MOLARDS - A NEW LANDFORM REVEALING ICE-EJECTA INTERACTIONS ON MARS.

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Introduction: Molards are conical mounds of debris that are formed by the loss of cementing ice from frozen blocks of sediment that have been transported in landslides in periglacial environments on Earth [1]. We report similar-looking conical mounds in the ejecta of the Hale Crater on Mars and investigate if these conical mounds could be molards.

The ~130 km-diameter 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; [2]). 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 and hosts abundant alluvial fans [2–5]. Our study area is located in the SE part of the ejecta, where conical mounds have already been mapped [5] (Fig. 1).

Approach: We used 15 m/pixel images from the High Resolution Stereo Camera (HRSC on Mars Express) with associated digital elevation models at a spatial resolution of 125-150 m/pixel. The HRSC images were used as a base for georeferencing 25 Context Camera images at 6 m/pixel (CTX on Mars Reconnaissance Orbiter). Using these data, we refined the map of the ejecta deposits and channels from [2]. 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/pixel only cover limited zones, and we used two stereo-generated elevation models at 1 m/pixel to perform detailed morphometric study of the conical 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 compare to three terrestrial analogue sites with molards: landslides in northern Iceland [1], the 2010 Mount Meager debris avalanche in Canada [6] and the 2000 Paatuut landslide in western Greenland [7].

Results & discussion: 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. The mounds are concentrated around the channels in the inner ejecta and towards its outermost limit (Fig. 1). We have found an intimate association between mounds and channels, lobate ejecta margins, polygonal ridge patterns and pitted surface morphologies of the ejecta (Fig. 1) – all pointing to a water-rich debris flow or mud flow origin. Our comparisons to the Mount Meager debris avalanche, where channels, lobes and mounds are found in a similar spatial arrangement (Fig. 2), support this assertion.

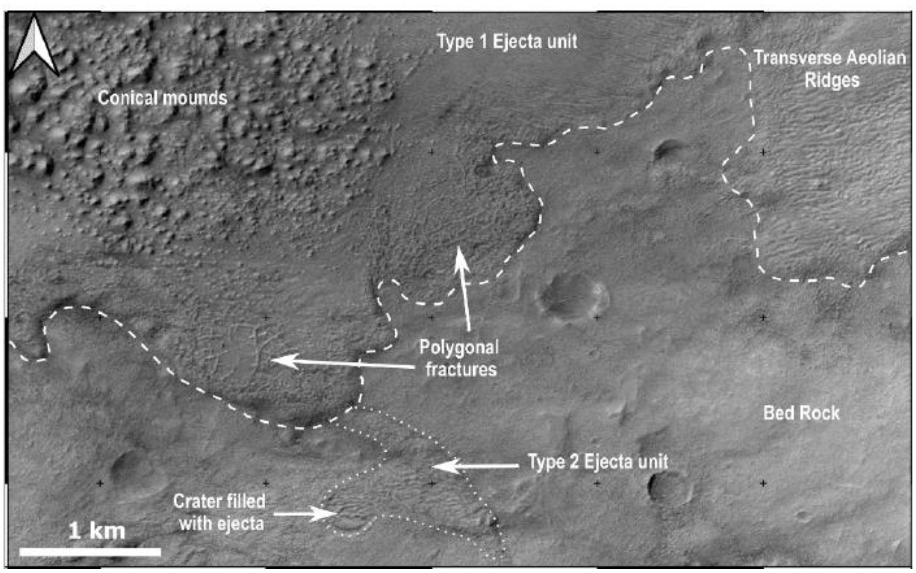

Figure 1. CTX image of conical mounds in the Hale Crater ejecta and associated landforms.

We analysed the morphometrics of 2175 conical mounds in the Hale Crater ejecta, finding that flank slopes ranged from 2 to 42° (median 17°) and are consistent with terrestrial molards (Fig. 3). Conical mounds in the Hale Crater ejecta have diameters between 4 and 238 m (median 32 m) and heights between 1 and 53 m (median 6 m). Compared to terrestrial analogues, the conical mounds in the Hale Crater ejecta are one order of magnitude larger, with Icelandic molards being only up to 22 m in diameter, but typically only a few metres in size. The scale of the molards on Earth is thought to roughly scale with the thickness of the flow that transported them, this result can be explained by the ejecta flows of the Hale impact being one order of magnitude thicker (as implied by our measurements of ejecta thickness) than the landslides that emplaced the molards on Earth.

Conclusions: We find that the morphology and setting of the conical mounds within the Hale Crater ejecta are consistent with the formation pathway of molards on Earth, i.e. they result from blocks of ice-cemented regolith (in the martian case produced by the impact) and transported by water-rich (ejecta) flows, and that degraded to cones of debris (molards) upon loss of the interstitial ice.

Comparison with terrestrial analogues reveals important geomorphological similarities between the ejecta flows of Hale Crater and debris avalanches in periglacial environments on Earth, where substantial quantities of water are involved. Our interpretation supports the prevailing hypothesis that the Hale impact event penetrated the martian cryosphere and further provides important constraints on the rheology of martian ejecta deposits that can be tested by future studies and in other locations on Mars.

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References: [1] C. Morino et al. (2019) *Earth Planet. Sci. Lett.*, *516*, 136–147. [2] A.P. Jones et al. (2011) *Icarus*, *211*, 259–272. [3] M.R. El-Maarry et al. (2013) *Icarus*, *226*, 905–922. [4] L.L. Tornabene et al. (2012) *Icarus*, *220*, 348–368. [5] J.L. Collins-May et al. (2020) *J. Geophys. Res. Planets*, *125*. [6] G. Roberti et al. (2017) *Geosphere*, *13*, 369–390. [7] T. Dahl-Jensen et al. (2004) *Nat. Hazards*, *31*, 277–287.

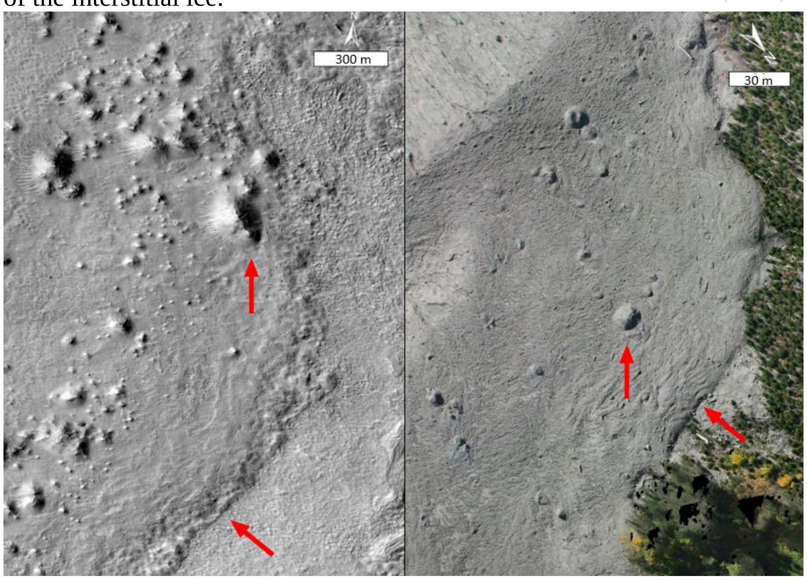

Figure 2. Comparison between candidate molards in Hale crater ejecta, left, and molards in Mount Meager, right. Top red arrow points to conical mounds and bottom red arrow to a flow front

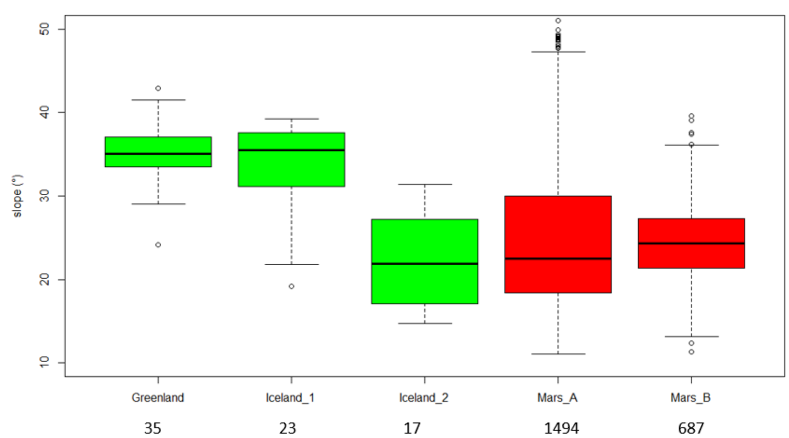

Figure 3. Flank slopes of conical landforms on Earth and Mars, where the number of measurements is given below the name of each site. For each boxplot, the median is represented by the black line in each box, which represents the interquartile range (50% of the sample).Whiskers spread to the maximum and minimum values discounting outliers. The Mars data span two separate sites where HiRISE elevation data are available