RESPONSE TO REVIEWERS

TITLE: The cryostratigraphy of thermo-erosion gullies in the Canadian High Arctic demonstrates the resilience of permafrost

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Review by Sebastian Wuterich

General remarks

The study by Gagnon et al. investigates by example to two thermo-erosional gully systems on Bylot Island (Canadian Archipelago) morphological dynamics and permafrost properties of such degradation features. The study is based on intense coring along several cross-transects from undisturbed surroundings to the gully bottom, detailed cryolithological core descriptions and analytical work covering relevant ground properties such as ice content, organic content and granulometry. CT imagery of the cores is of special value as it illustrates the ground composition and the cryostructures. The authors provide and discuss a conceptual framework of gully development including changes in permafrost state and subsequent dynamics in surface morphology. Therefore, the study addresses a relevant scientific topic and contains novel data and understanding suitable for publication in The Cryosphere. The employed field and lab methods are appropriate and allow deducing a comprehensive dataset that supports the interpretations and conclusions from the study. The paper is clearly and well-structured written in all parts, and relevant studies are cited. Some minor suggestions and comments are outlined below and in the attached PDF.

It would be useful to add in the Introduction section definitions on terminology that are used in the paper. As the authors refer to polygon development stages as high-center, low-center, flat and drained (firstly mentioned in ln109-110), this terminology should be explained in the Introduction section 1. In detail, I struggle to understand what is meant by drained polygons. Here, either the ponds filling the center of low-center polygons or the ponds above melting wedge ice surrounding polygon high centers might have drained. Please, clarify and use unambiguous terms.

We added the following paragraph in the introduction:

"Ice-wedge polygons are among the most widespread landforms in permafrost environments (French, 2017). They occupy about 3% of the Arctic landmass (Minke et al., 2009) and are the result of ground thermal contraction cracking leading to the formation of ice wedges and ridges (Lachenbruch, 1962; Fortier and Allard, 2005; Sarrazin and Allard, 2015; O'Neill and Christiansen, 2018; Matsuoka et al., 2018). Tundra polygons can range from several meters to a few decameters (Ulrich et al., 2011) and are separated by depressions, i.e., troughs, where the ice wedges form (French, 2017). They can be categorized into two main types based on their relief (Black, 1982; Lara et al., 2015; French, 2017): low-centred polygons, which have raised rims and wet, depressed centres where water can accumulate, and high-centred polygons, which have elevated centres relative to their surroundings. Flat-centred polygons can also form during the initial phase of ice-wedge development or as an intermediary stage between low- and high-centred polygons (Tanguy et al., 2023). Low-centred polygons commonly form in poorly drained areas of continuous permafrost and can evolve into flat- or high-centred polygons when there is an improvement in drainage resulting in stream incision in the troughs and the preferential melt of wedge ice (Mackay, 2000; French, 2017). A transition in the type of polygon can therefore be indicative of changes in surface conditions (Liljedahl et al., 2016; Gagnon and Allard, 2019). While changes in polygon relief and vegetation following a disturbance have been documented (Lara et al., 2015; Perreault et al., 2016; Godin et al., 2016), the effects on ground ice content and cryostratigraphy are unknown."

For the drained polygons, they result from the breaching and collapsing of rims of low-centred polygons during the formation of the thermo-erosional gully. We added the following sentence in section 3.1 when describing the sites where drilling was done: "For both sites, drained polygons corresponded to low-centred polygons that drained when thermo-erosion gullying caused breaching and collapsing of their rims (Godin et al., 2016)."

From the imagery shown in Fig. 1 it remains unclear what types of polygons occur in the study area. It is further unclear how polygons named as undisturbed (e.g., in Fig. 2) relate to the also used high-center/low-center polygons, although low-center polygons are mentioned in ln171-172. Such information should be given earlier, e.g., in section 2.

Section 2 mentions that low-centred polygons are present in the valley: "Well-developed networks of low-centred ice-wedge polygons that have formed syngenetically during the Late Holocene as well as thaw ponds, tundra lakes, and pingos cover the terraces (Fortier and Allard, 2004)."

We now specify in section 3.1 that the undisturbed sites are low-centred polygons: "At each subsite, one hole was drilled in an undisturbed low-centred polygon […]".

"The holes were located on a ~170 m transect going across TEG2 and sampled undisturbed low-centred polygons […]".

Furthermore, a short definition of transient and protective layers in the Introduction section 1 would be helpful.

We added a description of the layers and how they were interpreted in the methods, section 3.2:

“Cryostructures were used to produce the cryostratigraphy for each core and for the interpretation of geocryological layers, i.e., layers that describe temporal changes in active-layer thickness (Shur et al., 2005). The interpretation of the geocryological layers was based on the cryostructures and VIC and was used to describe permafrost resilience and recovery to thermal erosion. The geocryological layers were: active layer (unfrozen and frozen); transient layer, which is an ice-rich layer in the uppermost part of permafrost that is susceptible to thawing due to sub-decadal to centennial variations in active-layer thickness; intermediate layer, a more ice-rich layer directly below the transient layer that is susceptible to thawing due to decadal to multi-centennial variations in active-layer thickness; buried intermediate layer, an intermediate layer that has been buried under layers of sediment in which permafrost has aggraded syngenetically; and permafrost (French and Shur, 2010; Murton, 2013; Gilbert et al., 2016; Kanevskiy et al., 2017).”

The thaw front depth (TFD) seems to be used as synonym of the more common term active layer thickness (ALT). I wonder why, as ALT data are displayed in Fig. 4 and it is named in the title of section 4.1, but rarely in the text.

It was an oversight, we prefer using thaw front depth for this study. Thaw front depth is used instead of active layer thickness (ALT) because ALT refers to the maximal seasonal thaw depth, while thaw front depth can be measured at any time during the thawing season. We corrected references to active layer thickness (ALT) elsewhere in the text and in figure 4 when talking about our field measurements. Active layer is now only used to reference the layer of maximal seasonal thaw depth.

And finally on terminology: cryostratigraphy (cryostratigraphic pattern, permafrost cryostratigraphy), cryostructures (ground-ice pattern) and geocryological layers seem to be used in places synonymously. Please, consider a short definition in the Introduction section 1 (e.g., ln41), and consistent and correct use of the terms as “cryostratigraphy refers to the relationship between the lithological characteristics of rocks and their ground-ice amounts and distribution” on large scale, while small-scale ground structures “formed by the amount and distribution of ice within sediment and rock are termed cryostructures” (French & Shur, 2010).

We added in the introduction definitions of cryostratigraphy and cryostructures:

“Cryostratigraphy, which is the study of layering within permafrost, can provide valuable information on the conditions of permafrost formation and its potential response to warming and thawing based on the amount, distribution, and nature of ground ice within sediment or bedrock (Murton, 2013; Gilbert et al., 2016). Cryostructures, i.e., structures that describe the shape, amount, and proportions of ice, sediment or rock within frozen ground, are the building blocks of cryostratigraphy and can be used to infer ground thermal and hydrological conditions at the time of their formation (French and Shur, 2010; Murton, 2013)."

In the Study site section 2, background information on ground temperatures is missing, although it is further discussed in e.g., section 5.1.2 as 'low permafrost temperatures'. Please, add according information in section 2.

We added the following sentence in the second paragraph of section 2: "Mean annual ground temperature recorded by a thermistor cable in a borehole in an undisturbed low-centered polygon about two kilometres west of the study area (BYLOTPD; Allard et al., 2024) was -10.8°C at a depth of 3 m for the 2011-2020 period (missing 2013)."

The Material and Methods section 3 requires some additional information of the number of samples used for the different analyses.

We added the number of samples for the different analyses in section 3.1 and in table 1.

Furthermore, grain size analyses have been undertaken by sieving and particle size analyzer (ln147). Both methods are not described in the Methods and material section 3. If laser diffraction (i.e., particle size analyzer) was applied (1) the approach to combine the results from both methods in weight-based percentages (wt%) and volume-based percentages (vol%) should be described, and (2) I wonder why clay has not been measured.

This was initially described in the supplementary material (2 and 3). We added it to the manuscript at the end of section 3.1. We also added the clay samples (see comment line 136).

A statement on data availability is missing and should be added.

We added the following statement: The data that support the findings of this study are openly available on NordicanaD (Fortier et al., 2024a, b).

Minor remarks: Please, find minor remarks in the commented PDF (egusphere-2024-208_minor comments.pdf).

Here are answers to your comments, line numbers refer to the original submission where your comments are marked.

Line 13: Since we define what are cryostratigraphy and cryostructure after, we kept this more general term.

Line 20: Changed to short/medium term (years to decades)

Line 21: Changed to long term (decades to centuries)

Line 29: Not necessarily high-centered. Since we have not described the types of polygons, we prefer to leave it as it is.

Line 31: Yes, we agree. There is now a paragraph introducing those notions in section 1 (see above)

Line 36: Changed to landscape morphology, run-off hydrology, and ecosystem functions.

Line 39: Since it's before our definitions of cryostratigraphy and cryostructure, we prefer to leave a more general term.

Line 41: We added the definitions in a paragraph in the introduction (see above).

Line 60: We added letters to the boxes and in the caption.

Line 61: Thaw front depth is used instead of active layer thickness (ALT) because ALT refers to the maximal seasonal thaw depth, while thaw front depth can be measured at any time during the thawing season. We corrected any reference to active layer thickness (ALT) elsewhere in the text and in figure 4.

Line 67: We added the following sentence in the second paragraph of section 2: "Mean annual ground temperature recorded by a thermistor cable in a borehole in an undisturbed low-centered polygon about two kilometres west of the study area (BYLOTPD; Allard et al., 2024) was -10.8°C at a depth of 3 m for the 2011-2020 period (missing 2013)."

Line 70: Changed to ground temperature

Line 81: Reference corrected

Line 81: Changed to precipitation

Line 84: Reference corrected

Line 90: We removed The first TEG

Line 90: We added: "[…] and stretches about and stretches about 750 m from the base of the valley side to a stream that connects the lake near the CEN research station to the proglacial river."

Line 90: We added this sentence: “The gully was initiated in a sinkhole, from which it developed in opposite directions in the first year, then upstream and laterally (Godin and Fortier, 2012b).”

Line 94: We removed The second TEG

Line 99: Changed to and

Line 103: See comment at line 136

Line 105: See comment for line 61

Line 111: The terms are now introduced in the introduction (see above)

Line 117: We added to line 114 ‘to extract permafrost cores down to 0.95 to 1.46 m’

Line 123: We added a) and b) to Figure 2

Line 130: We changed the sentence to: “Then, the cores were cut into samples ranging from 0.5 to 49 cm for TEG1 and 2 to 36 cm for TEG2 that corresponded to the main cryostructures and sediment textures (TEG1 n = 173, TEG2 n = 56). The samples were vacuum sealed in plastic bags to determine […].”

The number of samples used for the calculations of VIC and OMC down to 1 m is indicated in Table 1.

Line 136: You are right, the clay fraction was obtained from the particle size analyzer. However, most of the samples (80%) had values of 0%, and most of those that did contain clay had values <1%, hence we did not initially describe it. We added clay values to figures 5 and 6.

Line 140: We specifically mean the cryostructure that we used to describe the shape, amount, and proportions of ice, sediment or rock within frozen ground. This is to describe what we produce in table 2.

Line 143: Changed to cryostructure/stratigraphic unit

Line 160: We added where ice-wedge melt and thermal erosion isolated polygons centers.

Line 170: We removed other

Line 170: We change the sentence to: “For both TEG1 and TEG2, the polygons adjacent to the TEG were drained, i.e., mesic to dry (TEG1-1-2-3Drained, TEG2-1-2Drained), compared to undisturbed polygons away from the gully incisions where ponds in the centre of low-centred polygons as well as in the throughs separating them were common.”

Line 174: We mean that thermal contraction cracks (‘frost cracks’) are found on the slopes of the gully as well as at the bottom. The stream is only active during the thawing season, thus winter cracking is possible.

We changed the sentence to: “Over 70 thermal contraction cracks were found in the flat bottom and in the slopes of TEG2”.

Line 177, 182, 184, 185: See comment for line 61

Line 188: Corrected to be the same length

Line 190: We added dots to the lines

Line 198: OK

Line 207: OK, we changed line 307 for 75.3%

Line 211: Not exactly what we mean. We mean the values of VIC found in each cryostructure. We changed the sentence to: “VIC within each cryostructure […].”

Line 212: We removed of the cryostructures

Line 212: Changed to “Sections with layered […]”

Line 220: Added

Line 232: We mean that the ice layers of the layered cryostructure of the bottom section increased when changing sediment. We changed the phrasing to “The ice layers of the bottom section […]”

Line 239: Total proportions changed to Cryostructure proportion.

Line 251: We added (68-116 cm)

Line 275: We mean the sediments, not the ice structures. We changed it to: “soil layers”

Line 277: We added the depth intervals of the sections

Line 304: Changed to: “[…] influenced by soil and organic matter composition of the deposits.”

Line 307: Changed to 75.3%

Line 328: Changed to grain size

Line 347: Changed to undisturbed

Line 372: Changed to active layer thickness, in this case we specifically mean the maximum extent of the thaw front at the end of the season, which causes the formation of the transient layer.

Line 380: Changed to undisturbed

Line 391: Changed to active

Line 395: We added New stable state

Line 433: We added "[…] and leading to deepening and widening of the gully."

Line 453: We added stable

Line 458: We added the following sentence: "Drainage in the troughs of the encompassing polygons toward the TEG has caused wedge ice melt and stream incision, which has led to broadening of the troughs and the lowering of the rims of the low-centred polygon (Mackay, 2000; French, 2017). As a result, the low-centred polygons along the margins of the TEG have changed into raised flat/high-centred ones."

Line 478: Removed

Line 480: Here we mean the polygonal network along the gullies, not just the shape of the polygons, this is mentioned in section 4.1. We changed the sentence to: "[…] raising the drained polygons encompassing the gully."

We added the following statement: The data that support the findings of this study are openly available on NordicanaD (Fortier et al., 2024a, b).

Line 498: We revised and corrected the References according to your suggestions.

Review by Go Iwahana

The manuscript, "The cryostratigraphy of thermo-erosion gullies in the Canadian High Arctic demonstrates the resilience of permafrost," submitted to The Cryosphere by Gagnon et al., discusses the formation of the cryostratigraphy of near-surface permafrost (and partly frozen active layer) of an area of degrading ice-wedge polygons and an area of stabilized degraded ice-wedge polygons in the Canadian high Arctic. The authors also discuss general landform evolution of ice-wedge polygons in the Arctic. This study provides a unique set of high-resolution geocryological information with detailed descriptions of the near-surface permafrost collected from two areas with different landform evolutionary stages.

This work is an important addition to the previously conducted excellent studies by the authors' group in similar areas. This manuscript is well organized, and I did not find any critical issues with their methodology. However, with the CT-scan core data, I think the authors could have retrieved more detailed and high-resolution information about volumetric ice content (VIC) and ground ice morphology, which are the main foundations of their discussion.

Below are some comments and suggestions to improve your manuscript:

The authors' discussion is mainly based on the profiles of cryostratigraphy and geocryological layers. The classification of cryostratigraphy is intuitive with the help of illustrations in Figures 5 and 6. On the other hand, the differences in transient/intermediate layers and buried intermediate layers are unclear to readers, especially those from different fields. Although some suitable references were provided, a brief explanation of the geocryological layers and how they were assigned to the core sections should be included.

We added a description of the layers and how they were interpreted in the methods, section 3.2:

"Cryostructures were used to produce the cryostratigraphy for each core and for the interpretation of geocryological layers, i.e., layers that describe temporal changes in active-layer thickness (Shur et al., 2005). The interpretation of the geocryological layers was based on the cryostructures and VIC and was used to describe permafrost resilience and recovery to thermal erosion. The geocryological layers were: active layer (unfrozen and frozen); transient layer, which is an ice-rich layer in uppermost part of permafrost that is susceptible to thawing due to sub-decadal to centennial variations in active-layer thickness; intermediate layer, a more ice-rich layer directly below the transient layer that is susceptible to thawing due to decadal to multi-centennial variations in active-layer thickness; buried intermediate layer, an intermediate layer that has been buried under layers of sediment in which permafrost has aggraded syngenetically; and permafrost (French and Shur, 2010; Murton, 2013; Gilbert et al., 2016; Kanevskiy et al., 2017)."

Information on heterogeneity of the ground parameters is important for a broader audience range. Can you provide statistical parameters (STD or SE; numbers of samples) for each TFD, VIC, and OMC.

We added the weighted standard deviations to the values of VIC and OMC in Table 1. We did not average TFD in our analyses so no need for uncertainty, but if you mean the uncertainty for the average of the transects, we did not have access to the raw data, just the average values for the transects, so it was not possible to add uncertainty.

We added the number of samples for the different analyses in section 3.1 and in table 1.

For the same reason, and to compare key parameters between sites/groups, can you create figures to show the profiles of the key parameters (e.g., VIC/OMC and geocryological layers) on the same X/Y axis graph (or sub-grouped graphs)? The current Figures 5 and 6 are useful for comparing different parameters within a single borehole, but it is difficult to compare the parameters between sites/boreholes.

We added two graphs (now figure 7) to show key parameters: VIC vs OMC and VIC vs Mean grain size. We did not add OMC vs Mean grain size because organic matter content accumulation is not linked with mean grain size, and vice versa.

Thaw depth at the measurement moment and active layer thickness are different concepts.

We agree. Thaw front depth is used instead of active layer thickness (ALT) because ALT refers to the maximal seasonal thaw depth, while thaw front depth can be measured at any time during the thawing season. We corrected references to active layer thickness (ALT) elsewhere in the text and in figure 4 when talking about our field measurements. Active layer is now only used to reference the layer of maximal seasonal thaw depth.

L17-18: This sentence is unclear. Please rephrase it for better understanding.

The sentence was changed to: "Although the TEG caused discernable cryostratigraphic patterns in permafrost, ground ice content and thaw front depth in the TEGs were comparable to measurements made in undisturbed conditions."

L47-48: The phrase "The capacity of permafrost to recover to a pre-disturbance state" implies the recovery of landform deformation. Please revise/add the sentences to avoid such a misunderstanding.

The sentence was changed to: "[…] which we define as the capacity of permafrost to maintain ground temperatures below 0°C and similar ground ice contents and morphologies, and to recover to such state following a disturbance and the associated perturbations (Chapin et al., 2009; Phillips, 2009; Jorgenson et al., 2010; Thoms et al., 2018; Piégay et al., 2020)."

L53: The impact of thermal erosion on surface characteristics should be included in this study (if available) by showing ground surface moisture contents and site photos of each coring site group (shoulders/drains/slopes/bottom).

Thank you for your suggestion. We do mention general changes in moisture content (breached/drained polygons vs undisturbed ones), but unfortunately soil moisture measurements were not part of this study. Other studies have reported it in greater detail for TEG1, which we now specify in the discussion:

"The breaching and collapsing of the rims of the low-centred polygons encompassing the TEG also contribute to TEG stabilization by causing drainage of the active layer and of ponds in the polygons, i.e., decreasing soil moisture content (Godin and Fortier, 2012b; Godin et al., 2016)."

For the photos, we also agree that it would have been a good addition to the manuscript, but we unfortunately do not have photos of the coring sites.

Figure 1: (upper right) The red extent areas should match the two areas below. IDs for TFD should be consistent. TEG*-TFD* and TFD* are used in the figures and captions. How about using TFD*-*?

We changed the size of the boxes to match the maps below. We updated the names of TFD points to TEG*-TFD*.

L91: Specify the number of years.

We changed the sentence to: **"**The rates of erosion of the gully were very high during the first ten years following its inception and decreased substantially after, from 75 m a^{-1} to 5 m a^{-1} for the 1999-2009 and 2013-2017 periods, respectively",

Figure 2: Please indicate there are three subsites for TEG1 in the figure.

The caption now reads: "Figure 2. Conceptual cross-section of the two thermo-erosion gullies, TEG1 (a) and TEG2 (b), showing the sections of the TEGs where thaw front depth was probed (only one side is annotated, but for slopes and shoulders, both sides were probed), and the locations where we drilled into permafrost. While TEG1 was composed of three subsites, TEG2 had cores relatively close to one another. The locations of the cores are relative to the cross-section of the gullies, for their exact location see Figure 1. Figure not to scale."

L214: There was no statistical difference. What about other parameters?

We added OMC and mean grain size, which also showed no statistical difference (p-value>0.05).

L374: Higher hydraulic conductivities are also a good condition for ice-lens formation.

Yes, but in this case we mean that the high hydraulic conductivities of coarser sediments leads to better drainage and is less conducive to the formation of layers of ground that are ice-rich, i.e., ice-rich layers, not ice lenses.

We changed the sentence to: "Those two cores were both characterized by coarser sediments than in other cores, resulting in higher hydraulic conductivities and therefore better drainage and less water available to form ice-rich ground layers."

L463-464: The phrase "…, recover to conditions … pre-dating the disturbance" is misleading as it suggests landform recovery. Please rephrase.

We changed the sentence to: "In this new state, the TEG has caused long-lasting geomorphological and hydrological changes to the landscape, i.e., the polygonal network will not recover to its pre-disturbance state. In comparison, the permafrost affected by the TEG can recover similar ground ice content and temperature as in undisturbed permafrost pre-dating the disturbance and thus is resilient."

Chapter 5:

This discussion is more of a review of previous studies and does not sufficiently utilize the findings from the current study. Initial ground ice content (both as intrasediment ice and ice-wedge dimensions) is critical for discussing landform evolution.

Analyses/descriptions of time-series photos of those TEGs or high-resolution satellite images would enhance this study.

This has already been done for different time periods. For TEG1, the active gully, rates of erosion and evolution of the channels have been reported since its inception in 1999 by multiple authors (Fortier et al., 2007; Godin and Fortier, 2012b; Rioux, 2020). For TEG2, aerial photos since 1958 have shown no change since 1958. Rates of erosion for different time periods based on aerial photos are reported in section 2 when describing the study sites.

We did not want to put too much emphasis on the initial changes caused by thermal erosion (in TEG1) since it has already been studied at length by previous studies. Our main goal was to demonstrate the difference between the initial state and a stabilized state. In the text, we describe landform evolution in section 4.1 by comparing the shape of two gullies, the state of the surrounding polygons, and thaw front depth. This new information is used later in the discussion to supplement what previous studies have reported. We did not want to be too specific about our gullies in the discussion because we wanted the study and section 5.2 to be far reaching. While stages 0 to II have been described before, Stage III is a new and original addition to the evolution of TEG based on our field observations.

The authors may have high-resolution DEM to display, at least, the relative height difference between the undegraded ground surface and the gully bottom to infer the difference in the volume of the ice wedge network.

Unfortunately, we did not have high-resolution DEM for the sites of this study. However, we were able to add depths of the gullies in the results based on field observations:

For TEG1: “The depth of the main channel varied between 1 m and 5 m, and younger areas where erosion was more active tended to be deeper, narrower, and with steeper slopes.”

For TEG2: “The main channel was wide (30-40 m from side to side) with a flat bottom (3-7 m) and was between 2 and 6 m deep.”

We added this sentence in the discussion in section 5.2.3 Stage II: “Together, the accumulation of alluvial sediment, the growth of vegetation, and ice segregation lead to a decrease in the depth of the gully.”

Regarding the volume of the ice-wedge network, other studies (Fortier et al., 2007; Godin and Fortier, 2012b; Rioux, 2020) have reported soil eroded volumes, thus we did not want to repeat those studies without updated numbers. Since we do not have DEMs at different times for the two gullies, it was not possible to estimate the change in volume from before erosion, after initial erosion, and after stabilization. Back-of-the-envelope calculations would be possible, but there would be too much speculation/assumption.

Can you add any age information to your cores to support your discussion?

We have some 14C dates from the thesis of a master's student (Veillette, 2019) at TEG2, but the samples for those dates were collected to establish a stratigraphic chronology of some of the stratigraphic units rather than to look at the cryostragraphic evolution of the gully, i.e., the focus of this study. More samples at closer intervals and at different depths for each borehole would be necessary because the accumulation of OM is not necessarily an indication of the age of ice aggradation as the organic layer could have thawed and refrozen due to surface disturbances, giving an older age than the actual moment of ice aggradation. We are currently looking into this in another paper where we investigate the evolution of the valley floor and hope to provide addition dates that will give a better indication of cryostratigraphic chronology.

Supplementary Material 2: Explain Vt.

We added V_t (total volume of the frozen sample) and explanations on the methods to supplementary material 2.