 271.5               | 412.2    | 158.9    | Unimodal | 0.535       | 1.376       |
| Trumpet           | 371.1               | 715.3    | 231.7    | Trinodal | 0.621       | 1.626       |
| Gobabeb A         | 146.4               | 214.4    | 98.03    | Unimodal | 0.434       | 1.129       |
| Gobabeb B         | 303.2               | 469.1    | 188.5    | Trinodal | 0.527       | 1.316       |
| Otavi             | 132.7               | 196.7    | 91.95    | Unimodal | 0.426       | 1.097       |
| Warsaw            | 326.9               | 494.8    | 196.2    | Unimodal | 0.538       | 1.334       |

Note. Parameters calculated using GRADISTAT software (2001) and 1/4 φ bins. Sorting calculated using the Folk and Ward (1957) method.
3.3. Site Descriptions

3.3.1. Barby, Kibnas, and Warsaw (High Dune Site)

The Barby and Kibnas targets (Figures 2a, 2b and 3a–3c) are at the upwind margin of a barchan named High Dune. The Barby target is an example of a relatively coarse armor near the crest of a large ripple. The Kibnas target is from the trough of the Barby ripple, where smaller ripples have overprinted and appear to be migrating over the larger ripple. We observed similar ripples at the Oceano Dunes, California, USA (Figure 6b). These targets are described in Bridges and Ehlmann (2018), Cousin et al. (2017), Ehlmann et al. (2017), Ewing et al. (2017), Edwards et al. (2018), O’Connell-Cooper et al. (2017) and Weitz et al. (2018). Most of these studies are mineralogical, but Edwards et al. (2018) measured 404 grains from two images of Barby with differing resolutions using a grid-by-numbers approach and reported a mean grain size of 321 and 353 μm. Weitz et al. (2018) report the size of the median grain (see Text S1 in Supporting Information S1) for Barby as 363 μm. Combined, the distributions for Barby and Kibnas clearly show a separation of grain size between large ripple crests and small ripples. Visual comparison of the two-scaled images (Figures 2a and 2b) also allows clear identification of distinct GSDs between images. The Barby bedform is classified as a “large ripple” (Bridges & Ehlmann, 2018) and as “meter scale” (Weitz et al., 2018).

The Kibnas target is described in Bridges and Ehlmann (2018), Ehlmann et al. (2017), Ewing et al. (2017), Cousin et al. (2017), and O’Connell-Cooper et al. (2017). The size of the median grain reported by Weitz et al. (2018)

| Target pair | Geometric mean (μm) | D90 (μm) | D10 (μm) | Sorting (φ) | D90–D10 (φ) | Description |
|-------------|---------------------|----------|----------|-------------|-------------|-------------|
| Megaripple  | 620                 | N/A      | N/A      | 1.08        | N/A         | Unimodal poorly sorted coarse sand |
| Enchanted Island–T. Little Toes | 371.4 | 847.2 | 137.9 | 1.026 | 2.619 | Polymodal poorly sorted medium sand |
| Oceano Dunes pair B | 558.8 | 1,396.1 | 222.7 | 0.995 | 2.648 | Bimodal poorly sorted coarse sand |
| Barby–Kibnas | 239.5 | 442.1 | 118.9 | 0.737 | 1.894 | Bimodal moderately sorted fine sand |
| Gobabeb–Otavi | 180.6 | 384.4 | 101.5 | 0.735 | 1.921 | Trimodal Moderately Sorted Fine Sand |
| Traquair–Ratharsair | 258.2 | 445.6 | 145.2 | 0.660 | 1.617 | Bimodal moderately well sorted medium sand |
| The Forks–Flume Ridge | 168.0 | 318.5 | 97.25 | 0.645 | 1.711 | Unimodal Moderately Well Sorted Fine Sand |
| The Shivers–Trumpet | 317.5 | 514.2 | 188.2 | 0.595 | 1.450 | Unimodal moderately sorted medium sand |
| Avery Peak–Flanders Bay | 174.5 | 273.9 | 100.3 | 0.555 | 1.449 | Unimodal moderately sorted fine sand |
| Shin Brook–Ripogenus | 191.7 | 306.1 | 113.6 | 0.554 | 1.430 | Unimodal moderately well sorted fine sand |
| Oceano Dunes pair A | 721.9 | 1,132.4 | 451.3 | 0.518 | 1.327 | Unimodal moderately well sorted coarse sand |
| Synthetic monodisperse | 162.7 | 243.6 | 107.9 | 0.452 | 1.175 | Unimodal well sorted fine sand |
| Impact ripple surface (Tsoar, 1990) | 272 | N/A | N/A | 0.42 | N/A | Unimodal moderately well sorted fine sand |

Note. Parameters calculated using GRADISTAT software (2001) and 1/4 φ bins. Sorting calculated using the Folk and Ward (1957) method. Entries in decreasing order of sorting.
for Kibnas is 117 μm. After volumetric conversion, we found a geometric mean grain size of 166 μm. We interpret that the consensus in the literature is that Barby is classified as being representative of the crest of a “large ripple” with some armoring and Kibnas as the trough of a “large ripple”. We also measured target Warsaw from the High Dune sampling site. Warsaw was acquired near the crest of a large ripple. Warsaw has been described in Ehlmann et al. (2017), O’Connell-Cooper et al. (2017) and Weitz et al. (2018). Warsaw, like other large ripple targets, has a distribution of medium sands similar to other large ripples.
Figure 3.
3.3.2. Gobabeb and Otavi (Gobabeb Site at Namib Dune)

The Gobabeb and Otavi targets (Figures 2o–2p, Figure 4j–4l) were taken among ripples on the western lee flank of a barchan named Namib Dune. Because of the quantity and variety of science activities that occurred at this site, these targets have been the most investigated. Several studies include images of the Otavi target, and descriptions of the target are given in Bridges and Ehlmann (2018), Ewing et al. (2017), Edwards et al. (2018), Sullivan and Kok (2017), and Weitz et al. (2018). The mineralogy of the Gobabeb sampling site is comprehensively addressed by Achilles et al. (2017) and Ehlmann et al. (2017). Edwards et al. (2018) report a mean grain size of 151 μm for the Otavi target. Weitz et al. (2018) report the size of the median grain as 127 μm. The Otavi target is taken on a small ripple. The Gobabeb Scoop 1 Dump A discard pile target is taken of sediment sieved by Curiosity’s 150 μm sieve and dumped; the Gobabeb Scoop 1 Dump B discard pile target is of sediment, which did not pass through the 150 μm sieve. The presence of relatively coarse material that did not pass through the 150 μm sieve suggests that there is a population of sediment not present on Otavi and other small ripples that may serve as a coarse armor for adjacent large ripples. The grain parameters from this scoop closely resemble that of other large ripple targets (Table 3). Unfortunately, no image target from the crest of a large ripple was acquired at the Gobabeb sample location. We note the targets of the Gobabeb site have been the source of some confusion regarding which targets are associated with which type of feature; see Text S2 in Supporting Information S1 of this work and Appendix III of Sullivan et al. (2020) for discussions of this issue.

3.3.3. Flume Ridge and The Forks (Mapleton Site at Nathan Bridges Dune)

The Flume Ridge and The Forks targets (Figures 2i, 2j and 4a–4c) were taken on the northern flank of the Nathan Bridges linear dune at a sampling site called Mapleton. The Flume Ridge target was acquired at the crest of a “large longitudinal ripple” (Lapôtre et al., 2018; Sullivan et al., 2020) superimposed with secondary and tertiary ripples. The Forks target is taken on a smaller ripple adjacent to the Flume Ridge target. Flume Ridge, similar to Avery Peak, represents the crest of a ripple with large wavelength but with relatively little prominence. The Flume Ridge target is described in Lapôtre et al. (2018) and Weitz et al. (2018). Figure 1g of Lapôtre et al. (2018) present a GSD for this site that is described as being “monodisperse”. By contrast, we found this target to be among the poorest sorted of the individual targets (0.666) and to be trimodal. We attribute this difference to the binning strategy and to the presentation of grain counts rather than grain volumes. We also note that there is a noticeable irregularity or kink in the distribution presented in Figure 1g of Lapôtre et al. (2018) that suggests intermediate sorting and may be the result of the use of kernel density (Figure S2 in Supporting Information S1). We also note that a visual inspection of the Flume Ridge image (Figure 2j) is compelling evidence that this target is not of well-sorted sand. The Forks target has not been addressed in any literature, but it exhibits intermediate sorting and provides additional context to this site.

3.3.4. Ripogenus and Shin Brook (Southern Cove Site at Nathan Bridges Dune)

The Ripogenus and Shin Brook targets (Figures 2e, 2f and 3g–3i) were taken on the eastern flank of the Nathan Bridges linear dune at a sampling site called Southern Cove. The Ripogenus target is at the crest of a larger bedform with apparent lower amplitude than most other large ripples in the area. The Shin Brook target is at the crest of a smaller bedform superimposed on the larger Ripogenus ripple. The Ripogenus target is described in Weitz et al. (2018). Shin Brook has not previously been described or measured in the literature. The Ripogenus target shows that a coarser population of grains, relative to the smaller Shin Brook ripple, have accumulated at the crest.

Figure 3. Context images and grain size distributions for target pairs. Bins for grain size distributions (GSDs) are 1/4 φ. (a, b) Context images with Kibnas and Barby targets. Kibnas target taken on small superimposed ripple and Barby on a large crest that is perpendicular to most crestline orientations in the ripple field. (c) GSDs for Kibnas and Barby targets. (d, e) Context images for Enchanted Island and Thomas Little Toes targets. Enchanted Island taken on the crest of a large ripple and Thomas Little Toes taken on a small ripple with crestline perpendicular to the large ripple. (f) GSDs for Enchanted Island and Thomas Little Toes targets. (g, h) Context images with Ripogenus and Shin Brook targets. Ripogenus taken on the crest of a low amplitude large ripple. Shin Brook taken on a smaller ripple superimposed on the larger ripple. (i) GSDs for Shin Brook and Ripogenus targets. (j, k) Context images for Traquair and Ratharsair targets in the Sands of Forvie ripple field. Traquair is taken on the crest of a large ripple and Ratharsair is from the trough of this ripple where small ripples have developed perpendicular to large ripple orientation. (l) GSDs for Ratharsair and Traquair targets.
Figure 4.
3.3.5. Flanders Bay and Avery Peak (Ounguit Beach Site at Mount Desert Island Dune)

The Avery Peak and Flanders Bay targets (Figures 2k, 2I and 4d–4f) were taken on the western flank of the Mount Desert Island linear dune. The Avery Peak target was taken at the crest of a larger bedform with small height relative to other large bedforms in the ripple field. The Flanders Bay target was taken in a disturbed wheel track. These targets are described in Weitz et al. (2018). The disturbance of the wheel track likely resulted in mixing of the sediment and includes grains that were previously on the surface and some that have been exhumed from the bulk. The Avery Peak and Flanders Bay targets represent an interesting experiment in comparing the distribution from the crest of a ripple to disturbed material from a nearby stoss slope. These distributions are strikingly similar. The Avery Peak target is acquired at the crest of a ripple with some prominence, but clearly smaller than other large ripples in the area and not greater in height than the nearby small ripples. We suggest this smaller height is attributable to the relative absence of coarser material compared to other large ripples in the field, for which no samples are available.

3.3.6. Enchanted Island and Thomas Little Toes (Stop En Route to Vera Rubin Ridge)

The Enchanted Island and Thomas Little Toes targets (Figures 2c, 2d and 3d–3f) were taken in a field of large bedforms whose troughs are superimposed with smaller bedforms. These ripples are in an isolated ripple field and are not developing on dunes. The Enchanted Island target is of the crest of one of these large ripples. Enchanted Island is described by Lapôtre et al. (2018) and Sullivan et al. (2020). The Thomas Little Toes target was acquired in the smaller bedforms in the trough between large bedforms. We interpret that there is consensus that the Enchanted Island target is representative of a “coarse-grained ripple” or “megaripple”, as it displays by far the coarsest GSD of all measured targets. Like the Barby-Kibnas pairing, Enchanted Island and Thomas Little Toes show a very clear distinction between the coarse crest of a large bedform and the finer material of smaller bedforms in the trough.

3.3.7. The Shivers and Trumpet (Stop En Route to Vera Rubin Ridge)

The Shivers and Trumpet targets (Figures 2m, 2n and 4g–4i) were taken on larger bedforms 200 m east-southeast of the Enchanted Island target. These targets are described in Weitz et al. (2018). These bedforms are superimposed with some smaller bedforms. The Shivers target is taken on the crest of a less prominent large bedform. The Trumpet target is taken on the lee slope of a bedform larger than The Shivers where no smaller bedforms have developed. The Shivers and Trumpet targets are taken from adjacent large bedforms and have similar grain size distributions. No small bedform target was acquired in this area.

3.3.8. Traquair and Ratharsair (Sands of Forvie)

The Sands of Forvie targets (Figures 2g, 2h and 3j–3l) are from the margin of a large ripple field named The Sands of Forvie visited by Curiosity in January 2021. Images were acquired at the crest of a large bedform and on a smaller bedform in the trough. Two crest targets, Airor and Traquair, and one trough target, Ratharsair, were acquired at this location. We used the higher-resolution Traquair target for this work. As of this writing, we have no knowledge of any description or analysis of these targets in the published literature. As with Enchanted Island and Thomas Little Toes, there is a clear distinction between the GSDs of the crest and trough at this location. The Traquair target at this site also had a relatively coarse-grained cap relative to the adjacent trough target and provides another distinct area of Gale crater with further evidence of a granulometric explanation for ripple size.

Figure 4. Context images and grain size distributions for target pairs, continued. Bins for grain size distributions (GSDs) are 1/4 \( \phi \). (a, b) Context images with The Forks and Flume Ridge targets. The Flume Ridge target was acquired at the crest of a longitudinal ripple with low amplitude. The Forks target was acquired on a small impact ripple adjacent to the Flume Ridge ripple. (c) GSDs for The Forks and Flume Ridge targets. (d, e) Context images with Flanders Bay and Avery Peak targets. Avery Peak target taken on the crest of a low amplitude large ripple. Flanders Bay target acquired in a disturbed wheel track. (f) GSDs for Avery Peak and Flanders Bay targets. (g, h) Context images with The Shivers and Trumpet targets. Both are taken on ripples with 20–30 cm wavelengths. Trumpet is acquired on the lee slope of a ripple and The Shivers is taken on the stoss slope of an adjacent ripple. (i) GSDs for The Shivers and Trumpet targets. (j, k) Context images with Otavi and Gobabeb targets. The Otavi target was acquired on small ripples. The Gobabeb targets were the results of a scooped sieve: the “A” target represents material that passed through a 150-\( \mu \)m sieve and the “B” target material that did not pass through the sieve. (l) GSDs for the Otavi and Gobabeb Scoop 1 A/B targets.
3.3.9. Comparison of Ripples: Individual Targets

There is an apparent continuum between ripple size class and grain size distribution (Figure 5). Most distributions are subtly bi- or trimodal, where a mode is any local maxima in the GSD. The primary mode of all ripples classified as “transverse large ripples” is >200 μm and the primary mode of all “impact ripples” is <200 μm. There is a clear granulometric distinction between ripple classes. In a very well-sorted sediment, most grains will be transported near their threshold of motion, and thus be equally susceptible to transport on similar length scales. Based on the assumption of such a transport environment, Lapôtre et al. (2016) use the impact threshold formulation of Kok (2010) with a single representative grain size value of 200 μm to characterize large Martian ripples. We investigate this sorting assumption by determining the continuum of impact thresholds for all measured grains using the Kok (2010) formulation with the same parameters as Lapôtre et al. (2016) (Text S4 in Supporting Information S1). The calculated thresholds are plotted as a function of the cumulative grain size distribution to demonstrate that the crests of large Martian ripples are more resistant to transport than the small ripples (Figure 5).

3.4. Comparison of Ripples: Paired Targets

Pairing the targets (Figures 3 and 4) allows for a complete assessment of the GSD of different ripple sizes formed in an identical wind regime (Table 3). This combination makes the assumption that the samples have the same mass; this is a poor assumption because measuring the distribution of the entire ripple would require in situ sampling, but it remains a good assessment of the range of grain sizes present on these features. To provide terrestrial context data, we examined two superimposed ripple sites at the Oceano Dunes, California, USA (Figure 6). Additional data from an impact ripple and megarripple measured by Tsoar (1990) provide further terrestrial context of well-sorted and poorly sorted bedforms, respectively. Finally, we also include parameters for a synthetic, fine and well-sorted GSD. This distribution was created to represent a symmetrical, mesokurtic, and well-sorted distribution (by the metrics of Blott & Pye, 2001) with a median grain size of fine sand in the range previously reported as representative for some of these large ripples. This synthetic GSD represents a baseline for evaluating if any of the target sites from large Martian ripples in Gale crater have a monodisperse GSD. Figure 7 compares the eight MAHLI target pair GSDs to each other and to this monodisperse distribution.

4. Discussion

4.1. Findings

Our method produced a volume-equivalent data set to re-evaluate the GSDs of aeolian bedforms in Gale crater. We find evidence that poorer sorting and coarser grains are present on the crest of large ripples relative to superimposed smaller ripples and troughs. We can replicate neither the finding that sands forming some large Martian ripples are fine, well-sorted, and all transported near their threshold of motion nor that small impact ripples and large ripples have the same GSDs. Results suggest that there is a relationship between the amplitude of a ripple and its grain size distribution, where coarser distributions and increasingly poor sorting are associated with larger ripples. This is consistent with aeolian impact-and-splash mechanisms that cause particle size segregation in terrestrial bedforms (Anderson & Bunas, 1993; Jerolmack et al., 2006; McKenna Neuman & Bedard, 2017). However, it remains that Martian ripples have larger wavelengths relative to terrestrial bedforms with equivalent GSDs. On Earth, the relatively potent fluid force from the wind limits ripple size. Here, our findings are consistent with the mechanisms suggested by Sullivan and Kok (2017), Sullivan et al. (2020), Siminovich et al. (2019) and Yizhaq et al. (2021) where the lower fluid force of the thin Martian atmosphere does not provide the same height-capping mechanism as on Earth and allows a broader range of ripple scales. There is clear separation in the threshold of motion for grains from adjacent large and small ripples (Figure 5). Figure 8 shows the ratio of the impact threshold, calculated using the method of Kok (2010), for D90 and D10 grain size for target pairs. For Earth, the impact threshold was calculated using the best fit formulation presented in Lapôtre et al. (2016). The monodisperse distribution has a ratio of 1.44 (i.e., the impact threshold of D90 is 44% greater than that of D10) for Earth. On Mars, using the Kok (2010) formulation, the same monodisperse distribution has a ratio of 2.48. In all observed MAHLI target pairs, the impact threshold of D90 is at least 300% greater than the impact threshold of the D10. In other words, the sorting-by-threshold of observed grains is poorer for all observed target pairs than for megarripples at the Oceano Dunes. This observed difference in threshold between and within
Figure 5. Grain size distributions and impact threshold distributions for all classified ripples. A continuum appears to exist between ripple size and grain size distribution, with clear distinction between the distributions of small and large ripples.
adjacent small and large ripples suggests an impact fractionation mechanism in which finer grains are mobilized in more energetic long hops and coarser material in shorter impact-driven hops, and coarser material accumulates at the ripple crest, analogous to megaripple development (Anderson & Bunas, 1993). This further suggests that equivalent granulometric sorting on Earth and Mars may result in the formation of different features, and that the mechanics of aeolian transport on Mars are more sensitive to deviations from ideal monodisperse sediment than on Earth. This implies that quantitative sorting metrics inherited from terrestrial research should not necessarily share common qualitative descriptors (“well”, “moderately”, and “poor”) when applied in an aeolian context across planetary environments. Importantly, our evidence from the grain size analysis supports the impact-driven hypothesis of large Martian ripple development and finds that these ripples are perhaps more poorly sorted than assumed in previous research. The mechanisms of lower wind dynamic pressure and impact fractionation are complementary in explaining large Martian ripple development.

Results suggest that the GSDs for different ripple classes at the Bagnold Dunes are not the same. We do not find a single case where small ripples and large ripples from adjacent targets have the same distribution. We do not find a single case where a large (>1 m wavelength) transverse ripple crest has a fine, well-sorted GSD. Large transverse ripple crests are typically medium sands with moderately well-sorted distributions. The only target available for longitudinal large ripples is relatively fine but displays poorer sorting and was generally trimodal. The “longitudinal large ripple”, for which only one target is available (Flume Ridge), remains unique and more data are required prior to drawing defensible conclusions.

Figure 6. Analogue ripples at the Oceano Dunes, California, USA. (a) Ripple pair “A” from the Oceano Dunes. Arrows indicate sampling locations for “large” and “small” ripples. We interpret the “large” ripples as megaripples. Length of pen cap 6 cm. These are a suggested analogue for the Ripogenus-Flume Ridge site (compare to Figure 3b). (b) Ripple pair “b” from the Oceano Dunes. Arrows indicate sampling locations for “large” and “small” ripples. We interpret the “large” ripples as megaripples. These are a suggested analogue for the Barby-Kibnas site (compare to Figure 3b). (c) Context image for A-B. Sinuous ripples of multiple scales are present climbing a dune at the Oceano Dunes, analogous to those observed at the Bagnold Dunes. (d) Individual and combined grain size distributions for samples acquired for pair “a” (red) and “b” (black).
Overall, there is a continuum of bedform GSDs for ripples at the Bagnold Dunes. Ripple classification in the field is the geomorphologist’s attempt to impose discrete order on what may be a continuous series of features. While ideal monodisperse distributions will result in certain reducible scales of bedforms (Duran Vinent et al., 2019), these GSDs are not ubiquitous in nature. The definitional ambiguity for ripples that do not have monodisperse distributions or conform to these scales has led to a proliferation of terminology. These terms have been based on morphometry relative to ripples (“megaripples” Yizhaq, Katra, Isenberg, et al., 2012) or assumed transport direction (“transverse aeolian ridges” Balm et al., 2008), absolute morphometry (“meter-scale bedforms” Vaz et al., 2017), relative granulometry (“coarse-grained ripples” Jerolmack et al., 2006), absolute granulometry (“granule ripples” Fryberger et al., 1992), transport mode (“reptation dunes” Lämmel et al., 2018), or some combination of these (“granule megaripple” Mountney & Russell, 2004 or “gravel megaripple” de Silva et al., 2013). Each term necessarily involves some contradictions and semantic awkwardness if applied to the full spectrum of ripples with some degree of relative coarseness, larger scale, or poorer sorting. Regardless of each worker’s preferred name for features observed in intermediate and poorly sorted GSDs, the challenge is clearly caused by

![Figure 7. Comparison of eight paired distributions sites to a synthetic fine and well-sorted distribution. See Table 3 for properties.](image)

![Figure 8. Ratio of the impact threshold for D90 and D10 grain size for MAHLI target pairs, monodisperse distribution, and Oceano Dunes samples.](image)
having agreement for the names of bedforms at only the fine, well-sorted “endmember” (Sullivan et al., 2020) of the sorting continuum (ripples) and a plethora of ad hoc terms that use “ripples” as a benchmark for everything else on the continuum. Further, this proliferation of terms and lack of definitional clarity give the impression that all bedforms not emerging in well-sorted GSDs are occasional exceptions to the better understood well-sorted ripples, when they are in fact relatively common in many aeolian environments. This issue is particularly relevant for bedforms observed in Gale crater, and perhaps Mars more broadly, where our observations suggest that most bedforms have intermediate sorting.

In addition to GSDs, the terminology applied to bedforms has a complex relationship with bedform sinuosity and patterning (Silvestro et al., 2016). Ripples forming on the slopes and flanks of dunes in Gale crater are particularly sinuous, whereas the largest ripples (e.g., Enchanted Island) in isolated fields have straight crests. As observed by Rubin (2012), planform straightness in well-sorted ripples occurs because of along-crest transport and lateral splash of grains. In more poorly sorted material, this along-crest coupling does not operate to the same degree (Yizhaq, Katra, Kok, et al., 2012). In light of the relatively poor sorting observed on MAHLI images of large Martian ripples, a possible mechanism explaining the sinuosity of ripples on the Bagnold Dunes is that there are fewer coarse grains available. Such a mechanism provides an explanation for the observed coarsening of large Martian ripple crests. In other words, these ripples are more sinuous and smaller because there is less armoring material available to allow straight crests to develop. Yizhaq, Katra, Kok, et al. (2012); Yizhaq et al. (2019) characterize this as the “transverse instability of megaripples”, in which the disproportionate accumulation of coarse grains along the crest and decrease in lateral transport cause megaripples to be more sinuous than well-sorted ripples. This relatively low content of coarser material was proposed by Gough et al. (2020) as being the cause of sinuosity and pattern development in “megaripple stripes”. If the cause of the observed sinuosity were mechanistic rather than an effect of granulometric proportion, then large, sinuous ripples would be expected on all dune slopes (Yizhaq et al., 2019). We suggest that the increase in sinuosity is not the result of a change in the mechanism of ripple formation, but rather a decrease of the available coarse material to promote the development of continuous large ripple crests. In summary, our results align with the interpretation that the observed heterogeneity of ripple forms in Gale crater are the result of the same mechanism operating on different proportions of materials rather than different mechanisms operating on the same proportions of material.

Ripples examined here suggest that poorer sorting and coarser material produce larger bedforms. Notably, Enchanted Island, the largest bedform, had the poorest sorting of the targets and Otavi, the smallest bedform, had the greatest sorting. Most targets showed poorer sorting than typical impact ripples, but greater sorting than typical “megaripples” (Table 3). All observed targets fall within a range of sorting observed for superimposed ripples of multiple scales observed at the Oceano Dunes on Earth. As noted, these sorting metrics are meaningful only in a terrestrial context, and the extent to which these qualitative descriptors translate to the Martian aeolian context is in need of further investigation.

4.2. Uncertainty

Grain size is much more difficult to measure on Mars. This is largely because aeolian research has almost exclusively used physical samples measured with sieves, laser particle size analyzer, or other methods that require a sample be removed from the field and brought to a laboratory. Obviously, Martian in situ analysis or sample acquisition and return are formidable engineering challenges. Until this is possible, there will remain a gap in measurement equivalence and understanding. Two issues affect GSD interpretations from MAHLI: the tiny sample sizes and errors introduced by analyzing GSDs from images alone.

4.2.1. Sample Size

Sample sizes are necessarily small on Mars. The total estimated volume of the 25,093 grains digitized in this work, assuming sphericity and 30% porosity, is 0.837 cm³ (≈17% of a teaspoon). However, this sample is the largest for active bedforms on Mars. Automated methods offer an opportunity for larger sample sizes but remain less accurate than digitizing. Regardless of method, sample sizes remain very limited by the low number of MAHLI images from active ripple surfaces.
4.2.2. Uncertainty in Image-Based Approaches

Images of sand are not sand. GSDs from images are not perfectly comparable to gravimetric GSDs; the value primarily comes in assessing relative differences within and between distributions. Images of the sediment surface are a focused measure of the grains that interface directly with the wind. A comparable monolayer surface sample is very difficult to take physically, and some field workers have used adhesives or plastics to attempt this (Sharp, 1963; Tsoar, 1990). While perhaps not directly comparable to physical samples, images may provide a superior measurement of the relevant grain sizes to aeolian transport. This noted, referencing GSDs from images to volume (or mass) proportion remains essential to relate to measures of grain size parameters, sediment flux, and bedform celerity.

4.2.3. Implications of Uncertainty for Current and Future Work on Martian Ripples

The quality and quantity of available data from Martian bedform GSDs lowers confidence in general process inferences and modeling based on these data. To interrogate this issue, it is instructive to compare the sample sizes and methodologies of grain size research typical on Earth to those conducted on Mars. In this work, we purport that the digitization of the volumetric equivalent of less than a teaspoon of sediment is an appropriate sample because it is “large” in the Martian context. An example of a similar recent typical comparative terrestrial granulometric study is Lopez et al. (2020), who collected and sieved 105 samples, each with an approximate volume of 500 cm$^3$. This is equivalent to a total sample volume of approximately 220 cups. In other words, each individual sample in this work is approximately 100 times larger than the cumulative MAHLI digitizing done in this study combined with all others mentioned herein, and the total sample is more than 10,000 times larger. Of course, the statistical value of individual grain measurements in a digitizing approach is greater than that of binned measurements in a typical sieving workflow. Directly measuring only those grains at the surface is of greater value for understanding aeolian processes than typical field sampling. How the value of photosieving results compare to gravimetric sieving results is a topic that needs further study.

How, then, can these important concerns regarding data quality and equivalence be reconciled with observations? Central to field geology and geomorphology are intuition and abduction, in which experience with a particular set of tools and previous experiences facilitates the interpretation of landscapes, often independent of empirical data or modeling (e.g., Baker, 2014; Raab & Frodeman, 2002; Siwabessy, 2021). For terrestrial research, the physics and modeling component of sediment transport is reconciled with a wealth of field work and data. With Martian geomorphology and remote sensing more broadly, we must make accommodations for the fact that both the intuition and data components of evaluating a landscape are compromised. How these accommodations are to be communicated is unclear, but modeling approaches must be reconcilable with the limited, but growing, available data. With MAHLI, in addition to the data produced here, a recalibration to assist intuitive understanding can still be achieved by rescaling each image to have equivalent dimensions. In other words, to make MAHLI truly function as a “hand lens” for interpretive purposes, a comparison of its images must be done with equivalent magnification (e.g., Ehlmann et al., 2017, Figure 4 and Lapôtre et al., 2018, Figure 1). Figure 2 is an example of this, and we suggest that to the experienced observer an inspection of these identically scaled MAHLI image pairs alongside other images from Curiosity’s suite of cameras makes the intermediate sorting and distinction between the GSDs of smaller and larger ripples as clear as the empirical GSDs presented in this work.

It is clear that the methodologies and nature of uncertainty in this work are distinct from those of terrestrial aeolian research. Expectations of sample quantity are different for terrestrial and Martian research. As with previous studies, we have made process interpretations of Martian bedforms based on less than a teaspoon of sample and have received editorial and reviewer flexibility that may not have been granted for terrestrial research with the same methodology because these represent the only available data (i.e., “what else can we do?”). In the same way that Mariner 9 images are now seldom used for aeolian research because of the availability of data from higher resolution sensors, we expect that “photosieving” and the samples presented here will be outdated in a few decades when in-situ grain size analysis and sample return are available. In brief, the science of planetary bedforms is still developing.
5. Conclusions

We have shown that by evaluating GSDs volumetrically, the perception of GSDs for large Martian ripples in Gale crater changes. We found no empirical support in our data for large transverse ripple crests with fine, monodisperse distributions or with the same grain size distribution as an adjacent small ripple. As on Earth, coarser and more poorly sorted GSDs were associated with larger ripples. This evidence supports the hypothesis that Martian ripples are driven by an impact mechanism. Presently, as suggested by Lorenz (2020), the fluid drag hypothesis is an elegant solution to a problem that may not exist. In the current environment of multiple working hypotheses, however, more data are needed. Barriers to the acquisition of Mars grain size data from images is the number of labor hours required to produce comparatively small volumes of sediment, and the relatively small number of images of these sediments. Manual digitizing remains the best approach for producing high-quality grain size data from images. While Martian grain size analyses will be limited until large-scale in situ analysis or sample return are feasible, the data and images we currently have can still be helpful in guiding the understanding of modern and ancient ripple formation and boundary layer processes.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data used in this work are available at https://doi.org/10.7910/DVN/F9GKCB (Gough, 2021).

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