STATISTICAL EVIDENCE OF POLYGONAL TERRAIN SELF-ORGANIZATION ON EARTH AND MARS.
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Introduction: Polygonal terrain is perhaps the most intensively studied landform found within the ice-rich, continuous permafrost landscapes of Earth and Mars [1,2]. These series of interconnected trough-like depressions on the ground surface form as a result of rheological responses to climatic forcing mechanisms, whereby a network of thermal contraction cracks open and propagate to relieve the stresses induced by rapidly falling air temperatures [3].

Although the processes responsible for polygonal terrain formation are thought to be consistent on both planets [4], there remains a gap in our ability to describe how the appearance of such surface patterns evolves. Specifically, because these features develop over much longer time scales (i.e. hundreds to thousands of years [5]) than that over which data exists, largely qualitative and rhetorical statements regarding changes in their geometrical arrangements have been derived and commonly accepted.

Research Question and Objectives: Throughout the archival literature, references have been made as to how polygonal terrain networks become more 'regular' as they develop over time [e.g. 5,6]. However, to our knowledge, no one has yet demonstrated this concept quantitatively. As such, the primary research question addressed here is: "can we develop a numerical technique by which to compare past and present geometrical arrangements of polygonal terrain networks on Earth and Mars?"

Our objectives were thus to: (i) use a selection of field sites in the Canadian High Arctic to determine present-day and historical polygonal network arrangements; (ii) apply Spatial Point Pattern Analysis (SPPA) [7] to quantify changes in network geometry at these sites over time, and; (iii) investigate if similar trends are evident at a variety of sites on Mars.

Formation and Evolution of Terrestrial Polygonal Terrain: On Earth, the three types of polygonal terrain exist: ice-wedge, sand-wedge, and sublimation polygons. Typically, these phenotypes can be distinguished based on a combination of surface morphology and subsurface characteristics.

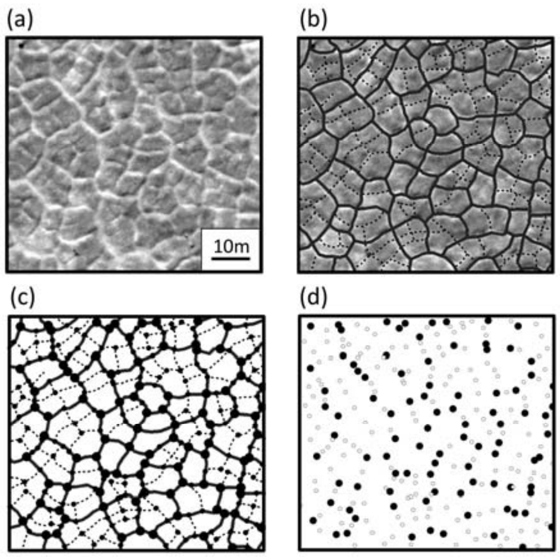
In ice-bonded materials that contain ice volumes less than or equal to total pore space, open thermal contraction cracks are filled with draining meltwater or windblown sediments (depending on local availability), to form early stage ice- or sand-wedges, respectively. If climatic conditions are warm enough to permit the formation of a seasonally-thawed active layer, thermal expansion of the ground results in the redistribution of sediments, forming raised shoulders that bound the troughs overlying the wedge materials [1]. Over time, thermal contraction cracking tends to reinitiate above the pre-existing wedges, which again become infilled with meltwater or sediments, ultimately leading to a thickening of the wedge and more pronounced geometrical patterns at the surface characterized by increasingly wider troughs.

Unlike ice- and sand-wedge polygons (which follow very similar evolutionary paths), sublimation polygons are found in locations where subsurface ice content greatly exceeds available pore space and surface temperatures rarely, if ever, exceed freezing. In these situations, sublimation of ground ice bodies along open thermal contraction cracks leads to localized subsidence of surface materials along the cracks' peripheries, forming a modified sand wedge [6]. As the sublimation process occurs over time, more sediments are added to the sand wedge and the troughs following the contraction cracks' trajectories widen substantially [8].

Tracking the Evolution of Polygonal Terrain on Mars: While consensus has not yet been reached as to whether the features observed on the Martian surface are more analogous to terrestrial sublimation- or sand-wedge polygons [2,4], two similarities between the phenotypes are evident: (i) over time, polygons bounded by the first-forming 'primary' troughs become subdivided by later-forming 'secondary' and 'tertiary' troughs [8,9], and; (ii) although the mechanism by which they do so differs, all troughs bounding both sand-wedge and sublimation polygons grow increasingly wider as they develop [8,9]. Therefore, for both types of polygonal terrain, primary troughs will tend to be wider than secondary or tertiary troughs, and thus can be rather easily identified.

Spatial Point Pattern Analysis: A complete explanation of SPPA as applied to polygonal terrain is provided by [7], summarized briefly here. SPPA is used to describe the geometry displayed by a particular polygonal network by determining how randomly or regularly the intersections of polygon-bounding troughs are distributed in space. A "Regularity Index" (RI) is generated for each site, ranging from values of 0 (completely irregular distribution) to 1 (completely regular distribution) [10].

Figure 1: Technique to derive historical point patterns of a polygonal terrain network: (a) subset of HiRISE image PSP_001419_2495; (b) digitized primary (solids lines) and secondary/tertiary troughs (dotted lines); (c) trough intersections separated by primary-primary (large points) and all others (primary-secondary or secondary-secondary) (small points), and; (d) observed spatial point pattern for primary-primary intersections (large points are retained for analysis and hollow points are excluded).



To calculate the present-day RI for a given site, all trough intersections are considered equal and the x-y coordinates of each are used as input data for the SPPA. To estimate the historical arrangement of each site, however, an assumption needs to be made. Because primary troughs (distinguished by their widths) are formed earlier than secondary or tertiary troughs, it is reasonable to assert that the earliest-forming intersections were between primary troughs. Thus, performing the analysis using only the coordinates of primary-primary intersections should sufficiently describe the appearance of the site at some undetermined time in its history (RI_p).

Data Collection and Processing: Five field sites in the Canadian High Arctic were selected for investigation, displaying widely varying polygonal network geometries that provide a representative selection suitable for comparative analyses. At each of the sites, high-resolution aerial photos were collected and stitched together to create a digital mosaic of the site at approximately 25cm/pixel. Similarly, five Martian polygonal terrain sites of differing geometrical arrangements were selected using HiRISE imagery (~25cm/pixel).

Using a Geographic Information System (GIS), all trough segments were manually digitized and separated as being either 'primary' or 'non-primary' (i.e. secondary or tertiary) (Figure 1). All trough intersections were then identified and digitized, and the x-y coordinates were extracted for subsequent numerical analysis. The SPPA was conducted using: (i) the intersections of primary troughs only (to generate the historical RI_p), and; (ii) all trough intersections (to generate the present-day RI). By comparing RI to RI_p for each site, the overall changes in network regularity were established.

Changes in Point Patterns Over Time: Very consistent trends for network evolution were observed for all of our study sites on both Earth and Mars, with the geometry displayed by each site having become progressively more regular over time. Specifically, the 'historical' point patterns generated by applying SPPA to only primary trough intersections yielded average RI_p values of 0.339. When the SPPA was re-run for each site using the present-day trough intersections, the networks were found to have an average RI value of 0.540, translating to an average increase of 0.201. In no cases did the RI value decrease for an individual site, regardless of its initial geometry.

Summary and Conclusion: The overarching goal of this work was to demonstrate, using sites on Earth and Mars, how polygonal terrain network arrangements change over time. To do so, we have used established terrestrial geomorphic theory to develop a novel technique by which to describe historical arrangements of polygonal terrain networks.

It was determined that all of our studied sites became statistically more regularly assembled as they evolved, regardless of initial geometry. Although the concept of polygon self-organization has been referred to previously, it had yet to be confirmed statistically.

The implications of such findings are that SPPA could potentially be used to reconstruct a site's geomorphic history, and thus help constrain the environmental processes responsible for landscape evolution of permafrost landscapes on both planets.

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