

RESEARCH ARTICLE

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Key Points:

- We report on properties of new dated crater clusters on Mars; most clusters in this study comprise <10 craters and span hundreds of meters
- Crater cluster dispersion increases for lower elevations when highest elevations are disregarded; impact azimuths are randomly distributed
- Impact angles are shallower than expected, which could be a possible observation effect

Supporting Information:

- Supporting Information S1
- Table S1

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Recently Formed Crater Clusters on Mars

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Abstract This study maps and measures assorted properties of new dated crater clusters that formed recently when impactors fragmented in the atmosphere of Mars. We report these statistics for 77 clusters: number of craters, size of cluster, dispersion of cluster, direction (azimuth) from which the impactor approached, and an estimate of the angle from vertical of the impact. Clusters range from a few to hundreds of craters, with most containing tens of craters. They are most commonly dispersed over hundreds of meters, with extents ranging from a few meters to a few kilometers. We find that dispersion generally does not correlate with topographic elevation. However, when the highest elevations are disregarded, clusters are more dispersed at lower elevations, as expected. Impact azimuths are randomly distributed and do not express a clear directionality of incoming meteoroids. Results suggest impacts occur closer to horizontal than expected, which could be due to observational effects. The characteristics we report here provide important constraints for future work in understanding atmospheric fragmentation processes; properties of the impactors themselves, such as density and orbital parameters; and the seismic detectability of impacts. These are critical aspects to understand, as approximately half of current impacts are observed to be clusters.

Plain Language Summary We studied clusters of new craters that formed in the last few years when meteoroids broke up in the atmosphere of Mars. We studied 77 clusters and measured the number of craters, the sizes of the clusters, how spread out the clusters are, the direction the impactors came from, and the angle of the impacts. Clusters range from a few to hundreds of craters, with most containing tens of craters. They are usually spread out over hundreds of meters, ranging from a few meters to a few kilometers. Except for the highest areas, clusters are more spread out at lower elevations, as expected. Impactors come from all different directions. Impacts are closer to horizontal than expected. This information will be used to understand breakup in the Martian atmosphere; properties of the incoming meteoroids, such as their density and orbits; and how well we would be able to detect impacts with a seismometer. This is important because about half of current impacts at Mars are clusters.

1. Introduction

New craters are currently being discovered on Mars by detecting the appearance of low-albedo surface disturbances around fresh impact sites (Daubar et al., 2013; Malin et al., 2006). We refer to these as “dated” impacts, as the time of their formation is constrained by before and after imaging; all craters studied here have formed within the last few decades. These are all small (<~50 m in diameter) primary craters (“primaries”), which are formed by the initial impact on Mars, as opposed to secondary craters (“secondaries”), which are formed by ejecta from a primary impact. Due to nonoverlapping constraining dates of formation, and lack of any primaries large enough to produce these as secondary craters, we can conclude that the dated impacts we study here are primary impacts and not secondary craters (Daubar et al., 2013). This unique data set of current primary impacts provides valuable information about modern processes operating on Mars and future exploration of the planet. Not only do impacts pose a hazard to surface robotic and human-led missions, impacts will also provide a source of seismic waves for acquiring data on the Martian interior. Geophysical investigations such as the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission (Banerdt et al., 2017, 2013) will utilize these impacts as a source of seismic energy to study the Martian interior. For example, they will reveal crustal structure along the ray path between the site of the impact and the InSight seismometer location. These recent dated impacts also allow measurement of the current cratering rate (Daubar et al., 2013), which has been used to predict the overall rate of impact-induced seismic activity on Mars (Teanby, 2015;

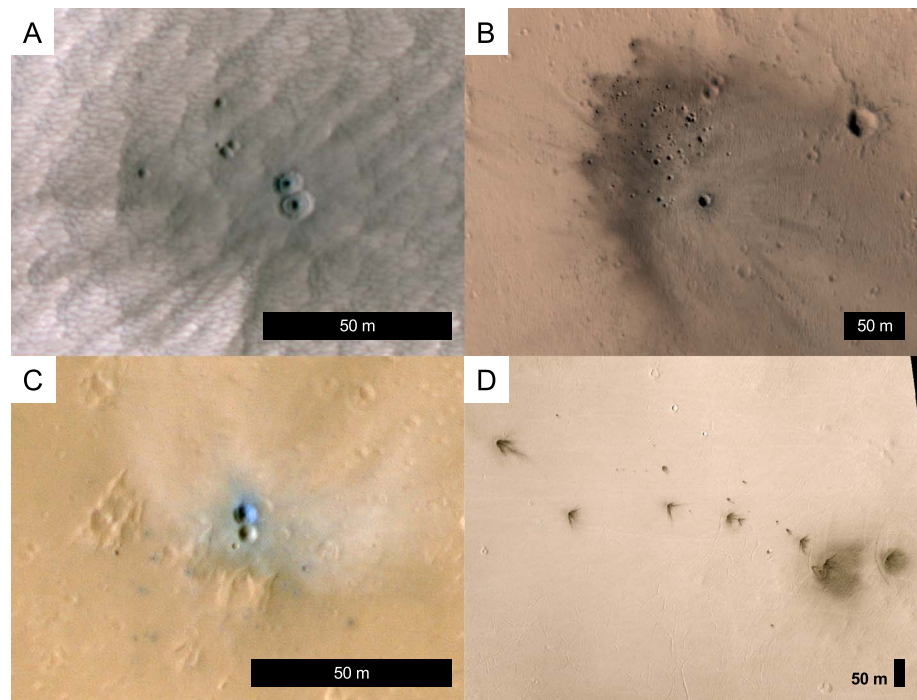


Figure 1. Examples of new dated impact clusters in High Resolution Imaging Science Experiment (HiRISE) images of Mars. Clusters can comprise from (a, c) several to (b) several hundred craters. The spatial distribution of craters in each cluster varies between (b) fairly circularly distributed and (d) extending along an elongated strewn field with a distinct azimuthal direction. Spatial dispersion within the clusters ranges from (c) tightly clustered to (d) spread out over hundreds of meters. (a) ESP_037706_1765 COLOR product at -3.437°N , 256.327°E . (b) ESP_038458_2030 MRGB product at 22.774°N , 247.591°E . (c) ESP_019983_1800 COLOR product at -0.066°N , 274.104°E . (d) ESP_028444_2040 COLOR product at 23.921°N , 41.466°E . North is up in all cases, enhanced false color images have been stretched to enhance contrast, and all scale bars are 50 m. HiRISE images credit National Aeronautics and Space Administration/Jet Propulsion Laboratory/University of Arizona.

Teanby & Wookey, 2011). InSight will provide a valuable additional in situ measurement of the current cratering rate, unbiased by surface properties such as dust cover (Daubar et al., 2015, 2018).

Our project, IMPACT-SEISM (Investigating the Morphometric Properties of All-New Craters and the Transfer of Seismic Energy from Impacts into the Subsurface of Mars), reports results of this investigation in this and a future paper (Schmerr et al., 2016). In this paper, we describe characteristics of current impact clusters on Mars and implications for the conditions of cluster formation; the second paper will present the results of our seismic model applied to those characteristics. Using the specific parameters of actual modern Martian impacts (rather than idealized hypothetical impacts) allows us to accurately model Martian impact-induced seismic signals. Using these model results, we hope to be able to determine characteristics of an impact from an observed seismic signal. By this we refer to not merely the basic parameters of size, distance, and direction, but also characteristics that affect the site's detectability by orbital imagers, such as a cluster versus a single impact, or a dispersed versus compact cluster.

A large proportion of new dated impacts are in the form of clusters of multiple craters (Figure 1), where the impactor fragmented in the atmosphere to form multiple craters roughly simultaneously (Ivanov et al., 2010, 2009, 2008). Daubar et al. (2013) reported 56% of dated, observationally constrained, impacts occur as clusters; as the number of discoveries has grown, that number has stayed fairly constant; currently 52% of known dated impacts occur as clusters. It should be noted that clusters are likely easier to detect in visible images taken from orbit, as the area darkened by the impact “blast zone” is proportionally larger for multiple, spread-out impacts. Surprisingly, however, clusters are completely absent in the slightly older, but still Late Amazonian, population of primary impacts identified on the north polar layered deposits (Landis et al., 2016). This may indicate either an age or size cutoff in cluster formation, or preferential erasure as a result of infill. On the other hand, Golombek et al. (2010, 2014) report many primary crater clusters in

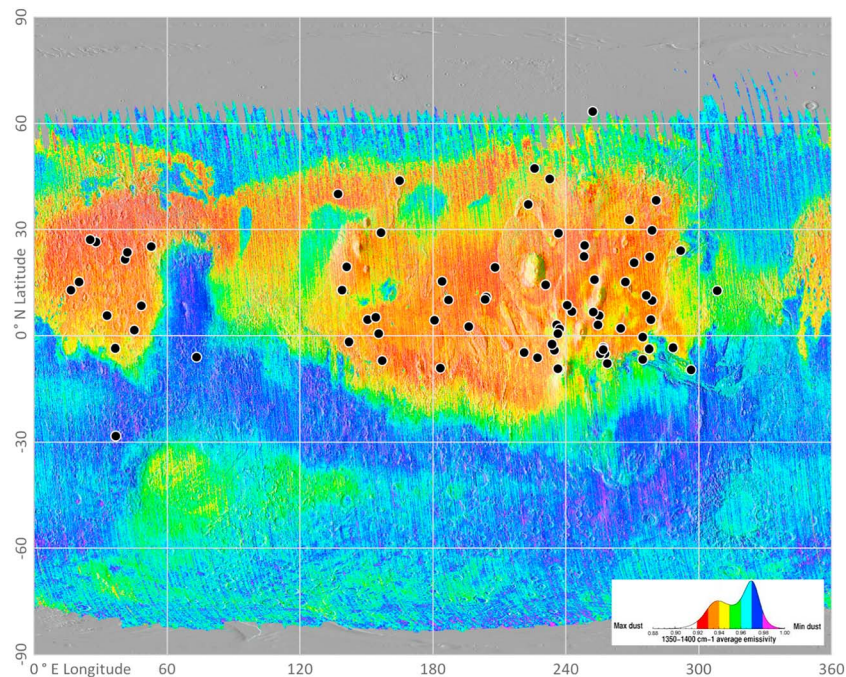


Figure 2. Global map of Mars showing locations of 77 new cluster impact sites selected for study (black dots). The base-map is the Thermal Emission Spectrometer dust cover index (Ruff & Christensen, 2002) over Mars Orbiter Laser Altimeter shaded relief base, courtesy of National Aeronautics and Space Administration/Jet Propulsion Laboratory/Goddard, showing that the majority of sites are in dust-covered areas; this is due to their detection method (Daubar et al., 2013). This map shows only those clustered impact sites studied in this work, not all dated impacts.

young ripples on Meridiani Planum that are estimated to be less than a few million years old. In any case, we know that clusters represent a considerable portion of the currently forming impacts on Mars.

Here we focus on the clustered impacts as their properties have not previously been studied, and they represent a significant fraction of the Martian cratering record at small sizes. We measure and characterize attributes of these crater clusters, such as dispersion and azimuth, to eventually provide insight regarding the seismic signals from clusters and the nature of the impacting bodies.

2. Methods

We measured crater morphometries at 77 new dated impact sites in images from the High Resolution Imaging Science Experiment (HiRISE) on the Mars Reconnaissance Orbiter (MRO), using map-projected RED Reduced Data Records (RDR) at 25 cm/pixel (McEwen et al., 2007). We made the measurements in Environmental Systems Research Institute's ArcMap (ArcGIS) software with the CraterTools add-in (Kneissl et al., 2011). The “fix_jp2” program, supplied by the Geospatial Data Abstraction Library team (<http://trac.osgeo.org/gdal/ticket/2706#no1>), was applied to fix the labels in released HiRISE RDRs in order to import them into ArcGIS with correct latitude and longitude values; without this step, in some cases, the absolute coordinate values could be slightly off. Experience with creating carefully georeferenced maps of landing sites (e.g., Golombek et al., 2017) indicates these map-projected images are typically within a few tens of meters of their true position. Regardless, because we only use the measured latitudes and longitudes to describe the relative positions of craters within a cluster, our results would not be negatively affected without this correction.

A map of the sites studied in this work is shown in Figure 2, and all measurements with the observation IDs of the images used are listed in supporting information Tables S1 and S2.

We selected an initial data set of ~100 new dated crater sites for our study with the goal of incorporating end-members of the various parameters we studied, as well as representation of different types of clusters (e.g.,

large and small numbers of craters; and discrete and dispersed clusters). Thus, our data set is not necessarily statistically characteristic of the entire set of new dated impact sites, which currently number ~700. The most complete set of known dated impacts, in turn, is also not necessarily representative of the true impacting population. For example, the percentage of clusters in the known data set (52%) is most likely higher than the true percentage, because clusters are more likely to be detected from orbit, based solely on geometrical arguments (Daubar et al., 2010). This is because low-albedo blast zones are created by removal or disturbance of a thin layer of high-albedo dust by mobilization forces generated during the emplacement of the crater (Daubar et al., 2016); it is these albedo features that allow for their discovery. These blast zones are ~10–100 times the size of the new craters themselves (Ivanov et al., 2010), with diameters roughly proportional to the square of the crater diameter (Bart et al., 2014). This means clusters will have a disproportionately larger visible footprint than single-crater impact sites. In addition, highly dispersed clusters, where the distance between craters is larger than the diameter of the individual blast zones around each crater in the cluster, will exhibit more low-albedo surface area, since there will be no overlap of blast zones. Thus, it may be that weaker bolides will be preferentially detected, because they are likely to break up at a higher elevation and result in more dispersed final clusters. There should be a falloff in this effect for very weak impactors, which would be entirely obliterated in the atmosphere. Those events would be undetected in orbital images, other than rare cases where only dust was disturbed on the surface but no crater formed. Several rare sites with new dark spots lacking central craters have been found and may be locations where this airburst phenomenon occurred (Daubar et al., 2013; Stevanović et al., 2017). Although this oversampling of clusters and added bias toward more dispersed clusters are likely observational effects, the exact nature and amount of this overrepresentation is unknown.

In some cases, the impact region exhibited preexisting small craters that were not created by the dated impact event. We used two criteria to distinguish these preexisting craters from the new craters at the site. In most cases the fresh appearance of the new craters (i.e., sharp rim, lack of erosion or muted appearance from degradation and eolian processing, and lack of bedforms on the crater floor) was sufficient to distinguish them from older, more degraded, and in some cases partially infilled, preexisting craters. An additional criterion for distinguishing between craters that are part of a new cluster and small, still fresh-looking, but unrelated preexisting craters was their association with the low-albedo blast zones created at the time of impact. Blast zones are not observed around older craters. If an otherwise apparently fresh crater near the dated cluster was not surrounded by a blast zone similar to others in the cluster, it was considered likely to be a preexisting crater and not included in our analysis. Thus, our database is conservative in its inclusion of craters within a cluster.

A lower size limit of 1 m in diameter (four pixels in bin-1 HiRISE RDRs) was used. We consider this the lowest limit of the HiRISE data's ability to resolve craters with sufficient confidence for accurate measurements. In addition, craters <1 m in diameter contribute very little to the total seismic signal of a cluster. Thus, craters with diameters <1 m are not reported or used in our analyses.

We avoided including obvious secondary impact craters (those that form from the ejecta of a primary crater). This includes those with elliptical or irregular planform shapes or those present in chains or subclusters. However, at these small sizes, individual primary craters that are part of a cluster are often difficult to distinguish from secondary craters. Both primary and secondary craters can be present singly or in clusters and can have similarly circular planforms and size distributions; this is particularly true for secondaries located far from their primary craters (e.g., McEwen & Bierhaus, 2006; Melosh, 1989; Shoemaker, 1965). For primary craters in the size range we are studying (~1 to 40 m in diameter), the largest secondaries would be in the range of ~5 cm to 2 m in diameter. This is based on previous studies that determined that diameters of the largest secondaries are ~3–8%, typically 5%, of the primary crater's diameter (Allen, 1979; Bierhaus, 2001; McEwen et al., 2005; Schultz & Singer, 1980; Shoemaker, 1965; Soderblom et al., 1974). For the most part, the hypothetical secondaries in this size range would not be detectable in HiRISE data.

Where possible, the low-albedo blast zones surrounding new craters were also used to differentiate between primaries and secondaries from the same impact. While the orientations of blast zones around primary craters may reflect the direction of the primary impact, the blast zones around secondaries are oriented away from the primary crater. We did identify probable secondaries in some images using this method, which were excluded from the cluster analysis.

Table 1
Cluster Properties

Statistic	Mean	stdev	Range
Number of craters in cluster	34.1	70.3	2–465
Minor diameter of best fit ellipse, $2R_1$ (m)	229.5	462.1	9.9–3,017.4
Major diameter of best fit ellipse, $2R_2$ (m)	431.3	684.7	53.2–4,222.8
Effective diameter, D_{eff} (m)	9.1	5.5	2.1–33.8
Dispersion, D (m)	83.1	121.9	5.9–721.0
Impact angle, ^a from vertical (deg)	62.3	11.8	34.8–85.3
Azimuth, ^a all ($0^\circ = \text{N}$, $90^\circ = \text{E}$, $180^\circ = \text{S}$, $270^\circ = \text{W}$; deg)	20.6	80.1	Full range (1.6–359.6)
Azimuth, ^a well constrained (deg)	50.6	78.2	13.9–359.5

^aImpact angle and azimuth mean and stdev (standard deviation) were calculated using circular statistics (Berens, 2009).

It is still possible we may have misidentified a small number of secondaries that were mistakenly included as a part of the primary cluster or that a small number of primary craters were excluded as misidentified secondaries. This would lead to small errors ($<1\%$) in the timing of separate impacts and estimation of the total seismic energy of a cluster. In rare cases possible secondaries could not be unambiguously differentiated from primaries within a cluster. We excluded those impact sites so as not to contaminate the analyses; one example can be seen in HiRISE image ESP_016203_2195. Thus, our study includes only sites we are reasonably certain are primary clusters and do not include secondary craters.

Measurements were made in ArcGIS of each crater position (areocentric north latitude and east longitude of the center of the crater rim) and diameter (using the three-point method in CraterTools). These results are reported in Table S1. To evaluate the consistency and reliability of our method, results obtained from two investigators in this study (Daubar and Banks) for the same sites were compared and found to be sufficiently similar. Variations in work by both investigators produced statistically insignificant differences in results; diameter measurements of individual craters differed by 0.5–0.6 m (~ 2 pixels) for only 5 out of 50 craters, with all others differing by <0.4 m; this small variability has a negligible effect on our results.

Our measurements of craters in each cluster were used to find the best fit ellipse to each distribution of craters. For clusters containing more than five craters, this best fit ellipse was determined using a solver based upon the Khachiyan algorithm (Todd & Yildirim, 2007) to find the ellipse with a minimum area encasing the location of the majority of craters in the cluster. We allow the ellipse fit to vary with a tolerance up to 10% of the point distribution. This algorithm uses a singular value decomposition of crater locations

(where there are more than five points in the distribution) to compute the set of eigenvectors that describe the orientation (azimuth), as well as the eigenvalues of the minor (R_1) and major axes (R_2) of the best fitting ellipse. Since most crater distributions are not fully elliptical, and outliers can strongly influence a single solution, we use a bootstrap method (Efron & Tibshirani, 1986) to derive uncertainties for the ellipse fit. The bootstrap operates by selecting a random subset of crater locations within a particular cluster, allowing replication of individual crater locations. Then we apply the Khachiyan algorithm to find the minimum area ellipse of the randomly chosen subset. This is repeated 300 times to form a bootstrap distribution ($N = 300$) of potential ellipse azimuths and radii that describe the data set and is used to construct the mean and standard deviation our crater cluster parameters (azimuth, radii, and ellipticity).

This best fit ellipse is used to determine the direction of the impact. A low ellipticity ($e = 0$), nearly circular result is assumed to be produced from a near-vertical impact angle, while elongation of the ellipse ($e > 0$) is

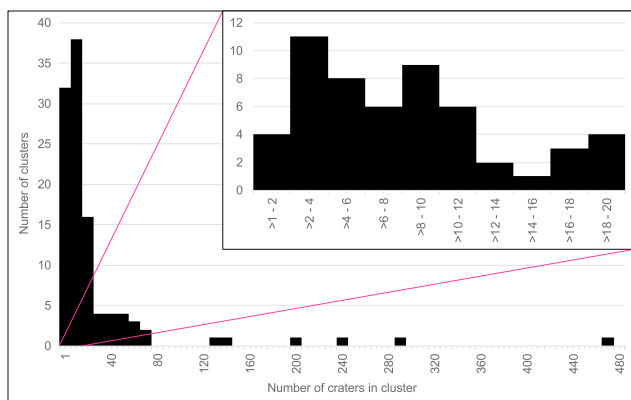


Figure 3. Histogram of number of craters in clusters. Clusters in the study contain from 2 to 465 individual craters, but most (64%) have 10 or fewer craters.

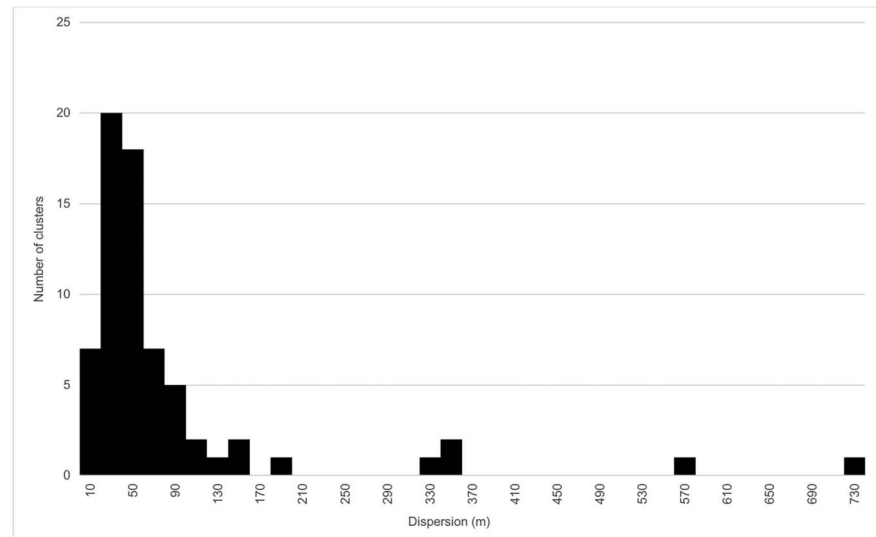


Figure 4. Histogram of dispersion values of 68 impact clusters. Dispersion bins (20 m wide) are labeled in the center, so, for example, the bin labeled 50 m includes clusters with $40 < D \leq 60$ m. The most populous bins are 20–60 m, which include over half of the clusters; the majority (74%) of the clusters studied have dispersions between 20 and 100 m.

assumed to result from lower incoming angles of the bolide. The ratio of the two axes of the best fit ellipse are used to estimate the angle of the impact from vertical (θ):

$$\theta = \cos^{-1}(R_1/R_2) \quad (1)$$

where R_1 is the minor axis radius of the ellipse and R_2 is the major axis radius. In this estimate, any spreading of the fragments during passage through the atmosphere is assumed to be the same in the along- and across-track directions. Such spreading effectively cancels out in equation (1). In other words, if the resulting craters are spread out by some factor $a > 1$, equation (1) becomes $\theta = \cos^{-1}(aR_1/aR_2) = \cos^{-1}(R_1/R_2)$; thus, spreading has no effect on the estimated impact angle. Differential spreading caused by varying atmospheric drag experienced by different-sized fragments is not considered in this simplified estimate. Impact angle, measured in degrees off vertical, is reported in Table S2.

The direction of R_2 , the major axis of the best fit ellipse, is taken as the initial azimuth. However, there is a 180° ambiguity as to the direction of the resulting azimuth. We found no evidence of cross-cutting relationships or other indicators of relative timing that would allow us to determine which impact may have formed first within a cluster, indicating the true impact direction. We considered using the orientations of the blast zones to resolve this ambiguity; however, such an approach has a number of problems. (1) The formation mechanisms of the blast zones are not fully understood. For example, low-angle ejecta “jetting” or atmospheric blast/surface interactions may be involved, which do not necessarily indicate the downrange direction. (2) It is difficult in most cases to differentiate the influence of impact direction from that of surface winds acting after the time of impact. After initial discovery in Context Camera (CTX) data, the first HiRISE image is typically acquired months to years after the impact occurred. During this time local winds may redistribute surface dust and create wind streaks and other eolian features. (3) Even if the first two effects were understood, only a small number of the sites exhibit an unambiguous directionality in the blast zones themselves. A brief visual survey revealed only 6 out of 150 new impact sites (4%) had a clear directionality to the blast zone. Thus, the blast zones do not help resolve the 180° ambiguity in our measured impact azimuths.

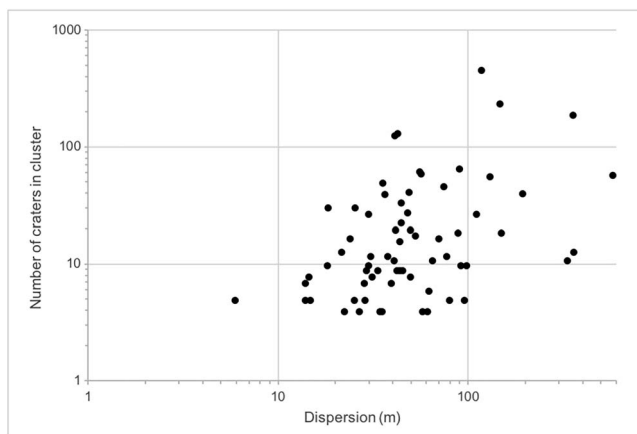


Figure 5. Dispersion of impact clusters plotted against the number of craters within the cluster (note log-log plot axes). There is a weak correlation between the number of craters and the dispersion ($\rho = 0.44$).

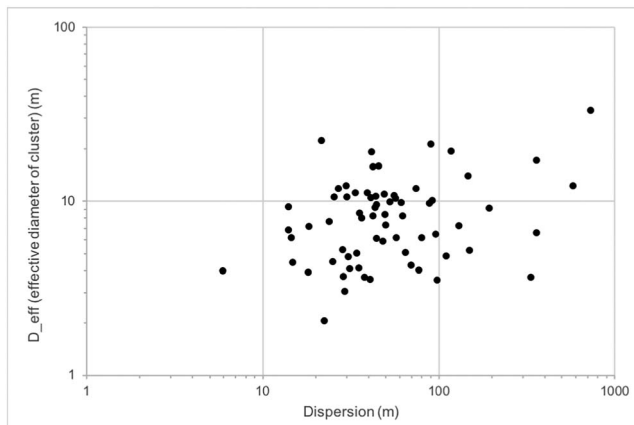


Figure 6. Dispersion of impact clusters plotted against the effective diameter (D_{eff}) of the cluster (note log-log plot axes). There is a weak correlation between the effective diameter and the dispersion ($\rho = 0.45$).

are more dispersed or spread out on the surface. This observational parameter could possibly be connected to the breakup process itself, the fragments' passage through the atmosphere, or various other aspects of the impact. We define dispersion, D , as the standard deviation of distances (in meters) between each possible combination of pairs of craters in the cluster. This definition avoids biasing by lone outliers, as would be done if the overall “size” of the cluster were used. Dispersion values are reported in Table S2.

3. Results

3.1. Cluster Size

Our compiled data set included 77 clusters of craters (Table 1), each comprising from 2 to 465 craters (Tables S1 and S2). The length of the best fit ellipses (long axis; twice the major radius, R_2) to the clusters range from

53 m to 4.2 km, and the widths (short axis; twice the minor radius, R_1) range from 10 m to 3.0 km. The average across all cluster ellipses is 229 m for the smallest dimension by 431 m for the largest dimension. We find that the number of craters within a cluster is highly skewed (Figure 3); 64% of clusters have 10 or fewer craters.

3.2. Dispersion

The dispersion (D , as defined above) measured for our data set ranges from 5.9 to 721 m. The distribution of dispersion values is strongly peaked (Figure 4), with a median dispersion of 43.6 m. There is a weak correlation between the number of craters in a cluster and the dispersion (Figure 5; Pearson's correlation coefficient $\rho = 0.44$). Most clusters have a dispersion of ~ 40 m, regardless of the number of craters in the cluster. Dispersion is also weakly correlated ($\rho = 0.45$) with the effective diameter of the cluster (defined as $D_{\text{eff}} = (\sum_i D_i^3)^{1/3}$; Daubar et al., 2013; Malin et al., 2006; Figure 6). Seventy-four percent of clusters have D/D_{eff} less than 10.

3.3. Azimuth

The azimuths of the impact clusters span the full range of possible directions (Figure 7). Statistics on the azimuth histogram were done using circular statistics using the implementation of Berens (2009). The resulting mean (21°) has little meaning with such a large standard deviation (80°). The distribution has a Rayleigh Z test p value of 0.97, indicating no significant departure from a random distribution.

Impacts close to vertical form nearly circular clusters; in these cases, an azimuth is difficult to distinguish. In order to consider only well-

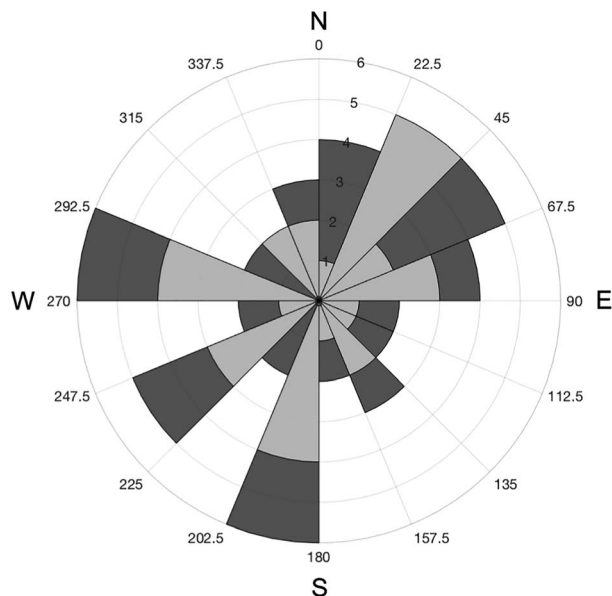


Figure 7. Circular histogram (“rose diagram”) of azimuths (degrees from north = 0°) of the best fit ellipses of impact clusters. To resolve the 180° ambiguity in this method, we examined the location of the largest crater(s) in the cluster relative to the ellipse center. All measured clusters ($N = 55$) are shown in dark gray; clusters with more well-constrained azimuths ($N = 32$) are in light gray. There is no preferred impact direction among these clusters.

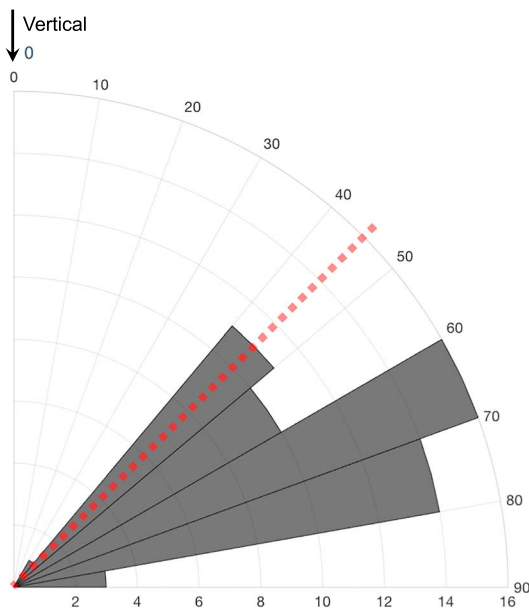


Figure 8. Histogram of estimated impact angle θ (degrees from vertical) for 55 new dated impact clusters. Most impact angles are in the range 40–80°. This is shallower than the most likely impact angle (red dashed line) of 45° (Shoemaker, 1961), which is likely an observational bias (see section 4).

model that imparts a horizontal velocity to the resulting fragments would result in higher dispersion at lower elevations.

However, this correlation between the dispersion of impact clusters and topographic elevation is not observed in a straightforward way in our data set (Figure 9; $\rho = -0.12$). Nor do we see any correlation between the number of craters in the cluster and the elevation of the site ($\rho = -0.08$) as was indicated in preliminary studies (Ivanov et al., 2009). However, if the highest elevations (6–10 km) are excluded (which also have a very small number of clusters), there is a correlation between the average of dispersion (rather than individual sites) and elevation: the ± 2 -km moving average of dispersion decreases with increasing elevation ($\rho = -0.94$; Figure 9). The dispersion of impact clusters decreases from an average of 155 ± 48 m for impacts at –6- to –2-km elevation, to an average of 47 ± 7 m for impacts at 4- to 8-km elevation. These results could support a model such as that proposed in Hartmann et al. (2018) where the weakest impactors fragment at very high altitudes (>6 km). Those impactors strong enough to survive deeper into the atmosphere show the expected behavior of increasing dispersion with elevation. The variation around the average also increases at lower elevations, as demonstrated by the larger error bars at lower elevations in Figure 9. This could be due to variations in the initial impactor strength.

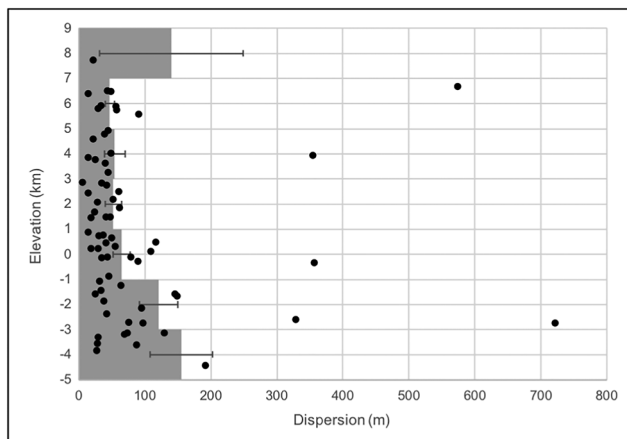


Figure 9. Dispersion of impact clusters plotted against elevation. Black circles mark values for individual sites. Gray bars every 2 km of elevation show the moving average over all values ± 2 km (e.g., the gray bar at 4 km shows the average of all dispersions with elevations between 2 and 6 km), and error bars indicate the standard error ($\text{stdev}/\sqrt{n}$) over the same range. There is no apparent straightforward correlation between individual site dispersion and elevation for all clusters ($\rho = -0.12$). However, if the highest elevations (uppermost moving average that includes 6- to 10-km elevation) are excluded, there is a correlation ($\rho = -0.94$) between the moving average of dispersion and the elevation, as seen by the decreasing value of the moving average of dispersion (gray bars) with increasing elevation.

constrained clusters, we separately plot those with standard deviations in calculated azimuths within the bootstrap method of less than 30°. The distribution of these well-constrained azimuths is similarly random as that of the full data set: mean 51°, standard deviation of 78°, and p value of 0.86 (Figure 7).

3.4. Impact Angle

Ellipticities of the best fit ellipses, defined as $(R_2 - R_1)/R_2$, range from 0.18 to 0.92 and average 0.54. The resulting estimated impact angles span 35–85° from vertical, with a mean of 62° and a median of 65° from vertical (Figure 8). This is considerably shallower than the most common impact angle of 45°, which is expected to be the most likely impact angle from a random distribution of incoming impactors based on geometric arguments (Shoemaker, 1961).

4. Discussion

4.1. Fragmentation in the Atmosphere

Higher atmospheric pressure at lower altitudes would be expected to cause more fragmentation and result in higher dispersion. In addition, a successive or cascading fragmentation model (Artemieva & Shuvalov, 2001; Bland & Artemieva, 2006) would lead to more widely spread clusters at low altitudes, as a longer passage through the atmosphere would give time for more fragmentation events. In fact, any fragmentation

4.2. Azimuth

The azimuths of impact clusters do not exhibit a strong trend that can be distinguished from a random distribution (Figure 8). Several effects might be expected to lead to an east-west trend in azimuths (more clusters with azimuth values near 90° and 270°). First, the rotation of the planet during the impact could cause some east-west “smear” between the first and last fragments to impact the surface. However, we calculate this to be a small effect: A group of fragmented impactors coming in at 10 km/s at 45° from the vertical with a final cluster downtrack diameter of 300 m would experience only 0.021 s between the first and last impact (see section

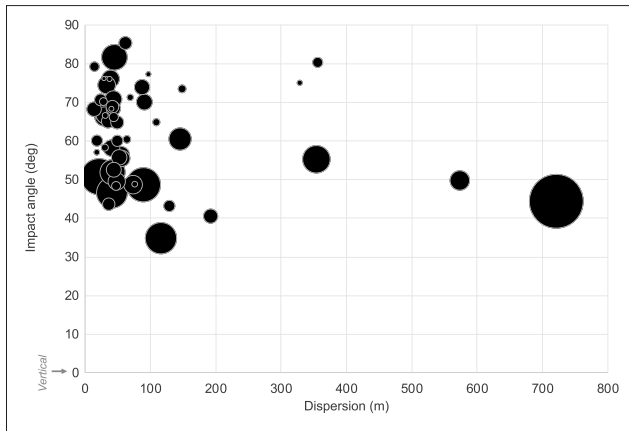


Figure 10. Dispersion of impact clusters plotted against the impact angle (degrees from vertical) of the cluster. The size of the symbols is scaled to the effective diameter (D_{eff}). Although there is a mix of sizes at all angles, clusters with larger effective diameters tend to have higher dispersion and more vertical impact angles.

4.4). At the equator, Mars rotates only 5 m in this time, or 1.7% of the cluster diameter. Even if atmospheric deceleration were taken into account, the effect is still small. Small impactors are expected to be decelerated the most, so, for example, a 0.1-m-diameter impactor entering the atmosphere at 10 km/s might be slowed to as little as 5 km/s before impact (Williams et al., 2014). At this speed, the first and last impact would be separated by only 0.04 s, during which time Mars would rotate ~ 10 m, or only $\sim 3\%$ of the diameter of the cluster. Therefore, we do not expect east-west elongation of clusters as a result of the planet's rotation to be significant.

The second factor that might be expected to affect azimuths is the orbital parameters of the impacting population. Asteroidal bodies in low-inclination orbits might have a stronger east-west trend than cometary bodies with randomly distributed inclinations. The majority of Mars-crossing asteroids have low inclinations $<10^\circ$ (Michel et al., 2000) or $<30^\circ$ (JeongAhn & Malhotra, 2015). The lack of an east-west trend in azimuths may mean that in-plane asteroidal fragments do not dominate the current impacting population at Mars. However, the dynamics of those bodies after gravitational capture are complex. Earth impactors have a distribution of azimuths uniformly distributed over all possible values, even though they are sourced mainly from low-inclination orbits (Rumpf et al., 2016; Shustov et al., 2017). Likewise, a low-inclination Mars-impacting population could also produce a uniform distribution of impacts coming from all azimuths. Therefore, we cannot necessarily make a clear connection between the impact azimuths we measure and the orbital parameters of their parent bodies before gravitational capture by Mars.

4.3. Impact Angle

The impact angles we observe are generally shallower than expected. Based on geometrical arguments, it is expected that the distribution of impacting angles should peak at 45° (Shoemaker, 1961; Figure 9). As with azimuth angle, our estimate of impact angle may be degraded for near-vertical impacts where the best fit ellipse becomes closer to circular. This could result in underreporting the number of impacts at low (near-vertical) impact angles. The shallower-than-expected impact angles we report here could also be the result of an observational bias: More oblique impacts create larger darkened blast zones that would be easier to spot in orbital images. In contrast, nearly vertical impacts would have a smaller footprint and thus may be more difficult to detect in orbital images. Another factor potentially influencing our impact angle results is that in more oblique impacts, impactors have a longer path length through the atmosphere and thus experience more aerodynamic stress and are more likely to fragment. Therefore, clusters are both more likely to form and more likely to be identified when the impactors have shallower impact angles. Following the same reasoning, impactors coming in at very shallow impact angles may be more likely to be destroyed completely due to their longer atmospheric path lengths, so we may be underobserving those at the very shallowest end of the distribution. Likewise, the smallest fragments of those clusters may be destroyed, biasing shallowly impacting clusters toward more sparse clusters.

Combining these effects, there may in fact be a detection peak in measured impact angles. Impacts formed at the steepest angles are the least obvious in images, and impacts with the shallowest angles are most likely to be destroyed in the atmosphere. However, this effect is difficult to separate from the geometric expectation of a peak in the distribution of impacting angles at 45° .

As seen in Figure 10, clusters with larger effective diameters (larger impactors) tend to have higher dispersion and more vertical impact angles. Steeper impact angles could be due to the observational biases discussed above. The correlation between impactor size and dispersion is the same seen in Figure 6 and could be related to more availability of mass to

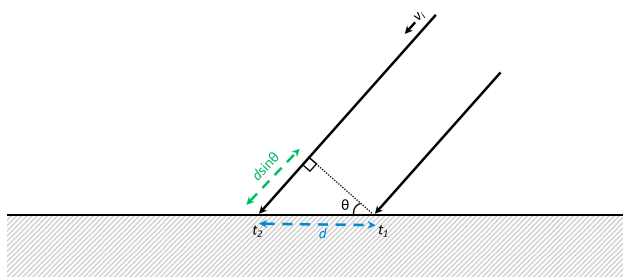


Figure 11. In a cluster of fragments impacting at velocity v_i and impact angle θ , the first and last fragments at a distance d from each other impact the ground at times separated by $d \sin \theta / v_i$.

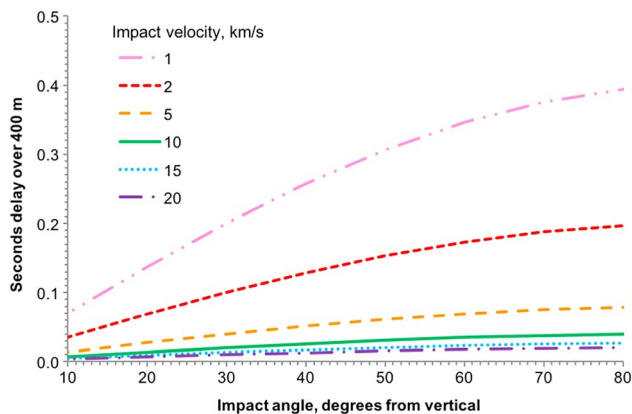


Figure 12. Plot of the difference in impact time, Δt , between the first and last fragments impacting in a 400-m-long cluster down-track, versus the impact angle from vertical. Results are shown for various impact velocities. For typical impact velocities of 10 km/s, time delays are always less than 0.04 s. Bolides would have to be decelerated to $< \sim 2$ km/s (sub-hypervelocity impacts) and/or impact at shallow angles in order to approach a Δt of even 0.1 s.

fragment, perhaps with a higher probability of prior fractures, with more cumulative transverse velocity imparted during fragmentation.

4.4. Indications of Impactor Density From Fragmentation Modeling

Preliminary atmospheric fragmentation modeling of a few new dated clusters (Ivanov et al., 2008) found that the original densities of the impactors ranged from 1.8 to 3 g/cm³ for most of the small set of clusters they analyzed. A few clusters, mainly their “overpopulated” “Type 3” clusters with >400 individual craters, gave model results of low impactor densities ~ 1 g/cm³, indicating possible cometary material. Our detailed study of new dated clusters shows crater size frequency distributions that for the most part fall within the range of types presented in Ivanov et al. (2008). If the progressive fragmentation model that Ivanov et al. (2008) used applies, then presumably the densities of the impactors forming our clusters also fall within the range they found, ~ 1 –3 g/cm³. Only one of our clusters has >400 craters in it, which might be categorized as the Ivanov et al. (2008) overpopulated Type 3 cluster. In their modeling, formation of these types of clusters requires a very low density, perhaps cometary, impactor. However, these are merely rough comparisons based on loosely defined “types,” and more detailed fragmentation modeling is needed in

future work that will better constrain the densities, strengths, and progression of fragmentation events of these impactors.

4.5. Relative Timing of Impacts Within a Cluster

A group of impactors encountering the Martian surface to form a cluster will experience a variation in impact time among the individual fragments, unless all fragments come in exactly simultaneously in a perfectly vertical impact. This timing difference can be calculated for various impact velocities (v_i), angles (θ), and cluster diameters (d). Close to the ground, the individual fragments can be assumed to be impacting at the same angle, θ (Figure 11). We also assumed that all fragments would have the same velocity, although in reality larger fragments will experience a different amount of atmospheric drag relative to smaller fragments. At the time the first fragment impacts the ground, t_1 , the last fragment still has the distance $d \sin \theta$ left to travel before it impacts at time t_2 . This last fragment crosses this distance at velocity v_i , so $\Delta t = t_2 - t_1 = d \sin \theta / v_i$.

For a typical 400-m-diameter cluster formed by fragments impacting at 45° at 10 km/s, the delay between the first and last impacts, Δt , is only 0.03 s (Figure 12). More shallow impact angles and slower impact speeds increase this time. Atmospheric deceleration affects the smallest and fastest impactors the most (Williams et al., 2014), and deceleration to sub-hypervelocity speeds is possible, although we might not expect these impacts to form recognizable craters. At 2-km/s impact speed, the slowest that might possibly be expected to create a high-velocity impact crater, our largest cluster (4.2 km in diameter) might have formed from impacting fragments with a Δt of 2 s, if they impacted at an angle of 80° off vertical, or nearly horizontal—an unlikely scenario (e.g., Chappelow & Golombek, 2010). Thus, we conclude that seismic activity resulting from clustered impacts will take the form of a distributed source, with individual impacts closely spaced (<100 ms) in time. This result will be applied in the seismic modeling of these clusters done in the follow-on study.

5. Conclusions

Approximately half of observed current impacts on Mars form clusters of multiple craters that form nearly simultaneously. Our study of 77 of these new dated (observationally constrained) impact clusters shows general trends for these fragmented impactors. Most clusters in this study comprise small numbers (<10) of craters. Cluster dispersion varies widely from a few to a few hundred meters, with most clusters having a dispersion of tens of meters. The dispersion of clusters does not correlate with elevation, possibly indicating progressive fragmentation models of atmospheric breakup should be reevaluated. If the highest elevations

are not included in the analysis, however, clusters are generally more dispersed at lower elevations. This could be explained by initial breakup of the weakest impactors at very high elevations, and then progressive fragmentation at lower elevations, with wide variations caused by differing individual strengths of impacting bodies. Clusters with larger effective diameters tend to have higher dispersion and more vertical impact angles.

The azimuths of cluster strewn fields are randomly distributed. This cannot be directly connected to a low-inclination, asteroidal population of impactors. Impact angles tend to be slightly shallower (closer to horizontal) than expected based on purely geometric arguments, which may be the result of observational biases that favor detection of clusters resulting from shallow impacts, which thus are more widespread and more visible from orbit.

These cluster properties will be used in upcoming studies to model seismic signals resulting from current cratering on Mars (Schmerr et al., 2016). This work will help address the question of seismic detectability as a function of impact size and distance, which for clusters is affected by the dispersed nature of the impact. Ultimately, we will address the question of how atmospheric fragmentation affects the seismic detectability and character of impacts on Mars and elsewhere.

In future work, these cluster properties will also serve as important constraints for several key areas of crater studies. For example, results reported here can be used to estimate how, when, and where the bolides broke up in the atmosphere (e.g., Ivanov et al., 2009; Popova et al., 2007; Williams et al., 2014), informing fragmentation processes in the Martian atmosphere (e.g., Daubar et al., 2017) and properties (strength and density) of the impactors themselves. Our results can also be used to aid in differentiating older primary clusters from secondary clusters and help clarify aspects of crater count chronometry (e.g., Hartmann et al., 2018).

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