GULLY FORMATION AT THE HAUGHTON IMPACT STRUCTURE (ARCTIC CANADA) THROUGH THE MELTING OF SNOW AND GROUND ICE, WITH IMPLICATIONS FOR GULLY FORMATION ON MARS.

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Introduction: The formation of gullies on Mars has been the topic of active debate and scientific study since their first discovery by Malin and Edgett [1] in 2000. Several mechanisms have been proposed to account for gully formation on Mars, from "dry" mass movement processes, release of water or brine from subsurface aquifers, and the melting of near-surface ground ice or snowpacks (see a recent review by [2]). In their global documentation of martian gullies, Harrison et al. [3] report that gullies are confined to ~27–83°S and ~28–72°N latitudes and span all longitudes. Gullies on Mars have been documented on impact crater walls and central uplifts, isolated massifs, and on canyon walls, with crater walls being the most common situation [2, 3].

In order to better understand gully formation on Mars, we have been conducting field studies in the Canadian High Arctic over the past several summers, most recently in summer 2018 and 2019 under the auspices of the Canadian Space Agency-funded Icy Mars Analogue Program. It is notable that the majority of previous studies in the Arctic and Antarctica, including our recent work on Devon Island [4], have focused on gullies formed on slopes generated by regular endogenic geological processes and in "regular" bedrock. However, as noted above, meteorite impact craters are the most dominant setting for gullies on Mars [e.g., 2, 3]. Impact craters provide an environment with diverse lithologies – including impact-generated and impact-modified rocks – and slope angle, and thus greatly variable hillslope processes could occur within a localized area. Here, we investigate the formation of gullies within the Haughton impact structure and compare them to gullies formed in unimpacted target rock in the nearby Thomas Lee Inlet [4].

The Haughton impact structure and surrounding terrains: The Haughton impact structure formed 23 Myr. ago on Devon Island, Canadian High Arctic. At 23 km in diameter, it is one of the best preserved and best exposed complex impact structures on Earth (see [5] for overview). A unique feature of Haughton is the preservation of crater-fill impact melt rocks and breccias, which cover ~56 km^2 in the central region of the crater and that are currently weathering in the prevailing polar desert environment (Fig. 1). The average temperature on Devon Island is ~ -16 °C, with ~ 160 mm water equivalent precipitation, predominantly snow [4]. Rainfall can occur, but snow melt and active layer permafrost processes are the primary source of liquid water. Periglacial and permafrost landforms and processes are the dominant agents of landscape evolution under present conditions, and the site contains a range of landforms that have been proposed to represent excellent analogues for Mars [6], including gullies [4], polygons [7], and subglacial channels [8].

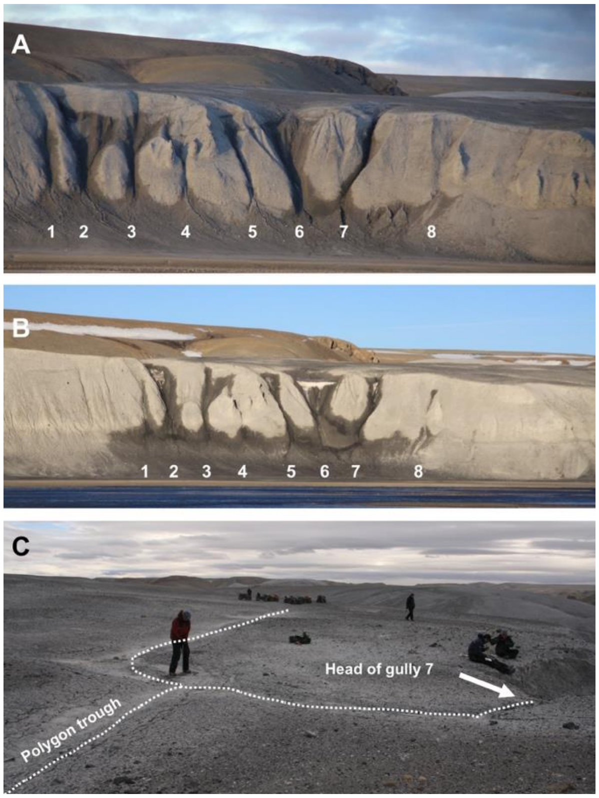

Fig. 1. Gullies formed in crater-fill impact melt rocks at the Haughton impact structure. A) View of gullied ~50 m high slope taken at the end of July 2013. B) Image of the same slope in mid-July showing remnant snow pack. C) Image taken on the plateau above the gullies.

Previous studies of gullies. In a recent study, we provided the first comprehensive study of gullies outside the Haughton impact structure [4]. This study showed that the geology of the slope- and cliff-forming rocks plays a major role in constraining gully morphology and evolution. The fluid sources for these gullies included seasonal and perennial snow pack, which was the most dominant source, with minor contributions from the melting of small cirque glaciers, ephemeral streams, and spread flow.

Some observations of gullies within the Haughton impact structure were previously made around the turn of the century [e.g., 8]; however, no comprehensive study of such landforms has been conducted to date. Our study represents the initial results of such an effort.

Methods: Fieldwork was conducted during 16 summers since 1999. Ultra-high resolution LiDAR topography, satellite imagery, and field observations were used to map gully occurrence and morphometry within the Haughton River Valley crater-fill impact melt exposures. Temporal LiDAR measurements, multi-year gully changes and observations of inter-season of snow melt/wetness, have been made over the past 20 years. Ground-penetrating radar and shallow drilling provided observations of permafrost depth.

Results: We have mapped 215 individual gullies on the crater-fill impact melt rocks within the Haughton impact structure (Fig. 1). It is apparent that gullies within the crater form on lower slopes (mean = 15°) than those in Thomas Lee Inlet (typically ~20–30°); they are also shorter than gullies outside the crater (Figs. 1, 2). This is consistent with our observations from outside the crater [4], which showed that the type of geological unit plays a major role in constraining gully morphology.

Figure 1A shows a series of gullies formed within impact melt rocks on a slope on the east side of the Haughton River. This image was taken at the end of July, when the snowpack in this region had mostly melted. Earlier in the season, it is clear that the gully alcoves are the site of greater accumulations of snow than outside (Fig. 1B) as is typical for this landform unit. There are two notably more deeply incised gullies on this slope (gullies #6 and #7; Figs. 1A,B). Figure 1C provides a view of the plateau on top of the gullied slope in Figures 1A and B. Large thermal contraction polygons with well-defined troughs are present on this plateau – ground-penetrating radar (GPR) and shallow drilling confirm the presence of ice in the prominent polygon trough (see dotted line in Figure 1C). Importantly, the two most deeply incised gullies both have alcoves that align with polygon troughs (Fig. 1C).

Discussion and conclusions: It is clear from our field observations that there are two main fluid sources for gully formation within the crater-fill impact melt rocks at the Haughton impact structure: melting of seasonal snowpack – as previously suggested by Lee et al. [9] – and melting of ground ice. As exemplified by Figure 2B, it is apparent that nivation plays an important role in gully formation, whereby melting of seasonal (and in some years, perennial) snow pack results in erosion that deepens and enlarges gully alcoves, in which more snow then accumulates in subsequent years.

The geometric connection of the two largest and deepest gullies (gullies #6 and #7; Figs. 1A,B) with ice wedge polygons troughs suggests that the melting of ground ice is a second and important fluid contribution that extends the duration of gully activity once the snow pack has melted. In addition, our observations suggest that the ice wedge and trough likely acts as a bit of a conduit for enhanced water flow during the active layer season.

As reviewed recently by Conway et al. [2], a wide range of formation mechanisms have been proposed to account for gully formation on Mars. Given the close spatial association of gullies with periglacial landforms (e.g., polygons) on Mars, we suggest that the melting of snow and ground ice, as proposed here for the Haughton gullies, represents a plausible mechanism to form martian gullies.

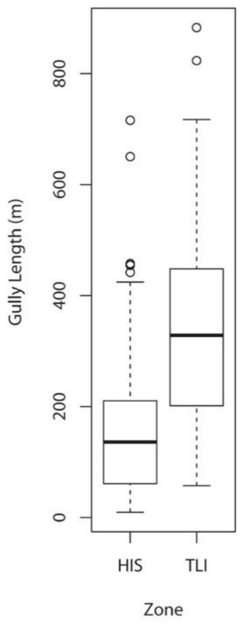

Fig. 2. Comparison of the length of gullies within the Haughton impact structure (HIS) (n = 215) and outside, in Thomas Lee Inlet (TLI) (n = 161).

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