A QUANTITATIVE ANALYSIS OF SORTED PATTERNED GROUND WITHIN THE HAUGHTON IMPACT STRUCTURE, DEVON ISLAND, WITH IMPLICATIONS TO MARS.

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Introduction: Permafrost underlies 24% of the Earth's land area and is a major control for the generation of patterned ground and other terrain anomalies that can also be found on Mars. The study area in Devon Island, located in the Canadian High Arctic (75.1982° N, 81.8512° W), is in the continuous permafrost zone where periglacial features are widespread [1]. Patterned ground, specifically sorted stone circles, are periglacial features of interest that can provide insight into past climate, water availability, and geologic substrate on both the Earth and Mars [2,3]. In this study, we test a quantitative remote sensing methodology coupled with understanding periglacial landform evolution with implications to Mars. This allows for identification of spatial variance and sorting of different stone circle morphologies found in an area in the Haughton River Valley (HRV) in a RS and Geographical Information System (GIS) interface. Spatial modelling of geomorphologic landforms and processes is currently one of the prevailing issues in geomorphology. Remote sensing provides an opportunity to collect spatially continuous and versatile information on environmental determinants of sorted patterned ground. The HRV is located within the Haughton Impact Structure, a well-preserved 23 Myr. old, ~23 km diameter impact crater [4]. This site is regarded as one of the best Martian analogue sites on Earth, since it has similar rock types, a polar desert climate, and is within an impact crater (the most ubiquitous geologic structure in the Solar System).

Methods: Data was acquired in late July 2017 using a high resolution UAV (for image context), tripod LiDAR scans (new Polaris instrument supplied by Teledyne Optech), and a novel backpack-mounted Kinematic Mobile LiDAR scanner (KLS) (developed at the Finnish Geospatial Institute; Fig 1). After processing the LiDAR data, we created several of the highest-resolution digital terrain model grids (~1–5 cm/pixel), one of which is used as a case study for this project due to its impressive saturation of patterned ground. A semi-automated classification method using a 50m x 50m LiDAR grid is used for analysis. The goal is for the identification and calculation of morphological attributes of stone circles as well as a plot of their cumulative sorting pattern (i.e. very well sorted, well sorted, moderately sorted, etc.).

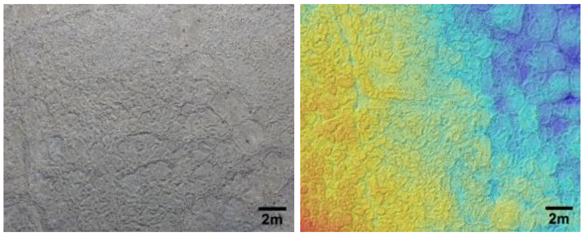

Figure 1. UAV (left) and LiDAR (right) images of the Haughton River Valley sorted stone circle field. Stone circles range from 0.5 to 2.0m in diameter.

To better understand the morphological variability of spatial sorting and variation in stone circles within the study area, and to identify any preferential spatial arrangement based on topographic relief, both non-spatial (Table 1) and spatial analyses were conducted. These analyses examine the geographic relationships between individual stone circle polygon vectors and their relative position within the study area (Fig 2). Specifically, kernel estimation is used to create maps of stone circle density values in which the density at each location reflects the concentration of points representing the geometric centers of stone circles (Fig 3).

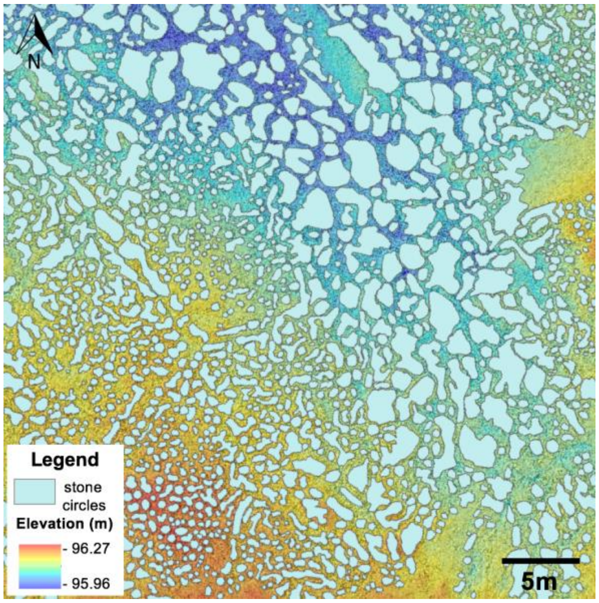

Figure 2. 50m x 50m grid distribution of digitized sorted stone circle polygons in the the study area. There are a total count of 1384 stone circles.

Results: *Geomorphometric Analysis.* Kernel density estimation (KDE) is an effective method for visualizing the distribution of event density, particularly of stone circles, over time and/or space but is underutilized in geomorphological data analysis [7].

KDE was used to create three maps of stone circle attributes such as concentration (Fig 3a), area (Fig 3b), and elongation ratio (ER; Fig 3c).

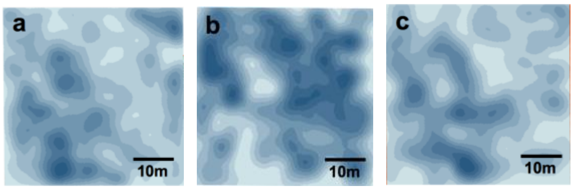

Figure 3. Maps illustrating kernel density estimations (KDE) of the density of stone circle distribution across the study area with darker blue areas representing increasing density. (a) KDE of all stone circles across the study area. (b) KDE of stone circles based on surface area (top quintile). (c) KDE of stone circles based on elongation ratio (top quintile).

Fig 3a shows density highs that represent areas in which there is a relatively high concentration of stone circles and density lows that represent areas of relatively sparse stone circle distribution. This provides a visual interpretation of relative clustering or spatial concentration showing that stone circles are not randomly distributed across the study area but are most highly concentrated areas with the highest relative elevation following specific morphologies. Fig 3b illustrates that stone circles with the highest area are concentrated in elevation lows. The darker blue areas in Fig 3c represent regions with the highest elongation ratio values (ER = length/width) meaning that these stone circles are morphologically longer or stretched. Non-spatial analysis included the examination of 'classic' statistical parameters, such as the standard deviation of calculated parameters (Table 1). These results can give further insight on periglacial surface kinematics.

Table 1. LiDAR-derived morphometric statistics of sorted stone circles from kernel estimation maps.

	Area (m)	Perimeter (m)	Elongation Ratio (l/w)
Min.	0.04	0.69	1.82
Max.	12.69	19.28	5.57
Sum	1220.11	4800. 09	639.25
Mean	0.88	3.47	2.31
Std. Dev.	1.26	2.59	0.53

Cumulative Sorting Analysis. For each sorted stone circle polygon vector, the cumulative area fraction over the total area was plotted against the cumulative perimeter fraction over the total perimeter. The resulting plot (Fig 4) clearly differentiates each sorting level. The fraction cut-offs are due to larger and more complex sediment grain/rock sizes that create an abrupt shift in the cumulative values [8]. Overall, the more sorting there is, the closer the slope value is to 1 showing a continuous linear distribution. The slope indicates a faster rate of fraction increase for the less-sorted ground with steeper and more discontinuous distributions. Poor sorting can reach slopes larger than 3. The red line in the graph (Fig 4) shows that the stone circles within the 50m x 50m study grid in the HRV is very well sorted.

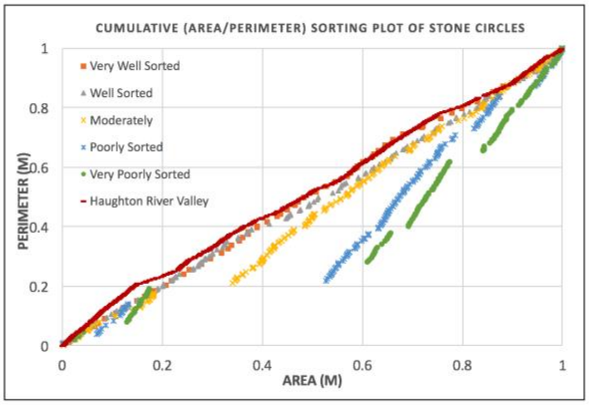

Figure 4. A scale plot of the degree of sorting using cumulative area and perimeter fractions for stone circles; initially used for melt-bearing breccia minerals [8].

Discussion: Quantitative analysis of the form and spatial distribution of sorted stone circles within the HRV identifies a number of distinctive patterns that may reflect spatial variability in processes and conditions responsible for their formation. There are several factors that control sorted stone circle morphology. For example, microtopography, water/ice availability, and the cyclic burial and exhumation of sediments/rocks is believed to play an important role in the sorting and spatial distribution of stone circles, which can then be used to determine periglacial surface kinematics [9].

The lessons learned from this study will be applied to variations of stone circles in Elysium Planitia, the mid-latitude region on Mars. Investigation of highly detailed LiDAR of other study areas will continue alongside subsurface data to support interpretations of factors such as microtopography, permafrost drainage, and substrate types influencing sorted stone circle morphology. The connection of sorted circles to buried ice conditions on Earth and its changes over time make these ground forms good spatial analogues for periglacial landsystems on Mars.

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