STATISTICAL ANALYSES OF GULLY CHARACTERISTICS IN THE HAUGHTON IMPACT STRUCTURE: IMPLICATIONS FOR MARTIAN GULLY FORMATION MECHANISMS. V.G. Rangarajan[1,2], E. Godin[3], G.R. Osinski[1,2] and L.L. Tornabene[1,2], [1]Institute for Earth and Space Exploration, University of Western Ontario, London, ON, Canada [2]Dept. of Earth Sciences, University of Western Ontario, London, ON, Canada (vrangara@uwo.ca), [3]Centre d'Études Nordiques, Université Laval, Québec, Canada.

Introduction: Gullies are erosion features often found on slopes, usually made of alcoves, narrow incised channels and with associated sediment deposits [1,2]. These common features are known to be active on both Earth and Mars [3,4]. Impact crater walls have been the most dominant settings for Martian gully formation, as they present steep slopes facilitating mass wasting [2,4]. Impacts also provide an environment with diverse lithologies, that include impact-generated and impact-modified rocks that may influence gully formation along its slopes [5]. Hence, understanding erodibility of impactites is critical to better explore processes involved in formation of gullies that incise through these materials, particularly for Mars, where in-situ surface investigations of these features have not yet been made. Our work presents a multivariate statistical analysis of gullies within the Haughton impact structure that predominantly incise into crater-fill impact melt rocks, to investigate their influence in gully characteristics and formation mechanisms.

Haughton Impact Structure: The 23-km diameter Haughton impact structure formed ~31 Ma on Devon Island, Canadian High Arctic in a predominantly sedimentary target sequence [6]. It is one of the most well-preserved and well-exposed complex impact craters on Earth and is often considered as a terrestrial analogue for Mars [4,6]. Rocks in this area comprise of the mid-Ordovician Bay Fjord Formation (gypsum, anhydrite, medium to thick bedded bioturbated limestone, dolostone); the mid- to upper Ordovician Thumb Mountain Formation (limestone, dolostone); and the upper Ordovician to Silurian Allen Bay Formation (majorly limestone) [6,7]. The crater also preserves crater-fill impact melt rocks rich in carbonates, silicates and gypsum [8]; and in the floor of the Haughton river valley, are alluvial and fluvial deposits deposited through a succession of river levels during the Holocene. Gullies have been previously identified and mapped within the Haughton river valley [5,9], found mostly along erosional remnants of the impact melt rocks. These are interpreted to post-date the last major glaciation event in Devon Island and present-day gully activity is attributed to melting of seasonal snowpack [9] and/or ground ice [5]. The close association of gullies with periglacial landforms at Haughton, similar to Mars, could in turn point to a comparable process for Martian gully formation and thus demands further detailed investigations.

Methods: This work follows a similar methodology to a recent morphologic study of gullies at Thomas Lee Inlet (~15 km east of the crater) by [7]. As such, similar terminology for qualitative and quantitative variables are used to enable future comparison between the two sites. We use a mosaic of WorldView-2 satellite observations acquired in August 2010 as a basemap. The panchromatic band (0.46m/px) was used to interpret size, shape and location of the gullies, while multispectral bands (1.84m/px) assisted in further qualitative interpretation of the landscape. ArcticDEM [10] strips were used to retrieve elevations for the area. A gully geodatabase was built using ESRI's ArcGIS 10.7, which includes the digitized gully features, and associated interpretations for each record as quantitative or qualitative variables. Quantitative records that included gully length, slope and orientation were presented in principal component (PC) space (Fig. 1a), while qualitative factors like gully layout, maturity, presence of supplementary water sources, etc. were represented as factor maps (Fig. 1b). Factor Analysis of Mixed Data (FAMD) was then performed to simultaneously analyze and correlate the two types of data using the Factoshiny package in R-Project 4.1.2. Similar gullies were then statistically clustered together into multiple classes through a consolidated Hierarchical Clustering on Principal Components (HCPC) approach.

Results: 214 individual gullies have been mapped in the Haughton river valley [5] with at least 174 of these fully incising into impact melt rock. A few gullies (~10) were also found to partially cut across the melt rocks and further incise into the underlying Thumb Mountain and/or Bay Fjord Formations. HCPC identified four distinct classes of gullies in the region (Fig. 1c), with all results having a p-value <0.05 indicating $\geq$ 95% classification confidence level.

About 85.7% of the gullies that incise into both impact melt rocks and the Bay Fjord Formation, fall into **Cluster 1**. This cluster is also characterized by predominantly well-defined gullies (96% in the cluster), those that have discernable alcoves, channels and aprons. Also, all gullies in this group fully reach the slope line highlighting that immature gullies were completely absent in this cluster. Cluster 1 was also dominated by complex gullies (with secondary channels) that constituted 74% of the group, while 54% of the gullies in the cluster also have proximity to ice-wedges. These gullies are generally longer (Mean = 241.7m) than the mean for the 214 gullies in total (151.5m), and are more likely to face south, with an average orientation of 104.4°. Most gullies in this group have gentler slopes (22.9°) with respect to the mean for the entire population (26.5°).

Cluster 2 was dominated by gullies that solely incised into the impact melt rocks, making up 98.4% of the gullies within the cluster. These were characterized by predominantly linear channels (89.9% in the cluster and 72% of all linear gullies) and a partial gully structure (64.3% in the cluster). About 76.7% of all immature gullies also fall in this cluster. These gullies were also shorter (Mean = 105.5m) than the rest of the population.

Cluster 3 is characterized by fluvially-dominated gullies (77.8% of the cluster) and these cut through both bedrock and deposits. These gullies are fully mature and are in close proximity to supplementary water sources (77.8%). Gullies in this cluster are typically found to incise both the impact melt rock and the Thumb Mountain unit, and constitute some of the longest gullies in the population (Mean = 306.5m).

Lastly, **Cluster 4** is dominated by non-melt incising gullies (100% of the cluster; 89.7% of the non-melt incising gully population). Gullies in this group are found to cut across both single (92.3%) and multiple (7.7%) target lithologies, and are predominantly linear (96.1%). All gullies in this cluster are also very distant from any ice wedges or supplementary water sources. Finally, these gullies are steeper (Mean slope = 32.3°) than the mean for all clusters (26.5°), and were more likely to face north with an average orientation of 53.6°.

Discussions: Results from initial morphologic and statistical analyses show that linear, immature gullies are preferentially seen when gullies singularly cut through either impact melt rock or bedrock alone, gullies that incise into melt rocks have relatively gentler slopes. Alternatively, if gullies cut through both melt rocks and underlying bedrock, they tend to be much longer than the remaining gullies in the region, and also become more complex and mature. The latter types of gullies have also been observed closer to patterned ground and ice wedges than the other groups.

Future work is planned to rigorously analyze gullies incising into the impact melt rocks, to explore heterogeneity, if any, observed within this subset. Work will also be done to compare gully characteristics between the Haughton river valley and Thomas Lee Inlet [7], to not only better understand the erodibility of melt for gully formation, but also shed some light on the snowpack and ground ice melt models for Martian gully formation.

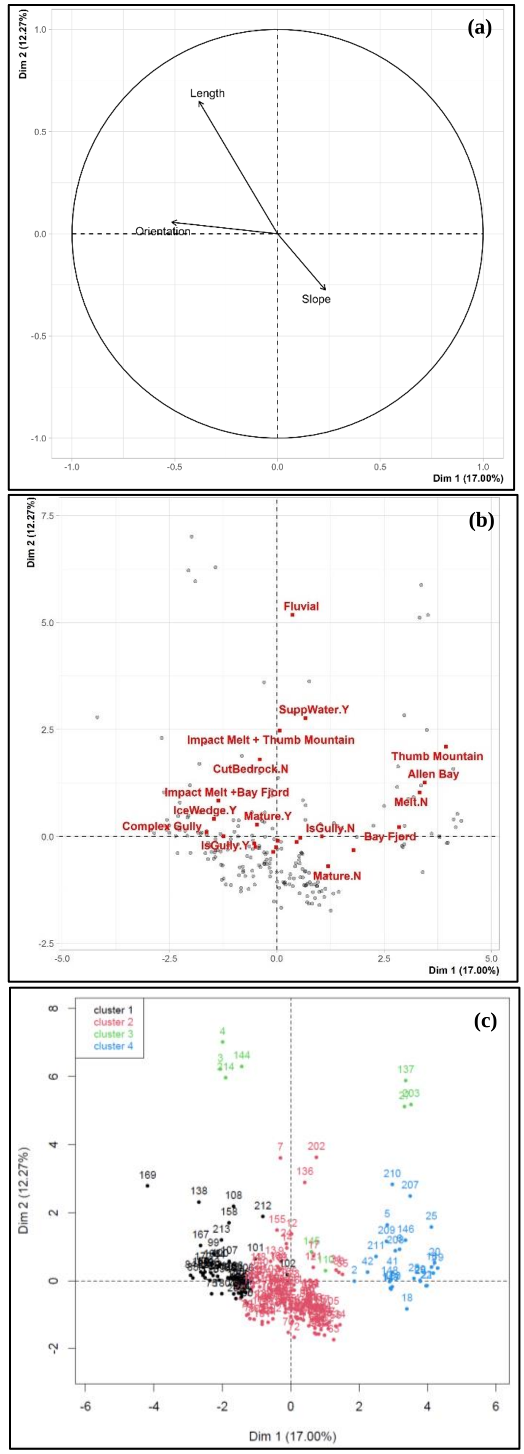

Figure 1(a) PC bi-plot graph showing the gully quantitative factors as an FAMD output **(b)** Representation of gully qualitative variables as factor maps. Each grey dot in PC space represents one individual gully and red points indicate the centroid position of a specific factor **(c)** Plot of the HCPC output classifying the entire gully population into four distinct clusters.

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