PATTERNS AND CURIOUS LANDFORMS OF THE CANADIAN HIGH ARCTIC

SUMMARY: We review examples of natural patterns found in Canadian Arctic landscapes and potential formation mechanisms.



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INTRODUCTION

Cold regions on Earth are dominated by cycles. On the millennial scale, Milankovitch cycles drive the global glacial coverage and the occurrence of Ice Ages. Over hundreds to thousands of years, individual glaciers advance and retreat, driving erosion and deposition of sediments and downslope movement of

meltwater in their forelands. In periglacial regions (cold, non-glacial environments), extreme yearly temperature cycles drive the seasonal freezing and thawing of the uppermost ground layer (active layer) above permanently frozen ground (permafrost) [1]. This repeated action generates thermal and mechanical stresses that reorganize sediments and fracture the ground. Both glacial and periglacial processes create a variety of mesmerizing patterns (e.g. [2]; Fig.1) in Earth's Arctic and high mountain regions over a wide range of timescales, effectively recording the climate history.

Scientists and mathematicians continue to be fascinated by the impressive collection of landforms and patterns produced by the cryosphere. Although mathematical theories have been developed that can reproduce similar patterns, a clear connection to the driving physical processes allows us to learn about past climate and landscape conditions on Earth and other planets from present day observations. As such, research is still underway to understand generative processes (e.g. [2]-3]), with much of the published research led by scientists at Canadian institutions. Canada, with its expansive permafrost and modern glaciers, is well positioned for studying these glacial and periglacial processes across Arctic and subarctic landscapes. The Canadian Arctic is a natural laboratory for investigating

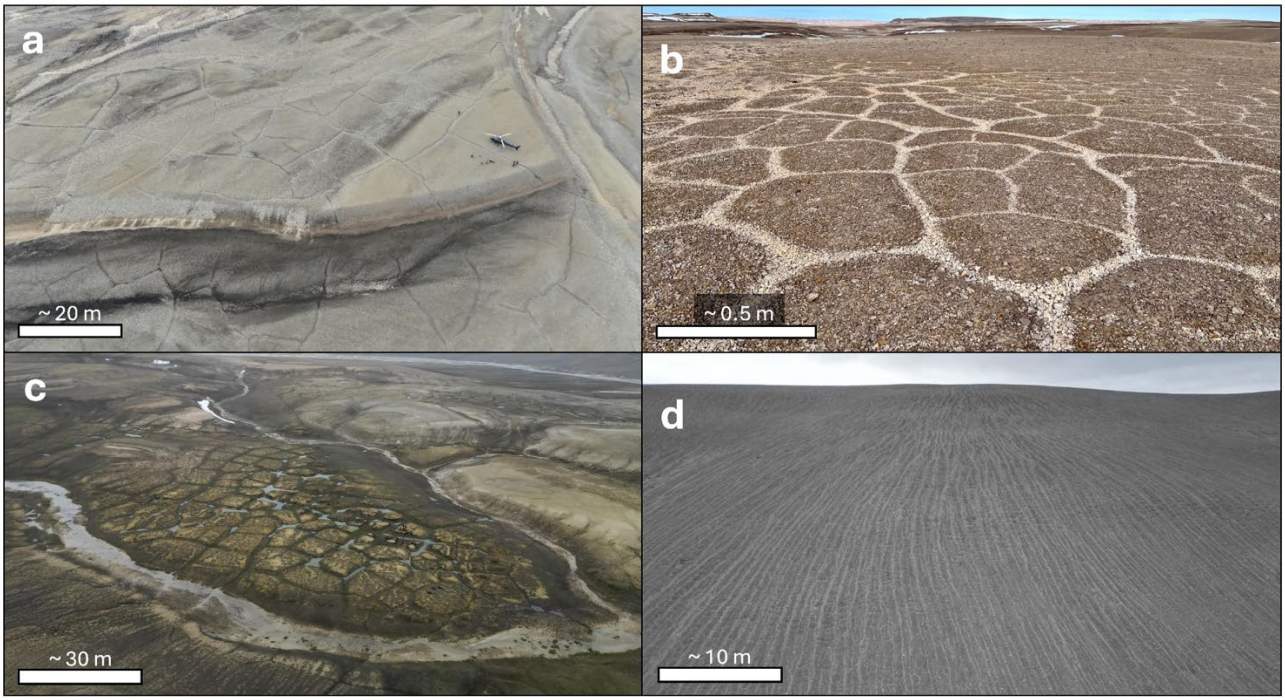


Figure 1. Examples of patterned ground found on Devon Island, Nunavut, Canada: a) a developing coastal polygon network (photo: Mark Jellinek), b) sorted polygon features on flat ground (photo: Shawn Chartrand), c) a degrading polygon network found alongside an arctic stream (photo: Sam Anderson), d) a hillslope exhibiting sorted stripe patterning, taken from the bottom of the hill and looking upslope. Photo by Grace Johnson.

how ice-rich landscapes evolve through time and respond to climate change. Below we provide a brief overview of research being done to understand some of the more curious landforms and patterns found in cold regions.

SORTED CIRCLES AND STRIPES

Sorted circles and stripes are a common periglacial landform found across a variety of cold region landscapes ([4]; Fig.2), including Mars (e.g. [5]). Sorted circles are characterized by circular to semi-circular ridges of concentrated coarse grains surrounded by a center of convex upward fine-grained material formed through a fascinating self-organizing process. These features are relatively small, with ridge heights ranging from a few millimeters up to 0.5 m, ridge widths from 0.5 to 1 m, and circle diameters from 2 to 5 m [6]. On slopes, they elongate downslope into sorted stripes with alternating coarse-grained ridges and fine-grained troughs (e.g. [3]). Sorted stripes found within the Haughton impact crater on Devon Island, Nunavut appear as darker-coloured topographic highs composed of compact, fine-grained sediments and lighter-coloured topographic lows composed of loose gravels (Fig. 2). These stripes are generally oriented along the direction of maximum slope and exist in the absence of vegetation and without clear evidence of seasonally flowing surface water. Stripe widths vary spatially across the hillslope and can be on the order of tens of centimetres up to several metres.

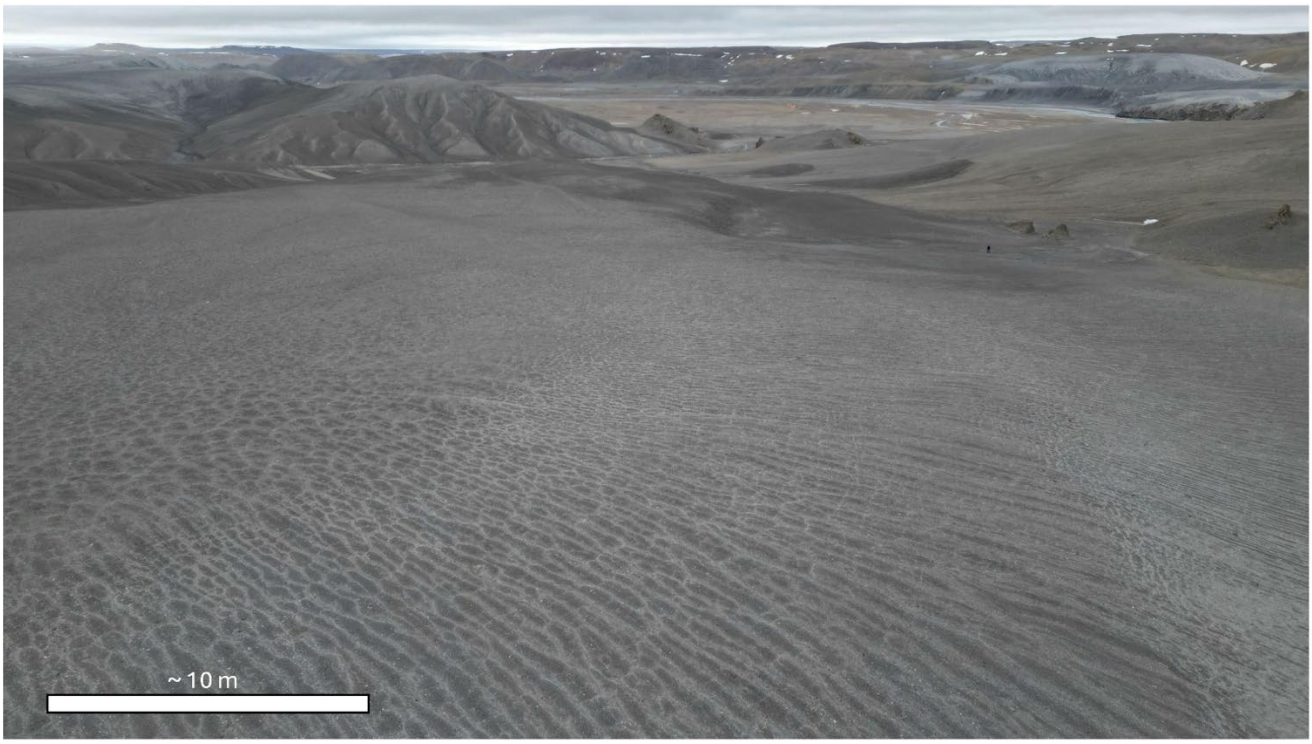


Figure 2. Sorted circular and hillslope stripes, Devon Island, Nunavut, Canada. Topographic gradient from higher to lower elevations is from image left to right. Photo by Grace Johnson.

Repeated freezing and thawing of the near surface is thought to preferentially move coarse grains upward and outward, effectively sorting the ground into fine grains encircled by a pile of coarse grains [7]. The preferential growth and collapse of needle ice in regions of fine-grained soils also act as drivers for stone sorting. Several attempts have been made to create frost-heave- and ice-needle-based models of sorted stripe formation using rules-based approaches (e.g. Kessler and Werner 2003), or analytical models derived from these rules [8]. These models, however, depend on geometric, rheological, and physical properties of the patterns that are poorly constrained. Similarly, convective models have been developed to simulate the growth of thaw front undulations located in seasonally-thawed surface and near-surface sediments (e.g. [9]). Water is unique in that, below 4 °C, the density decreases as temperature decreases. Thus, for a section of soil in the active layer with surface temperature higher than at the base of the frozen ground below, the density of water will be higher at the surface. If the viscous drag is sufficiently small, the dense surface water will tend to sink while the less dense water at the base will tend to rise, forming a pattern of convection cells. These cells transfer heat unevenly through the soil, creating undulations in the frozen front that are amplified with successive freeze-thaw cycles. However, observed sorted stripe spacing distributions are irregular and are not readily explained by these phenomena alone. It is evident that there are likely multiple competing processes at work to form hillslope sorted stripe patterns.

POLYGONS

Polygonal patterned ground ("polygons") is a type of sorted ground defined by a system of geometric raised mounds intersected by an interconnected trough network (Fig. 3). The raised polygons are typically tens of metres in diameter and are tens of centimetres to metres high (Fig. 4). Polygon networks are thought to develop over hundreds to thousands of years through a cycle where thermal contraction fractures open in the fall or winter when thermal stresses are relatively high. Fractures then fill with snow during winter storms, with meltwater or rain in the spring and early summer, or dust and sand in particularly dry polar deserts. Meltwater can percolate down into fractures and freeze once below the permafrost table, essentially filling the fracture with a vein of ice. This initial ice vein within the fractures then acts as a plane of weakness for subsequent thermal contraction fractures which get filled by ice, resulting in the growth of ice veins into metre-wide wedge-shaped bodies of ice that push the ground apart and up along the wedge margins [10]. Polygons are common landforms in Arctic landscapes, governing where water flows or stagnates within the landscape, and aiding in the formation of new river channel networks [11].

It is relevant and useful to ask how polygon landforms respond to changing climate conditions marked by amplified seasonal air temperature trends and more variable precipitation. As the Arctic warms and permafrost degrades, ice wedges melt at increasing rates, resulting in polygon troughs and shoulders subsiding more quickly than their centres. This can drive so-called low-centred polygons, where the polygon centre is lower than the shoulders and supports local water storage, into so-called high-centred polygons (Fig. 3). This decreases landscape water storage. However, the loss of ground ice also introduces new water into the landscape and rapid melting of massive ice during heatwaves can trigger

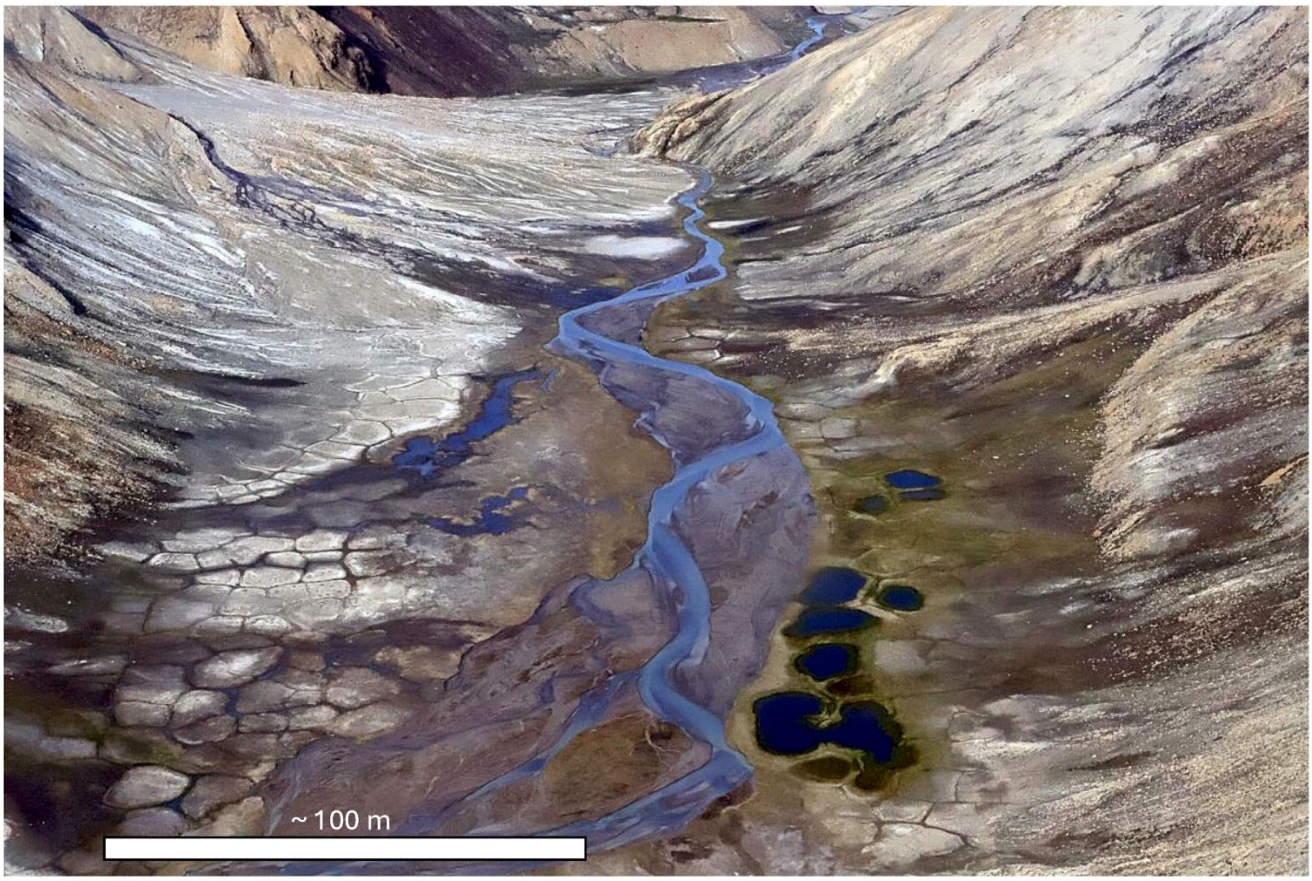


Figure 3. Polygons found on terraces along a river, Axel Heiberg Island, Nunavut, Canada. Both high-centred (image left) and low-centred (image right) occur on the terraces, and both are presently being incorporated into the developing river valley as increased melt waters from an ice cap promote river erosion of the terraces. Photo by Shawn Chartrand.

rapid channelization. It remains an open question whether the degradation of ice wedges will result in an overall drying or wetting of landscapes within and adjacent to polygons under climate change

In addition to contemporary changes due to permafrost degradation, polygon shape is known to evolve over time from primarily rectangular polygons with 90° trough intersection angles toward more circular geometries with 120° intersection angles. This is because when the initial fracture network develops, the most favourable configuration to release local stress is for two fractures to meet orthogonally. However, over subsequent fracture cycles, the network as a whole evolves towards the hexagonal polygons and intersection angles of 120°, minimizing total fracture length. This shift happens incrementally, with individual intersection angles increasing over each fracture cycle as the order of which fracture path is reactivated varies stochastically [12]. As such, the distribution of intersection angles potentially can be used as an indicator of relative maturity between polygon systems. While the uplift and shape evolution is typically neglected when considering polygon

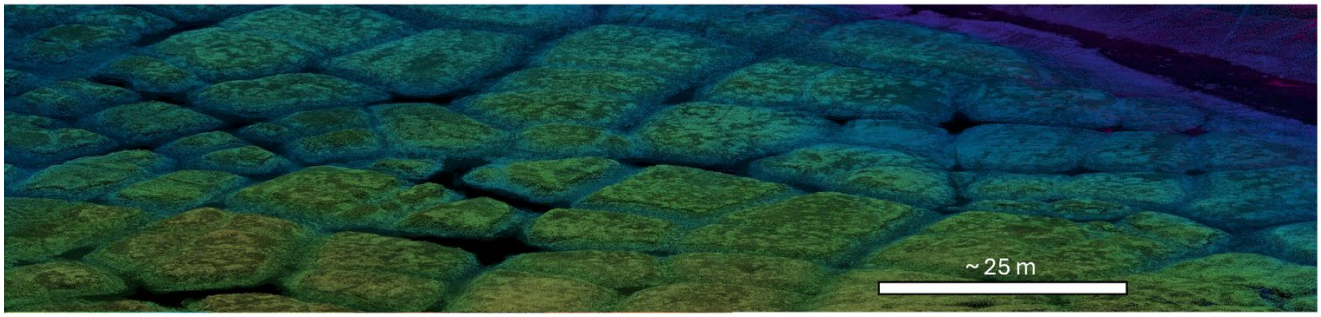


Figure 4. Digital terrain model of polygons found in the Haughton impact crater, Devon Island, Nunavut, Canada. The terrain model shows the relative topographic differences between polygons and the adjacent troughs. Terrain model by Antero Kukko.

evolution under climate change, recent observations show that polygons can form within decades, much faster than previously expected [11]. This suggests that permafrost degradation, channelization, and the evolution of the fracture network can act on similar timescales. This interaction between competing processes is still largely unexplored.

RING FORMS

Ring forms are an intriguing landform found in the Canadian High Arctic and across northern Europe, Scandinavia, and Alaska. These landforms are defined by their circular to irregular ring-shaped ridges and troughs that resemble brain-like patterns (Fig. 5). These features have been found on Devon Island ([13]; Fig. 5a) and Axel Heiberg Island [14] in Nunavut, Canada, with larger morphologically similar features found throughout continental Canada (e.g. [15-16]; Figs. 5b-d). Although the origin of these features remains debated, their formation is generally attributed to glacial processes, with many if not most of the details left to be determined. Hypotheses in the literature commonly suggest that ring forms develop within sediments left behind as buried glacial ice melts away at differential rates. As the ice melts, the overlying material shifts and redistributes into topographic highs and lows, leaving behind interconnected ridges and troughs which provide clues to the ongoing physical processes occurring long after glaciers have receded [13]. Others have suggested that these landforms develop due to squeezing of saturated subglacial sediments into cavities and crevasses at the base of a glacier. When the glacier recedes, the subglacial sediment rings become exposed and act as a fingerprint of past subglacial activity. Though specific glacial processes continue to be a topic of debate, others argue these may be periglacial in origin, forming from the formation and subsequent melting of ground ice derived from glacial meltwaters.

There is significant variation in the scale, association with other landforms, and sedimentology of glacial ring forms, with most examples disturbed by farming, infrastructure, and vegetation (Fig. 5). This may lead to the preferential preservation of large-scale ring forms leftover from the Last Ice Age. Those found in Nunavut, Canada (e.g. [13-14]) are the smallest and youngest of those described in the literature, with ridges ranging between 0.5 - 2.5 m in height and 4 - 72 m in diameter, within sands and

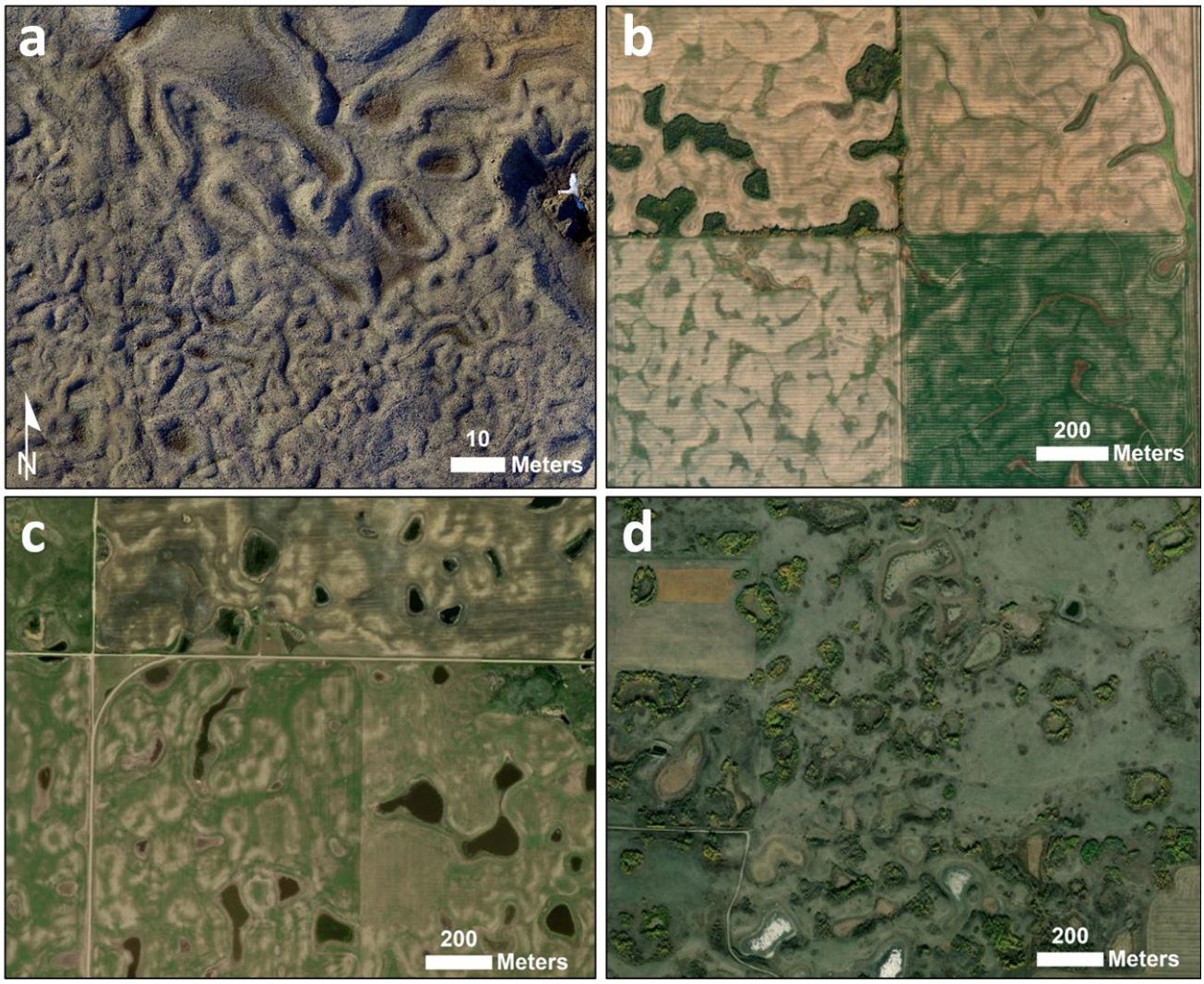


Figure 5. Examples of glacial ring forms across Canada. Ring forms in a) Devon Island, Nunavut, Canada, b) Saskatchewan, Canada, c) Saskatchewan, Canada, d) Alberta, Canada. Modified from Ref. [13].

gravels. These small-scale ring forms in Nunavut occur in a remote polar desert where vegetation and human impact is limited, acting as pristine examples that may provide additional insight into the origin of these features.

Understanding how ring forms develop not only aids scientists in reconstructing climate history over the past ~11,000 years and earlier within the Canadian Arctic and elsewhere, but it also helps to better understand how Arctic landscapes respond to a changing climate. Studying ring forms also holds value beyond Earth, as these landforms have been proposed to be a valuable terrestrial analogue for similar features found on Mars called “brain” terrain [14]. Understanding the processes that give rise to ring forms could provide insight into how brain terrain forms on Mars and how it is linked to ice and past

climate [17], providing opportunities for landing site selection for future Martian missions in the search for evidence of water ice.

SUBGLACIAL CHANNEL SYSTEMS

Subglacial meltwater channel systems are drainage pathways that develop underneath and at the margins of glaciers and ice caps. Although Devon Island in the Canadian High Arctic archipelago was covered by an ice sheet during the last glacial period, there is a conspicuous lack of typical glacial landforms in the region. Instead, subglacial meltwater channels dominate Devon Island's interior plateau (Fig. 6). In contrast to rivers, subglacial channels have networks that are composed of relatively short, straight, and evenly spaced valleys that drain into a wider, deeper main stem channel (Fig. 6d). Channel cross-sections are flat-bottomed with steep walls and along-channel (longitudinal) profiles are convex with some undulations, characteristic of formation or modification from pressurized water flow (i.e., subglacial meltwater) [18]. The presence of these interconnected channels in conjunction with distinct erosional surfaces suggests the development of a more complex out-branching of subglacial channel networks due to relatively high flow discharge events (i.e., floods). The characterization of subglacial meltwater pathways, including their spatial distribution and association with other landforms, can directly contribute to interpretations of paleoclimate and patterns of glacial advance and retreat.

Recent work has focused on the geomorphology of subglacial meltwater channels on Devon Island to build an interpretation of meltwater sources (i.e. supraglacial, englacial, subglacial) and timing and dynamics of meltwater delivery to the ice-bed interface [19]. Subglacial channels on Devon Island have also been the subject of analogue studies for morphologically similar features such as valley networks and shallow valleys on Mars. Due to the polar desert climate coupled with the lack of vegetation on Devon Island, it is a prime candidate analogue site for glacial and subglacial processes on Mars. Consistent with recent climate models that predict a cold and dry early Mars [17], valley network geomorphology on Mars [20] suggests erosion due to localized basal meltwater flow under ice sheets is a plausible explanation for these landforms. Continued work to further characterize and interpret terrestrial subglacial channels, particularly those on Devon Island, can also help inform and reconstruct Martian glacial history, ice dynamics, and paleoclimate.

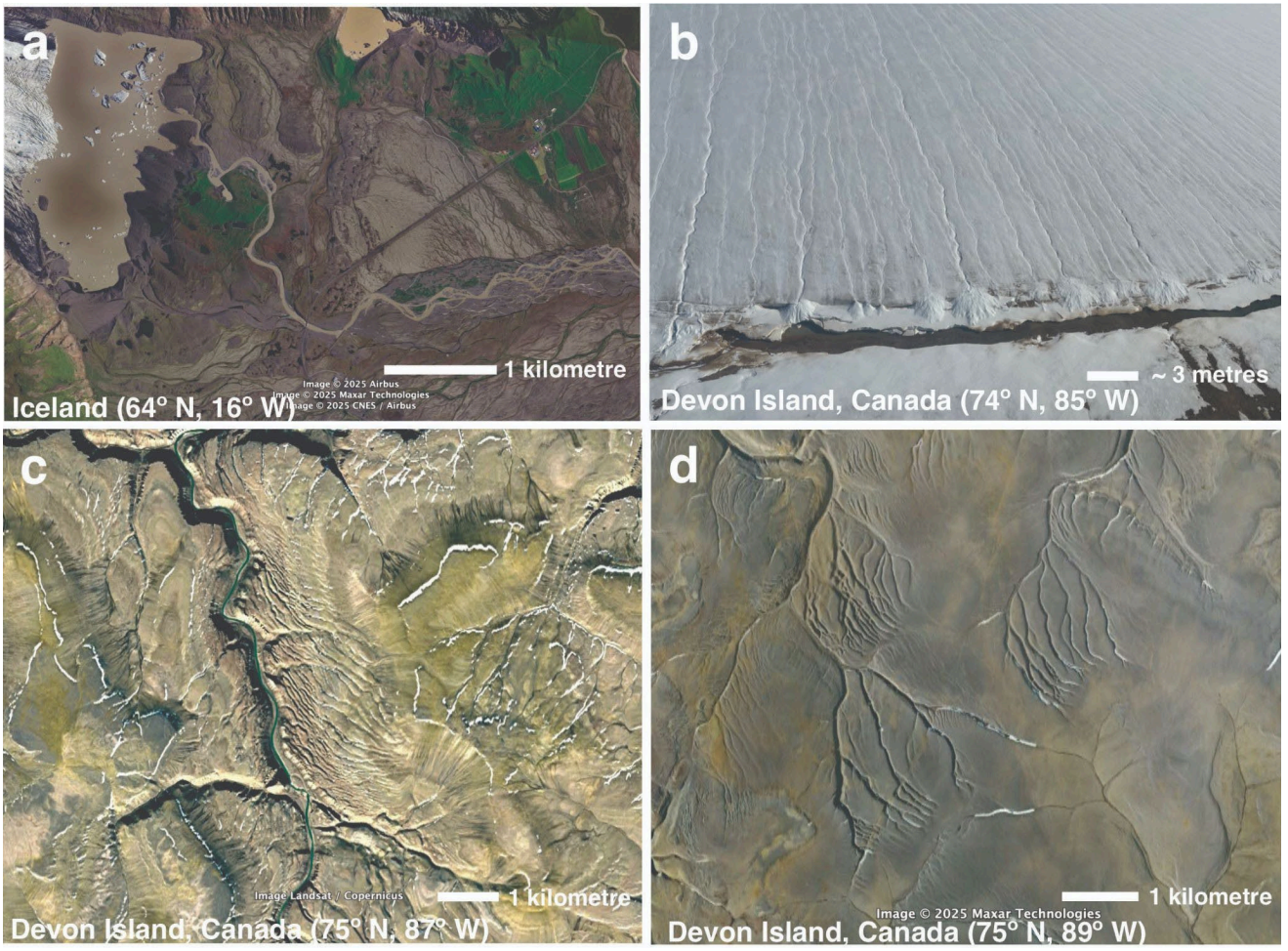


Figure 6. Various types of meltwater channels. a) Proglacial, b) supraglacial, c) lateral (marginal), and d) subglacial channels perched on the side of a large valley. Images a, c, and d from Google Earth (Airbus/MAXAR Imagery). Image b) taken in the field in July 2024 by Simona Ruso.

CONCLUSION

Earth's cold regions are home to a striking array of natural patterns on a range of scales. The Canadian Arctic provides a natural laboratory to study a variety of patterns of both glacial and periglacial origins, from metre-scale sorted circles and stripes to kilometre-scale subglacial channel networks. Though mathematical theories exist that can reproduce visually similar patterns, details of the driving physical processes are not fully understood. Research is being conducted across Canada to understand the mechanisms by which these patterns form and inform reconstructions of past climate conditions on Earth and other planets.

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