CRATER CLUSTERS ON MARS: IMPLICATIONS FOR ATMOSPHERIC FRAGMENTATION, IMPACTOR PROPERTIES, AND SEISMIC DETECTABILITY. Ingrid J. Daubar[1], M.E. Banks[2], N.C. Schmerr[3], M.P. Golombek[1], W.K. Hartmann[2], E.C.S. Joseph[2], K. Miljkovic[4], O. Popova[5], and N. Teanby[6]. [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA (ingrid.daubar@jpl.nasa.gov), [2]Planetary Science Institute, [3]University of Maryland, [4]Curtin University, [5]Institute for Dynamics of Geospheres RAS, [6]University of Bristol.

Introduction: Half of the currently occurring impacts on Mars occur in the form of clusters because the impactor fragments in the atmosphere [1, this work]. The characteristics of these clusters inform fragmentation processes in the martian atmosphere, properties of the impactors themselves [2,3], seismic detectability [4] for future seismic investigations such as InSight [5], and statistics of secondaries and crater chronometry [6,7].

Methods: We have assessed ~100 new clustered impact sites dated with before and after images, mapping and measuring individual craters in HiRISE [8] images. Here we report statistics of craters within clusters: strewn-field azimuths indicating impact direction; ellipticity of clusters, indicating impact angle; and size and dispersion of clusters, indicating combined effects of bolide strength and elevation of breakup. The overall fraction of clusters as a function of elevation is also presented, both for new dated craters and for older, non-dated primary crater clusters [7].

Results:

Impact direction: The azimuth of the impact direction was estimated using the orientation of the long axis of the best-fit ellipse to each new dated cluster of craters (Fig. 1). Ejecta, albedo patterns, and crater sizes that might indicate impact direction may improve these estimates. We do not see an east-west trend to the impact directions, as might be expected if the impactor population were dominated by low-inclination impactors such as asteroids, versus a high-inclination cometary population. Mars-crossers tend to have lower inclinations [9], so these observed azimuths are not yet fully understood.

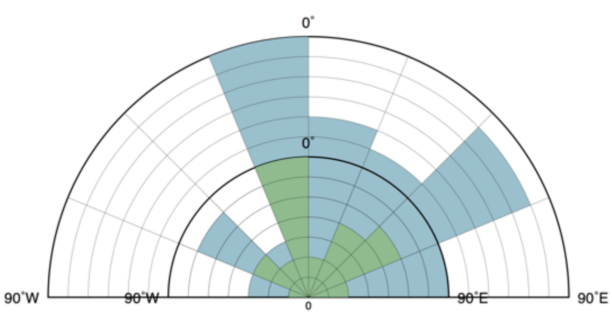

Fig. 1. *Rose diagram of azimuths (degrees from North=0°) of best-fit ellipses of clusters. This method has a 180° ambiguity, so only half of the rose is shown. All measured clusters (N=61) are shown in blue; clusters with more well-constrained azimuths (N=26) are in green.*

Impact angle: The angle of impact from vertical, θ, was estimated using the short (a) and long (b) axes of the best-fit ellipse to new dated clusters, where $\cos(\theta) = a/b$. We see a peak in θ ~50-80° (Fig. 2), more shallow than the expected 45° [10]. This could be a result of an observational bias: the more oblique the impact, the larger the footprint of the cluster appears from orbit.

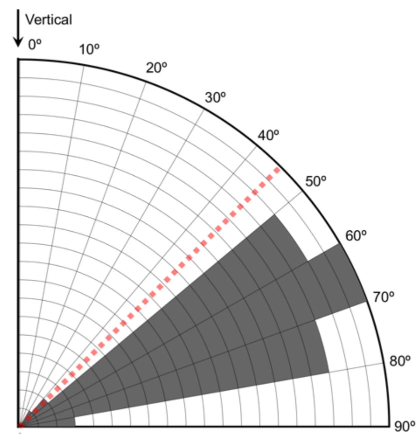

Fig. 2. *Histogram of estimated impact angle θ (deg from vertical) for 61 new dated clusters. Most observed impact angles are in the range 50-80°, whereas the most common expected impact angle (dashed red line) is 45° [8].*

Dispersion: As a measure of the compactness of a cluster, we define dispersion (D) as the standard deviation of distances between each pair of craters in the cluster. Dispersion ranges ~6-573 m, but 67% of the new dated clusters have D<60 m (Fig. 3). Clusters with the same number of craters vary widely in D, showing that dispersion is not dependent on the number of craters in the cluster, as might be expected. We also do not see a

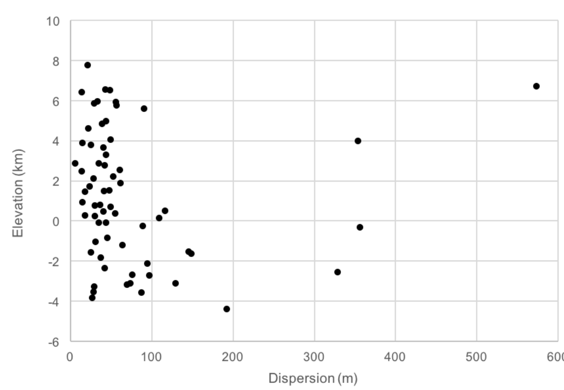

Fig 3. *Dispersion (D) of 67 new dated clusters vs. elevation.*

correlation of dispersion with elevation (Fig 3), as might be expected due to higher atmospheric pressure at lower elevations leading to more fragmentation events. A progressive fragmentation model [*e.g.* 11,12] also predicts more breakups at lower elevations given the longer time of flight, contradictory to these observations.

Clusters with elevation: We examined the fraction of all new dated impacts that form clusters (vs. single craters) at different elevations (Fig. 4). Among well-represented elevations, there is a surprising trend of more clusters forming at higher elevations.

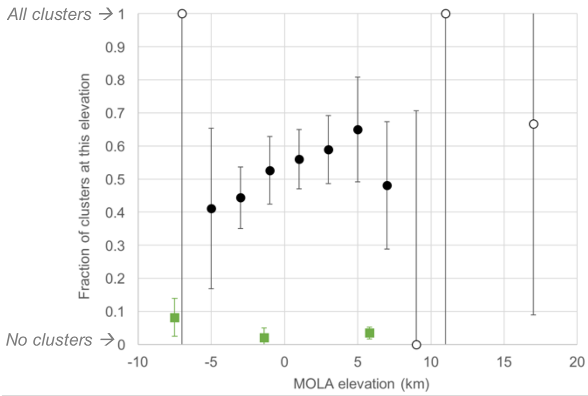

Fig. 4. *Fraction of impacts forming clusters as a function of elevation. 521 new dated (black circles) and 4808 older (green squares) impact sites are included. Error bars are* $1/\sqrt{N_{tot}}$*. Solid symbols are well-represented; open symbols mark elevation bins with* $\leq$*3 impacts.*

Among non-dated impacts, a much smaller fraction of identifiable clusters is present on older surfaces [7,13] (green squares in Fig. 4). Although this study was inconclusive in terms of an elevation trend, in both studies, primary clusters were identified at the highest elevations, indicating that fragmentation events are occurring in the martian atmosphere above 18 km.

Implications:

Fragmentation: The pancake model [14-18] approximates the fragmentation of impactors, predicting larger impactors form a single crater and smaller impactors ablate or decelerate enough to not form a resolvable crater [17]. Alternatively, data on terrestrial observations translated to Mars [7] suggest that up to about 60% of impactors would have fragmented to some extent.

Using the pancake model, estimated impactor sizes at entry [17] when compared to cluster effective diameters suggest multiple fragmentation events along the flight path. However, multiple fragmentation events at high elevations in the thin martian atmosphere seem unlikely. In reality, a combination of both mechanisms (pancake and progressive fragmentation) are likely contributing. Future work will use these new data on clusters to investigate this discrepancy, modify existing fragmentation models to match our observations, and constrain impactor strength and velocity; this in turn will affect the seismic signals of the impacts.

Impactor strengths: The trend of more currently occurring fragmentation at higher elevations (Fig. 4) [7] suggests complete disintegration and loss of weak impactors and their fragments after high-altitude breakup events; possibly only the strongest impactors and their fragments reach low elevations in the current atmosphere. A significant portion (~30-60%) of impactors have very low bulk strengths, ≤0.7-1.2 MPa [16,17], consistent with the bulk strengths of terrestrial impactors [19]. This could be related to the high-inclination source population we see, perhaps consisting of weaker cometary or chondritic material.

Seismic detectability: Clusters have smaller peak amplitudes and more short period energy in their source spectra. They also produce a more diffuse seismic signal and make it more difficult to identify P wave arrivals. This will add uncertainty to the identification of source location, but will allow us to predetermine if the impact craters are more readily detectable by imaging of the surface. The seismic signal of more dispersed clusters will be less detectable than the impact of an intact bolide and reduce the overall number of impacts InSight can expect to detect at Mars.

Conclusions: These studies of martian impact clusters reveal a currently impacting population that is not sourced from prominently low-inclination orbits and that impact more shallowly than expected. A large fraction of these impactors are weak and break up at high altitudes in the atmosphere. Thus when clusters do form, they are more likely to be at higher elevations. This fragmentation of impactors will negatively affect the seismic detectability of impacts on Mars, so it is important to understand the details of this process.

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