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Evidence for ice in the ejecta flows of Hale Crater, Mars

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Introduction: Hale Crater is located on the north-eastern rim of Argyre Basin (35.7°S, 323.6°E and has been dated to 1 Ga (Early to Middle Amazonian; Jones et al., 2011). This complex crater is elliptical (125 km across compared to 150 km wide), which can be explained by an oblique trajectory of an impactor from the South-East. This hypothesis is supported by the asymmetrical expression of its central peak and ejecta blanket (Jones et al., 2011). Its ejecta and interior show evidence for an ice-rich composition of the target surface: the ejecta are lobate and bear channels, and the interior is pervasively pitted with alluvial fans (El-Maarry et al., 2013; Jones et al., 2011; Tornabene et al., 2012). The ejecta also hosts conical mounds. Here we test the hypothesis that these mounds are “molards”. Molards are conical mounds of debris that are formed by the loss of cementing ice from frozen blocks that have been transported in landslides in periglacial environments on Earth (Morino et al., 2019). We suggest that the conical mounds in the Hale ejecta result from the degradation of blocks of ice-cemented ground transported by the ejecta flows.

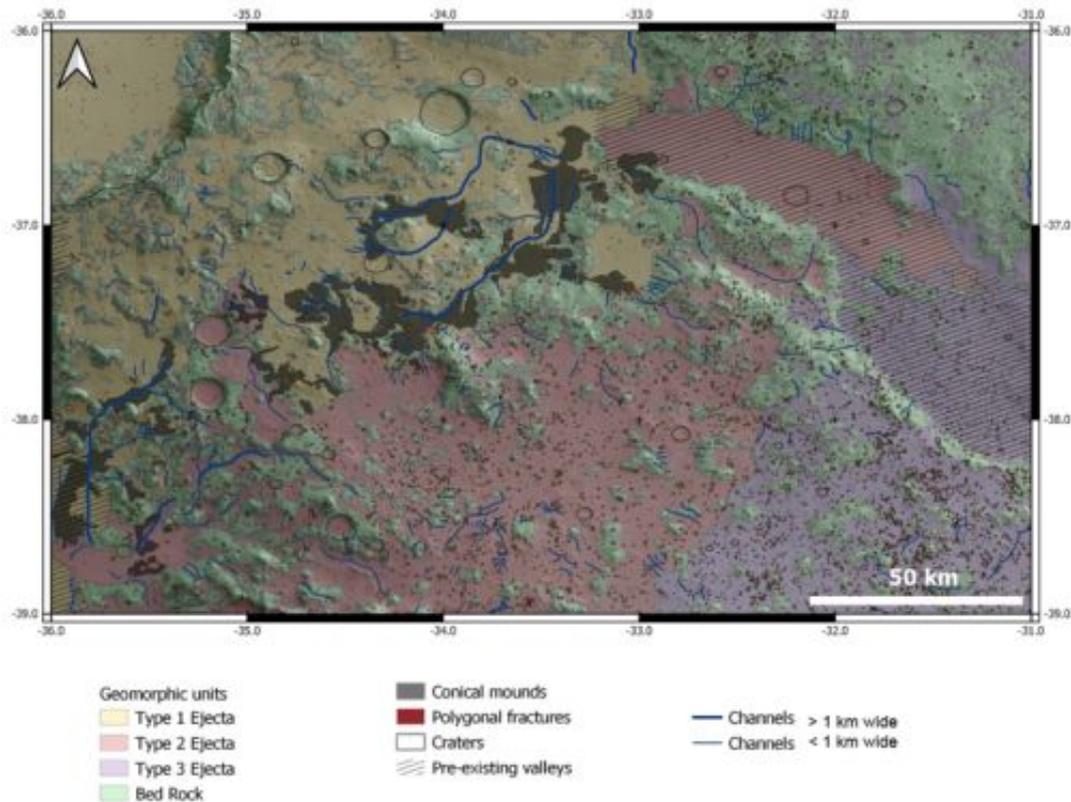


Figure 1: Geomorphic map of the South-East area of Hale Crater at a scale of 1:1.3M.

Approach: We have performed a regional and local analysis of the geomorphological setting, morphometry and morphometrics of the conical mounds in the Hale Crater ejecta. We focussed on a study area (240x180 km) in the South-East part of the Hale Crater ejecta (-36.0° – -39.0° N, 36.0° – 31.0° W), where the majority of mounds are found. The regional map was based on 25 m/pix images from the High Resolution Stereo Camera (HRSC on Mars Express). The associated Digital Elevation Models (DEMs) have a spatial resolution of 125-150 m/pix. The HRSC images were used as a base for georeferencing 25 Context Camera images at 6 m/pix (CTX on Mars Reconnaissance Orbiter). Using these data, we refined the Jones et al. (2011) map of the ejecta deposits and channels. We mapped all craters with sharp rims that were filled with the ejecta materials, in order to estimate the ejecta thickness by comparing the measured (filled) depth of the crater with the expected depth using the theoretical depth-to-diameter relationship.

High Resolution Science Imaging Experiment (HiRISE on Mars Reconnaissance Orbiter) data at 25-50 cm/pix cover limited zones, and we used two stereo-generated elevation models to perform detailed morphometric study of the mounds. We used closed 1 m contour lines to define the outer boundary of individual mounds. From this polygon, we calculated the mound diameter and the maximum elevation pixel, and thus the cone-height. We calculated flank slopes using profiles connecting the highest point of the cone to this outer-boundary. In the analysis presented here, we have used two terrestrial analogues, those in northern Iceland already presented in Morino et al. (2019) and Mount Meager in Canada (Roberti et al., 2017).

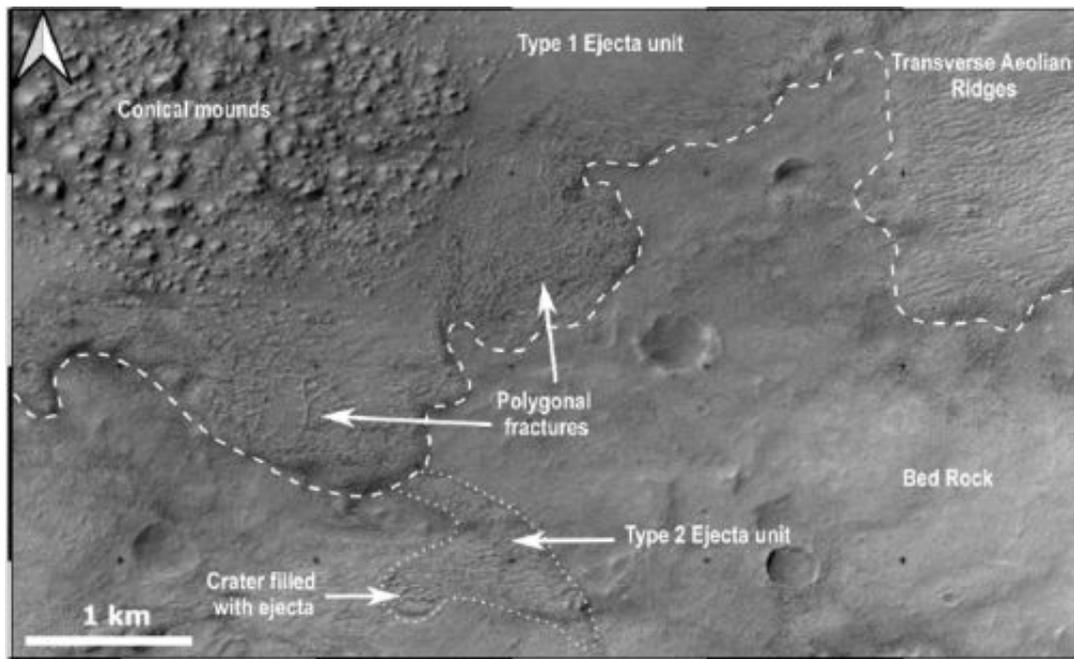


Figure 2. Context view of Hale Crater ejecta conical mounds and associated landforms.

Results: The conical mounds in the Hale Crater ejecta are restricted to the inner ejecta, which we have found to be on average 65 m in thickness (Fig. 1). The mounds are concentrated around the channels formed in the inner ejecta and towards its outermost limit (Figs. 1,2). A lower frequency of superposed hundred-metre craters on this part of the ejecta suggests that auto-secondaries were not preserved as this ejecta remained fluid for a prolonged time after the impact. We have found an intimate association between mounds and channels, lobate margins, polygonal ridge patterns and pitted surface of the ejecta – all pointing to a water-rich debris or mud flow. Our comparisons to the Mount Meager debris avalanche support this assertion, where channels, lobes and mounds are also found in a similar spatial arrangement (Fig. 3).

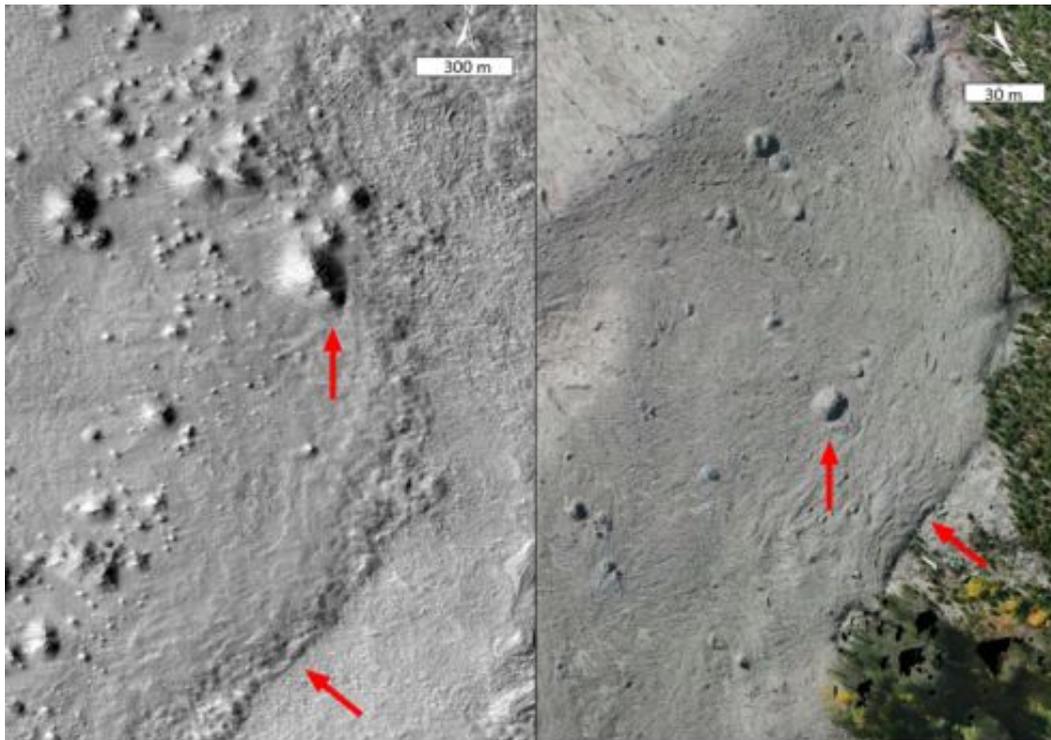


Figure 3: Comparison between candidate molards in Hale crater ejecta, left, and molards in Mount Meager, right.

We analysed the morphometrics of 2175 conical mounds in the Hale ejecta, finding diameters between 4 and 238 m (median 26-38 m) and heights between 1 and 53 m (median 5-7 m). Flank slopes ranged from 2 to 42° (median 13-22°; Fig. 4). Compared to a limited sample of 40 molards in Iceland, the conical mounds in the Hale ejecta are larger in spatial scale by one order of magnitude, with Icelandic molards being only up to 22 m in diameter, but usually only a few metres. As the scale of the molards on Earth is thought to scale with the size of the initial ice-cemented block, this result can be explained by blocks being initially several tens of metres to perhaps 100 m in size in the Hale ejecta (consistent with the 65 m average ejecta thickness). The conical mounds in the Hale ejecta have slopes at the lower end of those expressed by Icelandic molards, whose median is 16-35° (Fig. 2), which could be attributed to their extended exposure at the surface causing a decline in the flank slopes. Further work includes comparing to a larger sample of terrestrial molards of varying ages in Greenland and Canada, where we will particularly focus on the range of shapes expressed by molards.

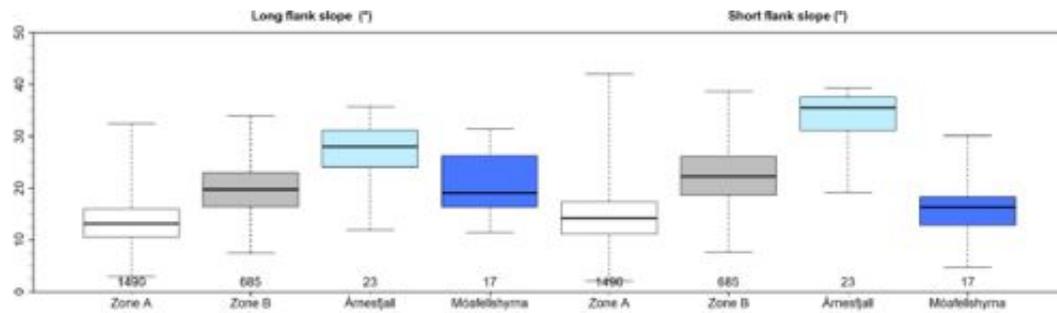


Figure 4: Flank slopes of conical landforms on Earth and Mars, where the number of measurements is given above the name of each site. Hale Crater zones A and B are represented in white and grey, whereas measurements from the two Icelandic sites are in blue. For each boxplot, the median is represented by the black line in each box, which represents the interquartile range (50% of the sample). Whiskers spread to the maximum and minimum values.

Conclusions:

- We find that the morphology and setting of the conical mounds within Hale Crater ejecta are consistent with the formation pathway of molards on Earth, i.e. they result from blocks of ice-cemented ground that were thrown out in the impact and transported by the ejecta flows, and that degraded to cones of debris on loss of the interstitial ice.
- Comparison with terrestrial analogues reveals important geomorphological similarities between the ejecta flows of Hale and debris avalanches in periglacial environments on Earth, where substantial quantities of water are involved.

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