Thermal contraction crack polygons in Nunavik (northern Quebec): Distribution and development of polygonal patterned ground

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Abstract
We evaluated the spatial distribution and morphological variability of thermal contraction crack polygon (TCCP) networks across Nunavik, a 440,000-km² region of northern Quebec that spans the northward transition from discontinuous to continuous permafrost. A population of 4,567 TCCP sites was sampled and analyzed from 80,737 georeferenced high-resolution aerial photographs and 264,504 km² of ESRI satellite basemaps. For each site, six parameters were inventoried and compiled into a database: (a) network geometric arrangement; (b) intersection angles; (c) number of subdivisions and nested polygons (referred to as generations of development); (d) dominant polygon morphology; (e) surficial geology; and (f) vegetation cover. Statistical analyses of the tabulated data revealed a strong association between Holocene glacial, glacio-fluvial, fluvial, marine, and organic landforms and the different intersection angles in the networks, providing insight into how the processes of thermal contraction cracking function and manifest geomorphically across varied permafrost landscapes. Orthogonal polygons (intersection angle of 90°) dominate on flat terrains where the thermo-mechanical stresses are probably spatially homogeneous. Hexagonal (angles of 120°) and poorly structured polygons tend to form where topography variability probably generates heterogeneous heat flow patterns and thermo-mechanical stresses in the ground, resulting in irregular cracking patterns.

Keywords
ice wedges, mixed wedges, Nunavik, permafrost, soil wedges, thermal contraction crack polygons, thermo-mechanical stresses

1 | INTRODUCTION

Tundra polygons are the most widespread periglacial landforms in subarctic and arctic environments, and the ice wedges that underlie them account for an important fraction of ground ice in permafrost. Polygons in the periglacial environment develop due to thermal contraction cracking under low winter temperatures and during spells of rapid cooling that generate vertical frost cracks that may reach depths of up to 10 m. Frost cracks organize themselves in various geometric patterns [e.g., quadrangles [90°, T-junction] or hexagons [120°, Y-junction]] depending on the geometry of the stress field in the terrain, following theoretical thermo-mechanical principles. Recent observations and field measurements with instrumentation using breaking electrical wires, extensometers, accelerometers, thermistors,
and data loggers have confirmed the theory and yielded some empirical information on the temperature regimes that regulate frost cracking.\textsuperscript{6–15}

Contraction cracks typically infill with snowmelt water in spring, and refreezing of this snowmelt leads to the formation of ice wedges.\textsuperscript{4} However, in some environments, depending on local conditions such as soil moisture and sediment availability, the cracks may be filled with sand, organic matter, mud, or mixtures of soil and ice, feeding the formation of sand wedges, composite wedges (mixed), soil wedges, and soil veins.\textsuperscript{5} Because the methodology in this study is based mostly on surface pattern classification and mapping over a vast territory with a limited number of field observations, we use herein the generic term “thermal contraction crack polygon” (TCCP) as it covers the different varieties of documented crack-filling polygons.

Nunavik (northern Quebec) is a region with a strong climate gradient transitioning between boreal forest and tundra. Moreover, the region has a complex Holocene history with soil materials derived from various surficial geological settings and with terrain exposure of various ages associated with deglaciation, post-glacial land emergence, Holocene climate changes, and vegetation history (e.g., tree-line fluctuations, forest fires and recent shrubification). Climate warming and subsequent permafrost thaw pose a significant risk to infrastructure in Arctic communities.\textsuperscript{16,17} Environments with TCCP networks are considered particularly sensitive to climatic disturbances and thawing permafrost and melting ice wedges can create ponds, settlement, and thermo-erosional gullies, resulting in possible damage to roads, houses, and airport runways.\textsuperscript{18–21} Despite abundant research in Nunavik on permafrost, TCCPs and on ground thermal contraction processes, no systematic mapping of TCCPs and analysis of their geomorphic and climatic controls has been undertaken before. As a result, the geological and ecological terrain conditions under which TCCPs formed and have evolved, as well as how they manifest across the landscape, are largely unknown. As most of the permafrost in Nunavik is epigenetic and aggraded originally in pre-existing Quaternary landforms, we can infer that the pre-existing geomorphological contexts exerted some physical control on the formation and the resulting morphologies of the TCCPs.

We propose that by classifying morphological and ecological differences at multiple polygon sites across a range of geological and climatic contexts, conclusions can be drawn about past and current cracking conditions in Nunavik, with some inferences on permafrost history and future terrain susceptibility to change. More specifically, the specific objectives aim to:

1. Classify the TCCPs in Nunavik based on their morphology.
2. Test statistical relationships between the morphologies of TCCPs and Quaternary deposits and landforms.
3. Improve understanding of the spatial distribution of TCCPs and their morphological characteristics.

These data and analyses will provide a basis for deriving thermo-mechanical processes of TCCP formation under a range of common/typical site conditions and inferring the impacts of Holocene ecological changes on TCCP activity and morphology.

2 | BACKGROUND

Frost contraction in permafrost terrain and opening of linear cracks forming polygonal patterns occur after freeze-back of the active layer, usually in midwinter when ground temperatures are below at least \(-10 ^\circ \text{C}\) for prolonged periods and a ground cooling rate ranged between \(-0.1 \text{ and } -0.6 \text{ } ^\circ \text{C} \text{ d}^{-1}\) for two or more successive days (Figure 1).\textsuperscript{1,5,10–15,22} Regardless of the type of crack infilling (i.e., ice, sand, organic matter), the networks share common configurations: a pattern of cracks forming often orthogonal (90\(^\circ\)) and, sometimes, hexagonal (120\(^\circ\)) surface patterns, which may be poorly organized or oriented with variable sizes of polygons.\textsuperscript{5} The surface factors governing the formation of TCCPs (air and ground temperatures, vegetation cover, snow cover, and soil materials and moisture) have been abundantly discussed by previous researchers.\textsuperscript{1,5–15,22} For instance, Mackay\textsuperscript{23,24} highlighted the relationship between air temperature and cracking in areas with low snow cover. In fact, heavy snowfall can inhibit cracking. Along the western Arctic coast, no ice new veins above the ice wedges were observed when the average snow depth exceeded about 60 cm.

Orthogonal patterns develop in an evolutionary sequence in which the primary cracks are intersected by secondary cracks that subdivide the stress field, thus forming right-angled, orthogonal patterns.\textsuperscript{1,25} Primary cracks develop perpendicular to the general orientation of the deposit (e.g., a raised beach or a river terrace). Secondary cracks (often smaller) intersect them, cutting out quadrilaterals. These observations apply particularly well to newly emerged areas where it is possible to see the propagation and expansion of cracks in sediments (Figure S1). For hexagonal networks (120\(^\circ\)), Lachenbruch\textsuperscript{26} and Plug and Werner\textsuperscript{26,27} suggest that the cracks develop simultaneously, probably from random points in a homogeneous soil with uniform thermo-mechanical properties.

Ice-wedge polygons are the most abundant, observed, and studied TCCPs.\textsuperscript{1,6,9–13,21} They are located exclusively in permafrost environments and cover almost a million square miles (2,600,000 km\(^2\)) in tundra and boreal forest across the Northern Hemisphere.\textsuperscript{28} They occur widely in nonbedrock permafrost environments, such as lowland areas, tundra wetlands, alluvial plains, along hilltops, and on glacial deposits,\textsuperscript{6,9,13,29–31} and can have different morphologies, being either low-centered, flat, or high-centered.\textsuperscript{9} Baydarjahks,\textsuperscript{32} also spelled baydzherakh,\textsuperscript{30,33} are patterned fields of mounds resulting from advanced ice-wedge melting in high-centered polygons (see section 8 Terminological note). Sand wedges are known to develop in cold and arid polar regions, where there is little or no water supply and a very thin snow cover.\textsuperscript{34} Sand wedges occur where mean annual air temperatures are between \(-4 \text{ and } -8 ^\circ \text{C}\) and mean annual precipitation is \(<100 \text{ mm}\). Black\textsuperscript{35} identified this type of wedge filling in Antarctica, and recently Wolfe \textit{et al.}\textsuperscript{36} highlighted the presence of sand wedges in sandy Quaternary deposits near Great Slave Lake in the
Northwest Territories. Composite wedges, or mixed wedges, are filled by a mixture of materials (i.e., sand and ice) filling vertical veins and growing into wedges. Unlike ice wedges, sand wedges, or composite wedges, soil wedges are distinguishable based on the V-shaped pedogenic horizons in the first few centimeters of the seasonally frozen layer under polygon sides (Figure 1). They are not limited

| Structure/T CCP Activity | Filled by ice (Ice wedge) | Filled by a combination of ice and sand (Mixed) | Filled by soil (Soil wedge with ice wedge) | Filled by sand (Sand wedge) |
|--------------------------|----------------------------|-----------------------------------------------|-------------------------------------------|-----------------------------|
| Active cracking          | ![Diagram](image1)          | ![Diagram](image2)                            | ![Diagram](image3)                        | ![Diagram](image4)          |
| Inactive cracking (dormant) | ![Diagram](image5)         | ![Diagram](image6)                            | ![Diagram](image7)                        | ![Diagram](image8)          |
| Cast                     | ![Diagram](image9)         | ![Diagram](image10)                           | ![Diagram](image11)                       | ![Diagram](image12)         |

**Figure 1** Different types of wedge fillings (TCCPs) that can be identified in Nunavik [Colour figure can be viewed at wileyonlinelibrary.com]

**Figure 2** Distribution of permafrost in Nunavik according to TTOP outputs for the period 2000–2016 (modified from L’Hérault and Allard [43]) [Colour figure can be viewed at wileyonlinelibrary.com]
to permafrost zones, but can also be found in seasonally frozen regions and are formed principally near the surface, in the active layer and the transition layer and do not propagate into permafrost.\textsuperscript{1,35–41} In Nunavik, soil wedges are in areas where mean annual ground temperatures are between 0 and –5°C.\textsuperscript{38}

3 | NUNAVIK

Nunavik is the Inuit territory of northern Quebec, above the 55th parallel and extending northward to the Hudson Strait, with an area of 443,685 km\(^2\). The spatial distribution of permafrost in Nunavik has been classified into five zones: continuous (>90% of the ground surface), extensive discontinuous (50–90% of the ground surface), discontinuous and dispersed (10–50% of the ground surface), sporadic (1–10% of the land area), and isolated patches or residual permafrost (<1% of the land area) (Figure 2).\textsuperscript{38,42,43}

In the Ungava Peninsula, permafrost is continuous and reaches depths of up to 630 m.\textsuperscript{44} In southern Nunavik, permafrost occurs sporadically or in isolated patches, and is often limited to ~10–20 m in thickness. Inland, bedrock geology consists of expanses of exposed Precambrian intrusive and metamorphic rocks, with surficial materials consisting of shallow (<2 m) and thick till covers and fields of glacial and glacioluvial deposits. In the coastal regions that were covered by the post-glacial Tyrrell (Hudson Bay side) and d’Iberville (Ungava Bay side) Seas, emerged silt and clays, post-glacial sandy–gravely deltaic sediments, and extensive series of raised sandy beaches make up large tracks of the landscape. Holocene organic deposits in the form of peatlands are distributed throughout depressions and flat areas over the whole territory.\textsuperscript{42,43} Southern Nunavik is covered by boreal forest and forest tundra (dominated by black spruce [Picea mariana]) and the northern part is covered by shrub tundra and herbaceous tundra. Approximately 40% of Nunavik is classified as subpolar/polar tundra (moss and lichen).\textsuperscript{42} Mean annual air temperatures (1981–2010) range from –3.6°C in Kuujjuarapik\textsuperscript{16} and –3.9°C in Kuujjuaq (2004–2018) near the treeline to –6.3°C in Salluit (2002–2018)\textsuperscript{17} near the tip of the Ungava Peninsula. The coldest part of Nunavik is on the Katnik Plateau in the Ungava Peninsula (~600 m a.s.l) where mean annual air temperature is about –10°C.

The post-glacial climate over the territory above the treeline in parts of Nunavik that was never submerged by post-glacial seas was conducive to the formation and the sustained presence of permafrost in what is now the continuous permafrost zone. However, the discontinuous permafrost parts of the region with shrub and forest tundra have a more complex ecological and climatic history that involves alternating periods of growth and decay of permafrost during the Late Holocene period and the 20th century.\textsuperscript{10,38} The timing of these paleoclimate shifts were also corroborated through the stratigraphic interpretation of past ice-wedge activity near Salluit (northern Quebec, Nunavik),\textsuperscript{10,45} and later backed by climate reconstruction by reverse modeling of deep temperature profiles at Raglan Mine.\textsuperscript{46} In all cases, the Little Ice Age (LIA) (roughly dated from ~1450 to 1900 AD) stands out as the probable coldest Late Holocene period in the region.\textsuperscript{10,45}

4 | METHODS

4.1 | Typological classification of polygonal networks

With reference to geomorphological observations in studies describing different varieties of polygon networks\textsuperscript{1,3,9,46–50} we developed a classification matrix to group the different morphologies of polygons across Nunavik. Six parameters were applied according to a series of attributes defined by their geometric properties and their local environmental settings: polygonal network geometric arrangement, intersection angles, surficial geology and Quaternary landforms, polygonal morphologies, number of generations (i.e., number of subdivisions and orders of nested polygons; referred to as “number of generations” in the remainder of the paper), and structure of the vegetation cover (Table 1).

When a polygonal network fulfilling the criteria established in Table 1 was either on aerial photographs or on the ArcMap basemaps, a marker was added on ArcMap 10.7 to collect the geographical coordinates. Then, the polygonal network was defined as a site. A 250-m buffer zone was delineated around each site, and other networks lying within the buffer zone were considered to belong to the same polygonal network. However, if a network within that 250-m buffer had different parameters (e.g., morphology, intersection angles, surficial geology), this other network was considered a unique and different TCCP network site. This method allows the identification of both extensive continuous (open) areas of polygonal networks and small discrete (closed) areas. In some cases, different characteristics related to the same parameter were found in the same network. In this scenario, the predominant form (≥60%) was noted in the classification grid. However, if two characteristics were equally distributed in the same network (~40–60%), they were classified as mixed. This occurred particularly for the parameters of intersection angles and polygon morphologies (high-flat or low-centered polygons).

4.2 | Acquisition of aerial photographs (TCCP mapping)

We used GPS-georeferenced high-resolution oblique aerial photographs collected between 2010 and 2015 and taken during helicopter flights by staff of the Ministère des Forêts, de la Faune et des Parcs du Québec (MFFP) for mapping vegetation, and by researchers of the Centre d’études nordiques (CEN) for mapping the coastline\textsuperscript{51} to investigate the spatial distribution of the TCCPs. We also used vertical aerial photographs provided by Natural Resources Canada (NRCan). These images are from 1953 to 1959 and are at 1:40,000 and 1:50,000 nominal scales taken at altitudes ranging from 5,540 to 21,650 feet. In total, 80,137 aerial photographs (MFFP: 42,474/CEN: 36,490/NRCan: 1,173) were analyzed to ascertain the occurrence of TCCPs across Nunavik (Figure 3a,b). In addition, ESRI ArcMap 10.7 satellite imagery basemaps were used to fill gaps in the photographic...
| Characteristic feature                  | Category                  | Definition                                                                                                                                 |
|----------------------------------------|---------------------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Network arrangement                    | Unorganized network       | The network consists of linear frost cracks that mostly do not connect and do not form geometric figures                                  |
| Random pattern                         |                           | The structure of the TCCP network was formed randomly (closed polygons have no specific structure in plan view)                           |
| Structured pattern                     |                           | The structure of the TCCP network was formed according to a general geometric pattern (concentric, hexagonal, and orthogonal).       |
| Angle (intersections)                   | Orthogonal                | Orthogonal (T-junction) pattern (90°, right angle)                                                                                      |
|                                        | Hexagonal                 | Hexagonal angle (Y-junction, 120°)                                                                                                        |
|                                        | Curved                    | The angles curved at intersections to form right angles. Always included with mixed angles                                               |
|                                        | Mixed                     | The TCCP network consists of several types of intersections                                                                               |
| \Generation (polygon subdivision)      | Primary crack polygons    | No subdivision is found in the TCCP network                                                                                               |
|                                        | Secondary crack polygons  | Primary crack polygon networks are intersected and divided by troughs that form smaller polygons                                          |
|                                        | Tertiary crack polygons   | Secondary crack polygon networks are intersected and divided by troughs that form smaller polygons                                          |
| \Polygon morphology (rims/troughs)     | Low-lefted polygons       | The left of the polygons is depressed and occupied by wetlands or contains water                                                              |
|                                        | Flat polygons             | The left of the TCCP is flat                                                                                                              |
|                                        | Slightly high-lefted polygons | The left of the TCCP is slightly domed                                                  |
|                                        | High-lefted polygons      | The left of the TCCP is greatly domed                                                   |
|                                        | Baydjarakhs               | Polygons with high lefts due to deepening of the troughs by melting ice wedges or by thermo-erosion                                         |
|                                        | Mixed polygons            | TCCP networks are composed of different types of shape (low-/high-lefted polygons, flat, etc.)                                         |
| Surficial geology                      | Fluvial                    | Usually consist of gravel and sand as well as a small proportion of silt and clay (stream)                                               |
|                                        | Glaciofluvial             | Sand, gravel, pebbles, stones, and blocks. Pro- or subglacial environment.                                                                |
|                                        | Glacial (till, drumlins)  | Poorly sorted material with a sand/silt matrix deposited directly by glacial ice and showing no stratification (blocks, stones, pebbles, sand, etc.) |
|                                        | Raised beaches (littoral/marine) | Made of sand, gravel, pebbles, stones, and blocks                                          |
|                                        | Current intertidal        | Current beaches and coastal marshes                                                        |
|                                        | Organic                   | Consisting of more or less decomposed organic matter, bogs, fens, lichens on surface when dry, etc.                                      |
| Vegetation cover                       | Ecological domain         | Forest tundra, shrub tundra, or herbaceous tundra                                          |
|                                        | Density                   |                                                                                                                                           |
The analysis of ESRI satellite imagery (1:10,000) enabled us to cover 264,504 km² of territory, representing more than half of the area of Nunavik (Figure 3c). The resolution of the basemaps ranged from 0.10 to 1 m, which was sufficient to distinguish the parameters associated with the polygons. Each site with TCCPs was systematically analyzed according to the list of parameters in Table 1.

TCCPs located using the oblique aerial photographs were repositioned to their appropriate locations to avoid duplication with the TCCPs located via the ESRI basemaps. Area measurements for polygon networks were performed using the raster basemaps and the editor tool in ArcMap 10.7. The areas were calculated based on the Quebec Lambert Conformal Conic projection. To assess the influence of local and regional topography on TCCP parameters, topography and slope data were derived from the ArcticDEM, which is a 2-m digital elevation model. One specific site (60°32′46.4″N, 71°09′41.8″W) was examined in detail to determine how elevation variations are related to polygonal patterns on hillslopes and irregular topography.

A database containing the surveyed sites was built in ESRI ArcMap 10.7, allowing for classification into polygonal network types and statistical analyses of polygonal network parameters. The metadata for the database contain the coordinates for each site, the date of acquisition of the aerial photographs, elevation, and the parameters described for each site from Table 1. A total of 216 TCCP sites were located without having their parameters determined because of the low resolution of the available images. To minimize the uncertainty of the mapping procedure, interpretation of the aerial photographs was done twice, once at the beginning of the project, and a year later before starting the statistical tests.

4.3 | Statistical tests

4.3.1 | Chi-squared test ($\chi^2$)

A statistical analysis of the parameters of the mapped polygons was applied to test whether associations existed between the different TCCP morphological parameters and between the TCCPs and the environmental factors. The association between two categorical variables can be assessed using the chi-square test ($\chi^2$) (Equation 1). The general formula for $\chi^2$ is:

$$\chi^2 = \sum \frac{(O - E)^2}{E}$$

where $O$ is the observed frequency and $E$ is the expected frequency.
Cramér’s V test (Equation 445 Row marginal total

For instance, the is 2,458.92. An alternative hypothesis (H1: O ≠ E) and are not independent. The null hypothesis is rejected when the probability or P-value is less than the alpha level (P ≤ 0.05 or P ≤ 0.01), also called a significance level, chosen according to the degrees of freedom (df) (Equation 3).

\[
Df = (R - 1)(C - 1)
\]

where R is the number of rows in the table and C is the number of columns in the table. For instance, the df between the intersection angles and the surficial geology [(3 − 1) × (6 − 1)] would be 10 (Table 2). For a degree of freedom that corresponds to 10, the value of \( \chi^2 \) (95%) is 18.307. As 2,458.92 is greater than 18.307 (P ≤ 0.05), the null hypothesis (H0: O = E) is rejected, and the alternative hypothesis is accepted (H1: O ≠ E). A significant test rejecting the null hypothesis suggests that the two variables tested are associated (H1: O ≠ E) and are not independent.

### 4.3.2 Association test: Cramér’s V (V)

Once the \( \chi^2 \) test establishes whether a dependency relationship exists between two categorical variables, other complementary tests must be used to measure the intensity of this relationship. Cramér’s V (V) determines the intensity or the degrees of association between the two variables or data sets. Cramér’s V test (Equation 4) is based on chi-square statistics and the applied formula is:

\[
V = \sqrt{\frac{\chi^2}{n(k-1)}}
\]

where \( \chi^2 \) is the chi-square test value, \( n \) is the total number of samples observed, \( k \) is the lower number of categories of either variable (row or column), and V denotes the strength association between variables. The value of V lies between 0 and 1. A value near 1 indicates that the correlation is strong between variables and a value near 0 indicates a weak correlation between variables.

### Table 2 Contingency table of surficial geology and intersection (angles) with observed (Obs.) and excepted frequencies (Exp.)

| Intersections (angle) | Surficial geology |
|-----------------------|-------------------|
|                       | Fluvial | Glaciofluvial | Glacial (till, drumlins) | Current intertidal | Raised beaches (littoral/marine) | Organic matter | Total |
| Mixed—Obs.            | 36      | 50            | 84                      | 0                 | 84                             | 191            | 445   |
| Mixed—Exp.            | 37.09   | 42.98         | 205.71                  | 1.03              | 80.59                          | 77.59          | 445   |
| Hexagonal—Obs.        | 43      | 254           | 1,810                   | 1                 | 108                            | 132            | 2,348 |
| Hexagonal—Exp.        | 195.71  | 226.79        | 1,085.41                | 5.45              | 425.22                         | 409.41         | 2,348 |
| Orthogonal—Obs.       | 280     | 112           | 97                      | 9                 | 588                            | 428            | 1,514 |
| Orthogonal—Exp.       | 126.20  | 146.23        | 699.88                  | 3.52              | 274.19                         | 263.99         | 1,514 |
| Total                 | 359     | 416           | 1,991                   | 10                | 780                            | 751            | 4,307 |

| Statistical test      | Value   | df    | Probability |
|-----------------------|---------|-------|-------------|
| \( \chi^2 \)         | 2,458.92| 10    | P ≤ 0.05    |

where O is the observed cell frequency, E is the expected cell frequency, \( i \) runs from 1, 2, … to \( n \), where \( n \) is the number of cells in the contingency table, and \( \Sigma \) stands for the sum of the results combined.56

For instance, the \( \chi^2 \) test was performed using the intersection angle and surficial deposit variables to determine whether these variables are associated (Table 2). This allows examination of whether the difference between the observed and expected frequencies (Equation 2) of two categorical variables (here, the variables are the network parameters) is due to chance.53

In Table 2, the number of TCCPs forming in fluvial deposits with mixed intersection angles (observed: O) is 36; to find the expected frequency (E) for the \( \chi^2 \) test, the following formula was applied:

\[
E = \frac{\text{Row marginal total} \times \text{Column marginal total}}{\text{Overall total}}
\]

where Row marginal total is the sum of the row entries (445), Column marginal total is the sum of the column entries (359), and Overall total is the total sum of the sample (4,307).56 Here, the expected value is 37.09. Once the values of all the expected frequencies are determined, we can deduce the \( \chi^2 \) values. In this example case, the \( \chi^2 \) value for Table 2 is 2,458.92.

Then, two hypotheses can be subsequently tested:

1. The null hypothesis (H0: O = E): the selected variables are independent.
2. The alternative hypothesis (H1: O ≠ E): there is an association between the two variables.
TABLE 3  Percentage of different geological environments where TCCPs are identified

| Surficial geology              | Number | Percentage |
|-------------------------------|--------|------------|
| Glacial (till, moraine, drumlin) | 1,991  | 43.6%      |
| Raised beaches (littoral/marine)| 819    | 17.9%      |
| Organic matter (peat)          | 751    | 16.4%      |
| Glaciofluvial                  | 416    | 9.1%       |
| Fluvial                        | 359    | 7.9%       |
| Current intertidal             | 15     | 0.3%       |
| Unidentified deposits          | 216    | 4.7%       |
| Total                          | 4,567  | 100%       |

4.3.3 Geographic information systems analysis of polygonal networks

Based on the work of Kokelj et al21 on the distribution and the size of ice wedges, we attempted to evaluate the variation of the surface area affected by polygonal networks with latitude across Nunavik. To calculate the relationship between the two variables, Spearman’s rho ($\rho$) test was used:

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)}$$

where $d_i$ is the difference between the two ranks of each observation, $n$ is the number of observations, $\Sigma$ is the sum of the results combined, and $\rho$ is the rank correlation between the observations, which ranges between $-1$ and $1$. A negative value indicates a negative correlation (i.e., when one variable increases and the other decreases), and a positive value indicates a positive correlation (i.e., when one variable increases, so does the other). For this, 259 identified polygonal network fields in a variety of sedimentary environments were randomly sampled across the territory to determine the relationship between their latitudinal distribution and surface area.

5 RESULTS

5.1 General distribution of TCCPs and frequencies of occurrence in various surficial geological and ecological settings

Examination of aerial photographs and assessment of TCCP parameters showed that the distribution of TCCPs is largely controlled by Quaternary geology, vegetation, and climate. In total, 4,567 TCCP networks were identified across Nunavik. The majority of TCCPs in Nunavik occur in glacial deposits (1,991 sites, 44%), such as till and on top of drumlins. TCCPs are also abundant on raised sandy beach deposits (819 sites, 18%) and in organic deposits associated with polygonal peat plateaus and drained lake beds (751 sites, 16%) (Table 3; Figure 4). The highest concentration of TCCPs is found in the forest tundra, in the drumlin fields ~50 km northeast of Umiujaq near the Hudson Bay coast (Supporting Information Figure S2). In southern Nunavik, the raised semi-ovoid or elongated shape of drumlins favors wind sweeping of snow on their tops, creating favorable ground temperature regimes for the development of TCCPs.

A total of 1,997 polygonal networks areas were identified across the forest tundra and shrub tundra domain. From these 1,997 sites, 1,680 were identified on glacial deposits, representing 84% of the total polygonal networks in the forest and shrub domains. Seventy six per cent (1,510 sites) of TCCP sites are hosted in glacial deposits on bare drumlin tops within the forest tundra and shrub domain and these are also associated with hexagonal angles, with flat shapes and no subdivisions within the networks (Figures 5 and 6).

North of the 60th parallel in the Ungava Peninsula, an increase in the diversity of TCCP characteristics is observed across the herbaceous arctic tundra domain. This is due largely to the diversity of surficial deposits. In this northerly region, 2,073 sites (45%) are located throughout the peninsula where most of the TCCPs are in organic matter deposits (573 sites, 28%), raised sandy beach deposits (531 sites, 26%), or fluvial terraces (304 sites; 15%). Conversely, despite the abundance of glacial deposits throughout the Ungava Peninsula, TCCPs hosted in glacial deposits account for only 8% (174 sites) (Figure 6).

The relationships between latitude and the polygon site area in the various Quaternary deposits are shown in Figure 7. The area of TCCP sites is negatively correlated with latitude ($\rho = -0.848, P \leq 0.05$), so a decrease in polygon area characterizing a “site” is observed from south to north. Despite a greater local abundance of TCCP sites in the north, the mean area of a site is less than ~0.10 km$^2$ in the north versus ~0.85 km$^2$ in the south (mean $[\bar{x}] = 0.24$ km$^2$, SD $[\sigma] = 0.26$). This can be explained by the mosaic of thin till veneers and bedrock outcrops that characterize Ungava Peninsula. Both environments are unfavorable terrain for the development of polygon networks, compared to the extensive fields of unvegetated and snow-free drumlin tops and thick blankets of glacial deposits prone to thermal contraction in the southern half of Nunavik. Daigneault’s58 map of the Quaternary geology of the northern Ungava Peninsula indicates that bedrock extends to the surface of over 10% of the territory, and that 60% of the territory is covered by thin till veneer deposits of <1 m thick. Despite the abundance of scattered TCCPs over the peninsula and low temperatures favoring thermal contraction cracking, the surficial geology of the northern part of Nunavik is less favorable for open and extensive TCCP networks.

5.2 Relationships between polygon network types and compiled characteristics

The $\chi^2$ tests between all geometric parameters of the TCCPs, their morphologies, and Quaternary sediments were statistically significant ($P \leq 0.05, P \leq 0.01$) and were supported with a moderate or high association between variables ($\geq 0.20$) (Table 5). The intersection angles of the polygons vary according to the types of surficial
deposits and the Quaternary landforms on which they formed. The χ² test shows that there is a dependency between the type of surficial deposits and resulting orthogonal and hexagonal intersection angles ($P \leq 0.05$; $df: 18.31$). The V test demonstrates a strong relationship between the surficial sediment and intersection angles (0.53) (Table 4). The proportions of observed orthogonal networks on alluvial terraces (19%), organic deposits (28%), and raised beaches (39%) are greater than the expected frequencies. The same is true for the dominance of hexagonal networks (77%) on glacial deposits forming drumlins and moraines and glaciofluvial deposits such as eskers (11%) (Figure 8a).

Comparison of the number of generations in polygonal networks and the surficial deposits indicates that the χ² value (521.16) is much higher than the critical value (alpha: 5%) of 37.65 ($df: 10$). The V test indicates a moderate level of association between surficial deposit type and polygon subdivision (Table 5). Primary polygons are distributed over the entire territory of Nunavik and are mainly found on glacial deposits (51%). Secondary networks are found predominantly in fluvial terraces (20%), organic matter deposits (23%), and littoral terraces or raised beaches (40%) which abound over the Ungava Peninsula. Tertiary polygons, which dissect secondary polygon networks, are only located in sandy raised beaches (100%) along the shore of Hudson Strait (Figure 8b).

The χ² tests also highlighted the strong association between the morphology of the polygons and the types of surficial deposits on which they formed. The null hypothesis is rejected because the χ² value (2,183.36) is higher than the level of significance (alpha: 5%) of 37.65 ($df: 25$). In addition, Cramér’s V is 0.32, indicating a moderate association between the morphology of the polygons and the types of surficial deposits (Table 5). Of the polygons classified as baydjarakh, low- and high-centered types are more abundant on alluvial terraces, littoral, marine sediments, and organic deposits. TCCPs with mixed morphologies (i.e., raised rims or elevated centers) preferentially occur in organic deposits. Flat polygons are common in various deposits, but occur preferentially in glacial and glaciofluvial deposits (Figure 8c).

6 | DISCUSSION
6.1 | Genesis, age, and activity of TCCPs in Nunavik

The distribution of TCCPs in Nunavik provides a good estimate of the extent of permafrost and perennially frost cracking processes at the end of the last deglaciation and throughout the Holocene. However, as we characterized TCCPs over a large area with limited field
FIGURE 5  Spatial distribution showing dominant TCCP characteristics based on 5 × 5-km grid cells across Nunavik for: (a) abundance of angles (intersections); (b) morphology of polygonal networks; (c) number of generations of polygonal networks (i.e., subdivision of polygons by multiple generation of cracks); (d) histogram based on the location of TCCPs according to the TTOP model (2000–2016) for Nunavik. The number (4,288) is slightly lower than the number of TCCPs (4,567) identified due to insufficient covering close to large water bodies and the coast [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 6  (a) Thermal contraction crack polygons according to surficial geology; and (b) thermal contraction crack polygons according to ecological domain [Colour figure can be viewed at wileyonlinelibrary.com]
observations, the genesis and age of TCCPs in Nunavik cannot be determined but can only be estimated by following the deglaciation model. In contrast to expectation, the oldest polygons are not necessarily those located in the first deglaciation area or along the coastline. The geological context and glacial history of Nunavik is more complex than this. Mackay and Burn observed that ground cracking by freezing and ice wedge growth could occur in the first year of soil exposure if climatic conditions are favorable for thermal cracking (e.g., on a suddenly drained lake bottom). Therefore, frost cracking may have occurred as early as deglaciation in northern Quebec, 8–7 ka BP. However, only the tip of the Ungava Peninsula was ice-free around 8 ka BP, and the coastal region was then quickly submerged by the postglacial Iberville Sea. The initial stage of polygon development below the marine limit in the Ungava region was estimated around 4 ka BP according to the emergence curve established by Gray et al and peat material dating near Salluit.

The first TCCP network would probably have formed between the ice sheet margin and the limit of the postglacial seas in the central Ungava Peninsula around 6–5 ka BP. The dominance of streamlined landforms such as drumlins, fluted moraines, and eskers indicate the warm-based nature of the Laurentide Ice Sheet across the study area. Such subglacial conditions were not conducive to the formation of subglacial permafrost or patterned ground.

The emergence of coasts due to glacio-isostatic uplift and the retreat of post-glacial seas have gradually subjected new environments to conditions conducive to permafrost formation and frost cracking. Along the Ungava coast, peat deposits started to develop about 4.5–4.3 ka BP following retreat of the post-glacial Iberville Sea, which suggest that TCCPs were not formed until at least 4 ka BP. Further south, near Umiujaq, ice wedges and composite wedges formed on newly emerged lands about 1 ka after post-glacial regression of the Tyrrell Sea. Payette et al obtained a similar age of 900 AD for the formation of ice wedges south of Lake Tasiujaq (56°14′58″N, 76°17′39″W), formerly Lake Guillaume-Delisle. From Puvirnituq to Quaqtaq, perpendicular and parallel frost cracks along the shoreline on recently raised beaches and in current intertidal...

**TABLE 4** Results of $\chi^2$ between surficial geology and intersection (angles)

| Intersection (angles) | Fluvial | Glaciofluvial | Glacial (till, drumlin) | Current intertidal | Raised beaches | Organic matter | Total |
|-----------------------|---------|---------------|------------------------|-------------------|----------------|----------------|-------|
| Mixed (90–120°)       | 36      | 50            | 84                     | 0                 | 84             | 191            | 445   |
| Hexagonal (120°)      | 43      | 254           | 1.810                  | 1                 | 108            | 132            | 2,348 |
| Orthogonal (90°)      | 280     | 112           | 97                     | 9                 | 588            | 428            | 1,514 |
| Total                 | 359     | 416           | 1,991                  | 10                | 780            | 751            | 4,307 |

**Statistical test** | Value | df | Probability | Coefficient | Value |
|---------------------|-------|----|-------------|-------------|-------|
| $\chi^2$            | 2,458.92 | 10 | $P \leq 0.05$ | Cramér’s V | 0.53  |
FIGURE 8  Comparison between observed and expected frequencies. The x-axis represents the number of observations, and the y-axis represents the classes. Observed frequencies are represented by darker color while expected frequencies are indicated by light color. If a light color is longer than a dark color, this means that the expected frequencies are superior to the observed frequencies. O, organic deposit; Mr/Md, littoral and marine deposit; T, glacial deposit; GF, glaciofluvial. At, fluvial deposit; Obs., observed; Exp.; expected [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 5 Chi-square ($\chi^2$) and Cramér’s V (V) values. $X =$ the table contains cells with more than 20% with theoretical values less than five ($n > 5$). *$P \leq 0.05$. **$P \leq 0.01$. All tests were significant at a level of significance of $P \leq 0.01$ and consequently at a level of $P \leq 0.05$
sediments testify to the processes of emergence, permafrost aggradation and TCCP development (Supporting Information Figure S1). Coastal permafrost and TCCPs are significantly younger than their counterparts found in central Nunavik, with some probably still forming on beaches and in tidal zones. In the southern part of Nunavik, some TCCPs are now covered with shrubs and trees. Snow insulation associated with dense vegetation in the subarctic zone results in buffered thermal conditions that are currently not favorable for frost cracking. Drumlins, where TCCPs are mostly found, are composed of coarse-grained sediments that require colder ground temperatures for cracking (below −6°C) than the current ground and air temperatures recorded from the temperature at the top of permafrost (TTOP) model by L’Hérault and Allard. However, treeless and snow-free conditions at the top of the drumlins resulted in deeper cold penetration that favored the formation of polygon networks during the Late Holocene, when the air temperatures were colder than today. Some networks on drumlins were formed after deforestation by forest fires in colder periods. Due to lower expansion coefficients and thermal stresses, dry materials and conditions, characterized by larger polygons but often narrow and shallow troughs, usually favor the formation of soil wedges over ice wedges (Figure 9). Furthermore, Lachenbruch and Ulrich et al. noted that larger polygons tend to form in matrices with lower ice content, while smaller polygons are associated with higher ground ice content. Analysis of our aerial photographs throughout Nunavik showed that the size of individual polygons within a network is larger in the southern part of the territory than in the north (Supporting Information Figures S3–S6), and that the largest individual polygons are often present on sloping terrains. The type of deposit is also important, with larger individual polygons occurring in coarse-grained sediments with dry soil and smaller polygons occurring in fine-grained sediment and peatlands where moisture is available. Indeed, Jetchick and Allard revealed that the size of individual polygons on drumlins ranges from 10 to 30 m, consistent with our observations. We also infer that permafrost adjacent to wedges located in heterogeneous coarse-grained sediments (i.e., on drumlins, eskers, and till mounds) is associated with low ground ice content due to a lower expansion coefficient and thermal stress. In contrast, permafrost adjacent to smaller wedges found in fine-grained homogeneous deposits may be related to higher ground ice contents (Figures 10 and 11).

6.2 | Morphology of TCCPs

Despite a comprehensive characterization of TCCPs over a large area, uncertainties remain regarding the polygon fills (ice, sand, or composites). However, major types of TCCPs were classified by morphology and grouped to distinguish between ice-wedge polygons, sand-wedge polygons or mixed-wedge polygons. In fact it was possible to identify low-centered TCCPs due to the trough shoulders that develop as the growing ice wedge displaces the adjacent soil. Similarly, most high-centered polygons and baydjarakhs have been associated with ice wedges because they probably result from the deepening of troughs due to the melting of wedge ice along their sides (Supporting Information Figure S7). The abundance of TCCPs in peatlands near Ungava Bay and over the Ungava Peninsula indicates the important role of organic deposits in ice wedge development as most of the high-centered, low-centered, and baydjarakhs were located in organic soils and fine-grained deposits where wedge ice growth could occur under the
past and current climate (Figures 5 and 6). Péwé also notes that low-centered polygons (or raised edges) are associated with cracking activity and the growth of ice wedges. Mackay nuances Péwé’s comments by adding that the trough shoulders and rims of low-centered polygons are not necessarily indicative of frequent ice wedge cracking as suggested, but rather associated with the degree of polygon development. However, flat-centered polygons cannot be excluded from the analysis and may also be composed of ice wedges that can be concealed by surface sedimentation or peat accumulation.

Analysis of TCCPs across Nunavik territory revealed an association between latitude, number of generations of TCCPs, surficial geology, and TTOP. The spatial patterns of TCCPs appear to be altered by extreme and cold climate conditions. TCCPs are mostly found where TTOP is currently between -7 and -3°C, and several TCCPs are located where TTOP is above 1°C (Figure 5c). The occurrence of multigenerational polygonal terrains matches the TTOP model of Nunavik by L’Hérault and Allard. According to their model, secondary and tertiary crack polygons lie where the current TTOP varies between -4 and -9°C, implying very low ground temperatures in winter (Figure 5d). Secondary and tertiary polygons occur mainly on wide, open north-facing coasts along Hudson Bay and Hudson Strait, with high wind (fetch) energy conditions where snow can be easily eroded and removed. It is more likely that the development of multigenerational polygons is the result of colder climate episodes affecting previously formed networks rather than the snow insulation of troughs.

6.3 Relationship between network geometry and local eco-geomorphological conditions

In Nunavik, polygonal networks with hexagonal angles are more abundant and widespread across the territory than orthogonal networks. Indeed, 54% of the networks identified were dominated by hexagonal angles. French noted that many descriptions of polygonal networks contradict the dominant theory proposed by Lachenbruch, in which orthogonal networks tend to develop more frequently than hexagonal networks. French attempted to provide a hypothetical explanation by noting that hexagonal networks would develop preferentially in a homogeneous material, subjected to long periods of continuous and uniform cold climate conditions, and that orthogonal networks develop in heterogeneous “young” materials with changing climatic conditions. Our χ² test results suggest otherwise.

Our data and analyses indicate that intersection angles formed according to the polygon size, local topography, and slope of the surficial deposit in which they are hosted (Table 4, Figures 5 and 6). It has been suggested that grain size distribution of soil materials and
surface wetness may play a function in the development of polygonal networks and that thermal contraction coefficients may vary with different sediment deposits. Thus, the stress field within certain substrates would not be homogeneous, such as in tills which are composed of various sediment sizes. However, it can be deduced from our statistics that the shape and extent of the ground surface area exposed to cooling largely determine the 3D homogeneity (mainly orthogonal intersections) or heterogeneity (mainly hexagonal and random intersections) of the temperature gradients in the ground that induce the stress field responsible for thermal contraction cracking. Our mapping demonstrates the influence of topography on polygonal network shape, where raised beaches, river terraces, flat and wide eskers, and flat and large drumlins preferentially support orthogonal networks, whereas well-drained reliefs, domed drumlins, round till mounds, and narrow eskers mainly support random and hexagonal patterns (Figure 9).

Topography, vegetation type, and abundance of snow influence ground temperature regimes that impact polygon network geometries. Observed orthogonal networks were preferentially associated with open flat surfaces without an insulating shrub and snow cover (Figure 8a). Thus, an equal (or thin) quantity of snow and a uniform vegetation cover over a wide area allow the propagation of uniform underground thermal stresses (Figure 10). Primary cracking would occur uniformly over the entire deposit, and then secondary cracking would develop perpendicular to the initial cracks, resulting in a dominance of orthogonal angles (90°). In contrast, in areas with irregular topography or variable vegetation height and snow depth, the thermal stress field is irregular due to the variation in surface conditions that influence ground temperatures. This creates a heterogeneous temperature field where thermal contraction is favored and initiated in colder elevated areas with little to no snow cover. A heterogeneous thermal stress field will disperse and fade into a less organized geometry on slopes where snow is thicker, resulting in more hexagonal networks such as on narrow esker ridges or elongated and oval drumlins (Figure 9b). On conical or rounded hills, the coldest spot in winter is the ridge top or the portion of flat tops exposed by wind erosion of snow, whereas the warmest location is the slope, also producing non-uniform stress fields in the ground (Figure 11). Indeed, Mackay suggests that primary cracking would initiate on the hilltop (i.e., the coldest location), which is consistent with our observations. The effect of variable snow cover induces variations in ground temperature distribution and gradients, resulting in heterogeneous thermo-mechanical stresses. Consequently, each crack on the hilltop to hill-slope transition occurs in response to local landscape dynamics and

![FIGURE 11](wileyonlinelibrary.com)
local thermal stress, based on local soil moisture, snow cover depths, and vegetation conditions. An example of the relationship between local topography and polygon geometries is shown in Figure 12, where an apparent hexagonal polygon network displays curved angles in response to sloping topography on an 18-m-high drumlin. Additional examples presented in the Supporting Information (Figure S3–S6) illustrate the influence of local topography on crack patterns and of preferential location for the development of polygonal networks. For instance, on convex slopes, the hexagonal networks gradually replace the orthogonal ones in the downward direction (see Figures S5B, and S6B). By comparing networks on an irregular versus flat topography, the preferential formation of orthogonal networks on flat spaces compared to the hexagonal networks on sloped landforms is apparent (see Figures S3-S6). Mixed networks, containing both quadrangles and hexagon angles, are more abundant in organic deposits; this appears to be due to the locations where those polygonal networks are formed. Most mixed networks formed on organic soils and peat deposits in topographic basins between rocky ridges where surface conditions, local topography, vegetation, and snow cover were highly variable (Figure 5).

In summary, polygon geometry is influenced strongly by local landscape topography, and relationships between slope, surface geology, and polygon intersections have been observed throughout Nunavik. Some similar observations have been made previously. For instance, Haltigin et al proposed that hexagonal and orthogonal networks may derive from different evolutionary paths; that is, orthogonal patterns do not evolve or transition into hexagonal patterns over time, as opposed to other theories implying that networks change after a substantial number of freeze–crack cycles.

For the orthogonal networks, some vertices may curve slightly over time, but the junction angles will remain mostly at $90^\circ$, and no evidence of pre-existing orthogonal cracks was found in the hexagonal polygons (Figure 5c,d). More recently, Frappier and Lacelle suggested that the spatial pattern of polygons is mostly influenced by the nature of the substrate. Our results appear to be consistent with these assumptions, but the nature of the substrate is often associated with landforms. Our results also show some inconsistencies with the often expressed idea that hexagonal polygons are formed in fine, homogeneous deposits while orthogonal polygons are found in coarse and heterogeneous materials. Further insight into the relationships between polygonal networks, topography, intersection angles, and ground conditions would benefit from work involving 3D modeling of thermal stresses on soils with different properties across different environmental, topographic, and climatic settings.

**CONCLUSIONS**

A total of 4,657 sites of TCCPs across Nunavik were identified, analyzed, and systematically described, with their key morphological and ecological parameters compiled in a GIS database. Significant statistical relationships were found between TCCP morphology, sediment type and landforms (topography), ground temperature (via TTOP), vegetation cover, and probable ice wedge presence. The following conclusions can be drawn:
1. In Nunavik, thermal contraction crack polygons are found preferentially in glacial, glaciofluvial, marine, littoral, and organic deposits. Areas of rock outcrops and till veneer ($\leq 1$ m) were not prone to polygon formation. In the southern part of the region, TCCPs are located on the top of drumlins and eskers. In contrast, TCCPs across the northern part of Ungava Peninsula are restricted to topographic depressions filled by organic matter, sandy river terraces in valleys, and sandy raised beach deposits along the coast. As a result of the spatial distribution of Quaternary deposits that favor TCCPs, polygonal networks are more prominent in the landscape in the southern part of Nunavik than in the northern part, along the Ungava Peninsula.

2. Polygon morphologies in Nunavik are influenced by the type of Quaternary landforms and deposits on which they have developed. Our field data and analyses show that orthogonal polygons dominate on flat surfaces and that hexagonal and open polygons dominate on sloping terrain and hillslopes with variable vegetation and snow cover. This suggests that homogeneous thermal gradients and stress fields probably occur over large flat surfaces with a single sediment type, favoring the development of orthogonal polygonal networks ($90^\circ$), whereas a heterogeneous thermal gradient and stress fields on variable topography and surface cover favor hexagonal or open networks with dominant angles of $120^\circ$ (Figure 5).

3. The northernmost portions of the Ungava Peninsula are where multigenerational polygon networks are found (nested networks), possibly a result of colder climate episodes during the Late Holocene affecting previously formed networks (e.g., subdivision during the LIA of pre-existing larger polygons). The oldest TCCPs in Nunavik probably began to form shortly after deglaciation around 6,000–5,000 years ago and have persisted through the Late Holocene in the continuous permafrost zone north of the treeline. In vast areas in southern Nunavik, TCCPs now covered by shrubs and trees must have formed under colder Holocene periods. TCCPs in the forest tundra zone probably have a complex history. Some may have formed after deglaciation and have become inactive (or fossil) with forest colonization. Others possibly formed in cold periods of the Late Holocene after deforestation and wild fires.

This study provides the first broad-scale empirical dataset describing the spatial distribution of TCCPs, ice-wedge polygons, and their characteristics over a large part of Nunavik. The present analysis offers a better understanding of the relationship between frost cracking, surficial geology, vegetation, snow cover, and topography in Nunavik. Some TCCPs may be associated with soil and sand wedges, but additional field validation is required to further examine their respective presence and spatial distribution. This study provides helpful data for calibrating and validating models that predict ground ice distribution in northeastern Canada. The TCCP dataset will be available on NordicanaD and PINGO.

8 | TERMINOLOGICAL NOTE

In this paper, we refer to thermal contraction crack polygon (TCCP) as patterned ground or tundra polygons resulting from thermal stresses in the ground. It was not possible to determine with certainty from aerial photographs whether polygon sides were filled with ice, sand, or a mixture of sediments. It was more prudent to use a generic term to create a classification that includes all types of polygonal networks. The term baydjarakh can be debated. Baydjarakh is an advanced stage of degradation of ice wedge polygon networks resulting from deepening of the troughs by melting ice wedges or by thermo-erosion. They are very similar to high-centered polygons, but baydjarakhs are more degraded, and, in some cases, the ice wedges are completely melted. In 1988, the Glossary of Permafrost and Related terms recommended against using this term and insisted on using the term “thermokarst mound.” However, the term thermokarst mound removes any connotation or references to ice-wedge polygons. A comparison of baydjarakh and high-centered polygons is provided in the Supporting Information (see Figure S8).

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DATA AVAILABILITY STATEMENT

The chi-square distribution table is available in the Supporting Information (Figure S9). Extra topography and slope models are available in Figures S10–S12. Large size maps from Figures 5 and 6 are presented in Figures S13–S17. Additional images of TCCPs are also available in the Supporting Information. The TCCP dataset will be soon available on NordicanaD and PINGO.

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REFERENCES

1. French HM. *The Periglacial Environment*. Hoboken: John Wiley & Sons; 2017:544.
2. O’Neill HB, Wolfe SA, Duchesne C. New ground ice maps for Canada using a paleogeographic modelling approach. *Cryosphere*. 2019;13(3): 753-773.
3. Leffingwell Ed K. The Canning River region, northern Alaska. *US Geol Surv Prof Pap*. 1919;352:9:193-253.
44. Chouinard C, Fortier R, Mareschal JC. Recent climate variations in the subarctic inferred from three borehole temperature profiles in northern Quebec, Canada. *Earth Planet Sci Lett*. 2007;263(3-4):355-369.

45. Gagnon S, Allard M. Changes in ice-wedge activity over 25 years of climate change near Salluit, Nunavik (northern Quebec, Canada). *Permafrost Periglac Process*. 2020;31(1):69-84.

46. Washburn AL. Classification of patterned ground and review of suggested origins. *Bull Geol Soc Am*. 1956;67(7):823-866.

47. Drew JV, Tedrow JCF. Arctic soil classification and patterned ground. *Arctic*. 1962;15(2):109-116.

48. Dostovalov BN, Popov AI. Polygonal systems of ice-wedges and conditions of their development. *Proceedings, 1st International Permafrost Conference. National Academy of Science - National Research Council of Canada*. Publication 1287. 1966;102-105.

49. Péwé TL. Ice wedges in Alaska - classification, distribution and climatic significance. *Proceedings, 1st International Permafrost Conference. National Academy of Science - National Research Council of Canada*. Publication 128. 1966;76-81.

50. Mackay JR. Active Thermokarst Processes, Eastern Banks Island, Western Canadian Arctic. *Can J Earth Sci*. 1974;11(6):785-794.

51. Boisson A, Allard M, Gauthier L, Grenier I. Dating ice-wedge polygons in Nunavik (northern Quebec, Canada). *Arctic Science*. 2020;6(4):488-508.

52. Porter C, Morin P, Howat I, et al. ArcticDEM. *Harvard Dataverse*. 2011;134(3-4):197-216. doi:10.1016/j.geomorph.2011.07.002

53. Franke TM, Ho T, Christie CA. The Chi-Square Test: Often Used and More Often Misinterpreted. *Am J Eval*. 2012;33(3):448-458.

54. Upton G, Cook I. A Dictionary of Statistics 3e. Oxford University Press; 2014.

55. Tallarida RJ, Murray RB. Chi-square test. In: *Manual of Pharmacologic Calculations*. New York, NY: Springer; 1987:140-142.

56. McHugh ML. The chi-square test of independence. *Biochem Med*. 2013;23(2):143-149.

57. Denham BE. Categorical Statistics for Communication Research. John Wiley & Sons; 2016:296.

58. Daigle E. Géologie du Quaternaire du nord de la péninsule d’Ungava, Québec. Commission géologique du Canada, Bulletin. 2008:126.

59. Dyke AS. An outline of North American deglaciation with emphasis on central and northern Canada. *Dev Quat Sci*. 2004;2:373-424.

60. Mackay JR, Burn CR. The first 20 years (1978-1979 to 1998-1999) of ice-wedge growth at the Illissarvik experimental drained lake site, western Arctic coast, Canada. *Can J Earth Sci*. 2002;39(1):95-111.

61. Gray J. Lauriol B, Bruneau D, Ricard J. Postglacial emergence of Ungava Peninsula, and its relationship to glacial history. *Can J Earth Sci*. 1993;30(8):1676-1696.

62. Gahé E, Allard M, K-Seguin M. Géophysique et dynamique holocène de plateaux palsaïques à Kangiqsualujjuaq, Québec nordique. *Géog Phys Et Quat*. 1987;41(1):33-46.

63. Dostovalov BN, Popov AI. Polygonal systems of ice-wedge polygons in Nunavik (northern Quebec, Canada). *Permafrost Periglac Process*. 2020;31(1):128-140. doi:10.1002/ppp2033

64. Porter C, Morin P, Howat I, et al. ArcticDEM. *Harvard Dataverse*. 2011;134(3-4):197-216. doi:10.1016/j.geomorph.2011.07.002

65. Romanovskii NN. Distribution of recently active ice and soil wedges in the USSR. *Field and theory: lectures in geology*. 1985:154–165.

66. Lachenbruch AH. Contraction theory of ice-wedge polygons: a qualitative discussion. *Proceedings, 1st International Permafrost Conference. National Academy of Science - National Research Council of Canada*. Publication 1287. 1966;63-71.

67. Ulrich M, Hauber E, Herzschuh U, Härtel S, Schirrmeister L. Polygon pattern geomorphometry on Svalbard (Norway) and western Utopia Planitia (Mars) using high-resolution stereo remote-sensing data. *Geomorphology*. 2011;134(3-4):197-216. doi:10.1016/j.geomorph.2011.07.002

68. Dutilleul P, Haltigin TW, Pollard WH. Analysis of polygonal terrain landforms on Earth and Mars through spatial point patterns. *Environ Off J Int Environ Soc*. 2009;20(2):206-220. doi:10.1002/env.924

69. Haltigin TW, Pollard WH, Dutilleul P, Osinski GR. Geometric evolution of polygonal terrain networks in the Canadian High Arctic: Evidence of increasing regularity over time. *Permafrost Periglac Process*. 2012;23(3):178-186. doi:10.1002/ppp1741

70. Mackay JR, MacKay DK. Snow cover and ground temperatures, Garry Island, N.W.T. Arctic. *Can J Earth Sci*. 1974;27(4):287-296.

71. Hofmann M, Anderssohn R, Bahr HA, Weiβ HJ, Nellesen J. Why hexagonal basalt columns? *Phys Rev Lett*. 2015;115(15):154301. doi:10.1103/PhysRevLett.115.154301

**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of the article at the publisher’s website.

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