# Fine-Scale Spatio-Temporal Monitoring of Multiple Thermo-Erosion Gully Development on Bylot Island, Eastern Canadian Archipelago

Etienne Godin, Daniel Fortier
*University of Montreal, Geography Department, Montreal, QC, Canada*
*Center for Northern Studies, Laval University, Quebec, QC, Canada*

## Abstract

Water infiltrating ice-wedge contraction cracks can enable the formation of tunnels in the permafrost, leading to collapse and thermo-erosion gully initiation. The valley of Glacier C-79 on Bylot Island in Canada features dozens of thermo-erosion gullies, ranging from a few meters up to 2 km in main axis length. Five of the largest gullies were chosen for fine-scale spatio-temporal monitoring between 1958 and 2011 using field observations, differential GPS mapping, and aerial and satellite imagery from 1958, 1961, 1972, 1982, 2007, and 2009 to 2011. Gullies developed in aeolian, colluvial, and organic depositional environments. Two gullies were nearly stabilized while three were evolving during the 2007–2011 period at rates ranging from 14± 3 m $y^{-1}$ to 25 ± 4 m $y^{-1}$. One gully mouth has eroded over 82 ± 6 m in length during the last three decades by riverbank erosion. Two gullies were formed before 1958, while the other three were initiated at least after 1972 but before the current decade.

**Keywords:** permafrost; thermo-erosion; ice wedges; gullies; mapping; long-term monitoring; high Arctic; change detection.

## Introduction

Ice-wedge polygons are widespread in continuous permafrost terrain characterizing the valley of Glacier C-79 on Bylot Island. Ice wedges grow during spring when water from streams or snowmelt runoff infiltrates thermal contraction cracks and refreezes in contact with the frozen ground to form an ice vein. Several cycles of cracking, water infiltration, and refreezing enable ice-wedge enlargement. Infiltration of concentrated flow into thermal contraction cracks can, in turn, enable the formation and expansion of underground tunnels directly in the ice wedges and the permafrost. Convective heat transfer between flowing water and ice contributes to ground ice melting, permafrost thawing, and tunnel development by thermo-erosion. Repeated water infiltration can enable tunnel enlargement, which regularly leads to tunnel roof brittle failure and collapse, resulting in gully inception. Once the gully is initiated, positive feedback effects can contribute to its rapid development, essentially according to ice wedge location in the ground, and eroding up to several tens of meters per year (Fortier et al. 2007). Gullies in this study were exclusively located on low topographic gradient glacio-fluvial river terraces at the bottom of a U-shaped, glacially eroded valley. In most cases, gullies were expanding and developing in humid low-center ice-wedge polygons representative of the area.

Thermo-erosion gullies in permafrost environments have been observed and studied in several areas of the Northern and Southern hemispheres (e.g., Leffingwell 1919, Hyatt 1992, Mackay 1997, Sidorchuk 1999, Levy et al. 2008, Rowland et al. 2010). While thermo-erosion gullies are mentioned in a few papers, much work needs to be done on the long-term spatio-temporal dynamics of thermo-erosion gullying at a fine-scale level.

The objective of this paper is to present the spatio-temporal development of five thermo-erosion gullies (between ~300 and >1000 m in length) over the period 1958 to 2011, using historical air photography, satellite imagery, and field observations.

## Site Characterization

The study site is located in the valley of Glacier C-79 on the southwestern plain of Bylot Island (73°9′N, 79°57′W) in the Canadian Arctic Archipelago (Fig. 1). The valley is ~65 $km^2$ in area, ~17 km long, and 4 ± 1 km wide. It is oriented ENE-WSW and bordered by plateaus ~500 m a.s.l. (Fig. 2). The plateau remnants are deeply incised, and alluvial fans are being formed near the base of the valley walls. A braided river flows from the glaciers at the valley head in a sandur, forming a delta in the Navy Board Inlet. On each side of the proglacial river, syngenetic ice-wedge polygon terraces have developed and aggraded since the Late Holocene (Fortier et al. 2004). The terraces are primarily composed of fine to coarse aeolian


Figure 1. The study site is located on Bylot Island, in the Canadian Arctic Archipelago, ~85 km northwest of the village of Pond Inlet.

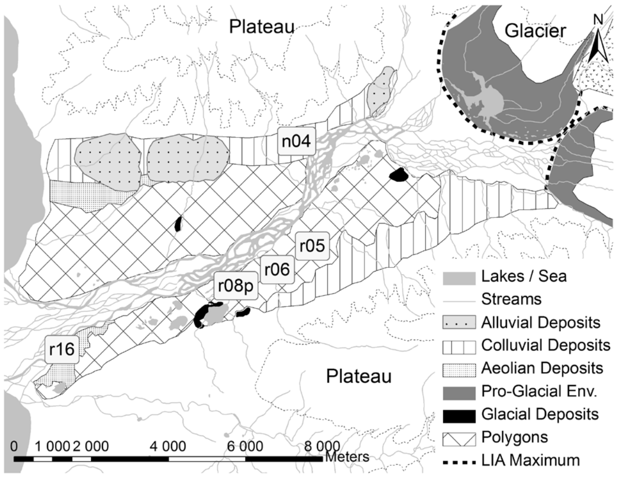



Figure 2. Valley of glacier C-79 geomorphic map, based on Allard (1996) and Klassen (1993). Gully (r05, r06, r08p, r16, and n04) locations are indicated on the map. The dashed line named LIA refers to the Little Ice Age terminal moraine.

silts mixed with poorly decomposed peat. Ice-wedge polygons observed in the valley are either low-centered, high-centered, or flat. Three types of sedimentary environments are active in the valley: 1) aeolian deposition (sand) near the deltaic area adjacent to the Navy Board Inlet; 2) fen peat accumulation with an aeolian component (loess); and 3) colluvial and mass movement deposition (silt to boulders diamicton) at the base of the plateaus. The mean annual temperature (1971–2000) measured at Pond Inlet airport (72°41′N, 77°57′W), some 85 km southeast of the study site, is -15.1°C. Average annual total precipitation (mostly in the form of snow) is around 190 mm (Environment Canada 2002). Permafrost thickness has been estimated to be at least 400 m in the study region (Heginbottom 1995). Active layer depth usually varies between 50 and 60 cm in peaty-silt deposits and up to 1 m in sand and gravel deposits (Fortier et al. 2006).

## Methods

The geomorphological features and topographic contours of 36 gullies have been mapped in the valley of Glacier C-79 using a Differential GPS (DGPS) since 2009: six on the northern bank and thirty on the southern bank of the proglacial river. For the current study, only larger active thermo-erosion gullies have been mapped, but several smaller gullies were also observed. The gullies selected for analysis were chosen according to the following criteria: 1) the gully must have been studied in the field; 2) the gully must be large enough to be identified on aerial photography (up to scale = 1:70,000); 3) satellite imagery and aerial photography must be cloud-free over the gullied area; 4) the study area must cover active and nearly stabilized gullies; and 5) gullying in aeolian, organic, and colluvial depositional environments must be included.

Gullies were mapped using a DGPS in 2009, 2010, and 2011. The DGPS used to characterize the gully was a Trimble Pathfinder Pro XRS with a TSC1 data collector. Differential correction was applied to the DGPS readings by using recordings from Thule reference station, Greenland (496 km from Glacier C-79 valley). (For additional details, see Godin and Fortier 2010). DGPS precision (x,y,z) after differential post-processing was 0.5–1 m for 99% of the records. Post-processed data were transferred to a geographic information system (GIS) built with ESRI's ArcGIS v10.

High-resolution satellite imagery (IKONOS mid-July 2007, 1 pixel = 1 m, GeoEye early September 2010, 1 pixel = 0.5 m) and aerial photography of the study site obtained from the Canadian National Air Photo Library for late June 1958, late July 1961 (scale = 1:60,000), June to August 1972 (1:15,000), and early July to early August 1982 (1: 70,000) were imported in the GIS.

Airborne images were co-registered with the satellite image with a RMSE value ranging from 1.6 m to 30 m (mean RMSE ≈ 17 m). Ten to 12 ground control points were used to register each image. A 2nd to 3rd order polynomial transformation and a nearest neighbor re-sampling was applied to the registration process.

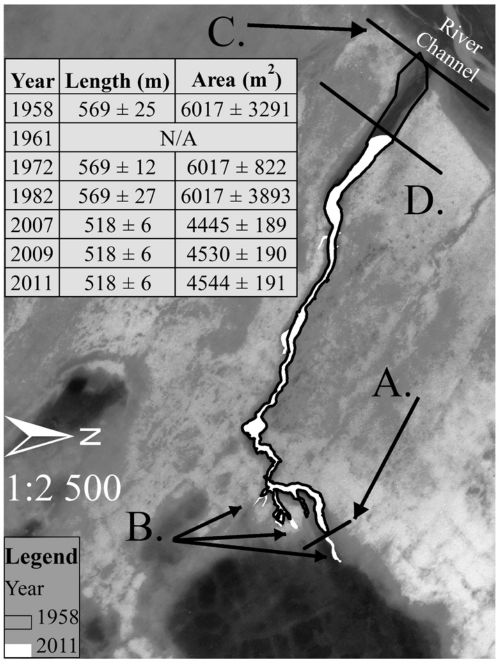
The DGPS mapped gully layer was used as a reference to measure gully development over time. Changes in areas on older or more recent gullies were compared to the reference gully and were manually delineated, thus defining gully sizes for 1958, 1961, 1972, 1982, and 2007. Gully metrics were computed using the 'Measure' tool on each redrawn gully to estimate the length and area for each time segment.

Manual gully delineation implied a level of subjectivity on the subsequent geospatial results generated. The uncertainty was computed based on image resolution. This uncertainty was based on a conservative maximum interpretation error of 0.5 mm on any measurement taken on the images: 1958 and 1961 (scale = 1:60,000, uncertainty = 30 m), 1972 (1:15,000, uncertainty = 7 m), and 1982 (1: 70,000, uncertainty = 35 m). These uncertainty values were used in a relative RMSE calculation for computed length and areas.

## Gully Developing in an Aeolian Depositional Environment

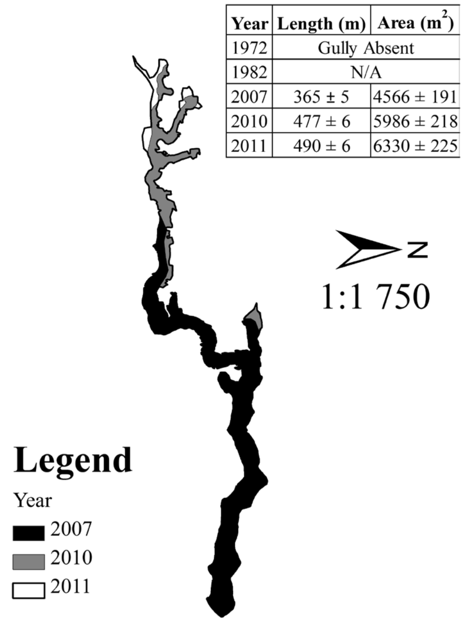
The gully r16 developed in an ice-wedge polygon network on the south bank of the braided river ~1.5 km from the delta connecting the river to Navy Board Inlet. The main channel of the gully connected to the proglacial braided river. The gully was incised into an aeolian depositional environment grading into an aeolian-organic transition zone, which is darker on Figure 3. This transitional zone featured some low-centered ice-wedge polygons with ponds and very sparse vegetation. The main body of the gully developed in a dominantly flat surface composed of coarse to fine sand in which ice wedges formed. The gully was already well developed in 1958, and its boundaries did not change significantly during the 1958–1982 period. The gully channel width varied from 10 m downstream to less than 1 m in the gully head area.

Figure 3 shows riverbank erosion where the gully mouth was located in 1958. On the 1982 image, a river channel was migrating toward the bank, but no significant erosion of the




| Year | Length (m) | Area (m$^2$) |
|---|---|---|
| 1958 | 569 ± 25 | 6017 ± 3291 |
| 1961 | N/A | |
| 1972 | 569 ± 12 | 6017 ± 822 |
| 1982 | 569 ± 27 | 6017 ± 3893 |
| 2007 | 518 ± 6 | 4445 ± 189 |
| 2009 | 518 ± 6 | 4530 ± 190 |
| 2011 | 518 ± 6 | 4544 ± 191 |

Figure 3. The background image shows the 1972 aerial photography of gully r16 (Fig. 2). Black gully contours show the 1958–1982 gully layout; A) head position for that period; B) 1982–2011 development. Bank erosion between 1982 and 2007 helped to reduce the gully size from C to D. The river channel is shown in the upper right corner.




| Year | Length (m) | Area (m$^2$) |
|---|---|---|
| 1972 | Gully Absent | |
| 1982 | N/A | |
| 2007 | 365 ± 5 | 4566 ± 191 |
| 2010 | 477 ± 6 | 5986 ± 218 |
| 2011 | 490 ± 6 | 6330 ± 225 |

Figure 4. Gully n04 was observed for the first time on a 2007 IKONOS satellite image. Observations of tunnels, sinkholes, and exposed ice wedges near the gully head during summer 2010 and 2011 indicated that the gully was actively developing.

gully had begun. The gully contours in white, as mapped with the DGPS in 2009 (Fig. 3D), clearly show the recession of the bank compared to the 1958 location of the gully (Fig. 3C). The estimated eroded bank width between 1982 and 2007 was 82 ± 6 m. Consequently, the overall length decreased from 569 ± 25 m to 518 ± 6 m during the 1982–2007 period, while the main channel in the gully head area increased by 30 ± 6 m (Fig. 3A.). Small (few meters) branches and slumps contributed to enlarging the gully slightly during this 35-year period (Fig. 3B). Between 2007 and 2011, the gully length did not increase, but erosion resulted in an overall area increase of ~99 ± 28 m$^2$.

## Gully Developing in a Colluvial Depositional Environment

Gully n04, located in a colluvial depositional environment on the north bank of the braided river, was first observed on the 2007 IKONOS image. On the 1972 and earlier images there was no gully, but rills and water tracks were running over the area where the gully eventually developed. No information could be extracted from the 1982 photo-interpretation due to cloud cover over the gully location. This gully, shown in Figure 4, therefore initiated during the 1972–2007 period, and the gully main axis length was estimated to be 365 ± 5 m in 2007 with an overall calculated area of 4,566 ± 191 m$^2$ (average 10 ± 1 m y$^{-1}$ and ~130 ± 32 m$^2$ y$^{-1}$ over 35 years). During the DGPS field survey in 2010, this linear gully was affected by thermo-erosion mainly at its head via tunnels and underground water flow, sinkholes, ice-wedge exposures, and recent ground slumping. During a visit in late June 2010, a small stream was continuously flowing into the gully head. Vegetation was present but sparse on the hummocky terrain and polygons near the gully. The colluvial deposits of gully n04 were characterized by a matrix of angular blocks, poorly decomposed peat, and sand. The gully main channel was ~13 m wide near its outlet and was ~6 m wide in the recently formed channels near the gully head. The gully main axis length and overall area development rate were 25 ± 3 m y$^{-1}$ and 353 ± 53 m$^2$ y$^{-1}$, respectively, for 2007–2011.

## Gully Developing in an Organic Depositional Environment

Gullies r05, r06, and r08p*,* located on the south shore of the river, all initiated in an organic depositional environment. This area was characterized by well-developed syngenetic ice-wedge polygon networks with polygon width ranging from ~8 m to ~35 m. Low-centered polygons, often with small ponds in their center, high-centered, and flat polygons were observed near the gullied zones. An almost continuous vegetation cover composed of, among others, *Salicaceae*, *Cyperaceae,* and *Poaceae* was present in this part of the valley. Polygon centers often featured cryoturbation and hummocks. Gullies r05 and r06 were directly connected with the proglacial river. The outlet of r08p was connected to a stream that flowed ~1 km downstream in the river. These three gullies were 1–3 km apart from each other and were all oriented in a normal way to the valley walls and to the braided river (NNW-SSE to N-S).

*Gully r05*

This long gully was already present on 1958 aerial photography. Aerial photographs from 1961 and 1972 did not show any evidence of development by thermo-erosion processes. A 50-m-long channel formed a fork-like pattern in the gully head area between 1972 and 2007, but no significant thermo-erosion was observed for the 2007–2010 interval. No recent thermo-erosion signs, such as exposed ice wedges or evidence of other permafrost thawing, were observed during site visits. Water was observed to be flowing in the gully during early summer. This nearly stabilized gully, formed before 1958, is therefore one of the oldest and largest of the valley, with an estimated main axis length and overall area (not mapped with a DGPS) of 1899 ± 7 m and 29,485 ± 485 m$^2$, respectively.

*Gully r06*

The gully r06 (Fig. 5) was not present on the 1972 photograph and the location was hidden by clouds on the 1982 image. The gully therefore initiated during the 1972–2007 interval. Water rills and low-centered polygons with small ponds were present on the 1972 image at the current gully location. The gully main axis length in 2007 was 626 ± 8 m, with an area of 10,004 ± 283 m$^2$. During a field visit in 2005, narrow but sharp waterfalls were observed entering the gully near its head, favoring thermo-erosion processes. This complex gully was developing linearly toward its water source and laterally through partly melted ice wedges.

The gully continued to enlarge during the following years at a rate of 14 ± 3 m y$^{-1}$ for the main axis and 343 ± 52 m$^2$ y$^{-1}$ area during the 2007–2009 period. A field visit in 2009, when the gully contours were recorded by DGPS, made it possible to record the presence of recently formed sinkholes, tunnels, thaw slumps and sharp, freshly exposed gully branches.

The channel near the gully head upstream was 6–8 m wide and 2–3 m deep. The channel was narrower downstream near the outlet, with a width of ~3 m and a depth of ~1 m. A second DGPS campaign (2011) provided evidence of gully enlargement over the 2009–2011 period to 717 ± 9 m for the main gully axis and 14,825 ± 344 m$^2$. Gully r06 had the greatest thermo-erosion and development rate of all gullies, with an overall development of 18 ± 3 m y$^{-1}$ (main axis length) and 964 ± 88 m$^2$ y$^{-1}$ for the 2007–2011 period.

*Gully r08p*

This gully (Fig. 6) was monitored since its inception in 1999 (Fortier et al. 2007) and during most years until summer 2011. The 1972 air photograph showed numerous water tracks and rills in the area where gully r08p formed in 1999. Over the 1999–2007 period, the gully expanded by 720 ± 7 m over its main axis (rate of 80 ± 2 m y$^{-1}$) and 23,130 ± 430 m$^2$ in overall area (rate of 2,570 ± 143 m$^2$ y$^{-1}$).

During 2009 and 2010, gully contours were digitized and field observations were recorded. This non-linear gully was developing simultaneously at six distinct emplacements where significant water flow entering the gully was observed. Sinkholes, waterfalls, ice-wedge exposures, sharp gully walls, and permafrost tunneling were characteristic of the expanding gully. Several baydjarakhs (an advanced stage of erosion of ice-wedge polygons forming a mound) were found in the

| Year | Length (m) | Area (m$^2$) |
|---|---|---|
| 1972 | Gully Absent | |
| 1982 | N/A | |
| 2005 | Gully Exists | |
| 2007 | 626 ± 8 | 10004 ± 283 |
| 2009 | 683 ± 8 | 11377 ± 302 |
| 2011 | 717 ± 9 | 14825 ± 344 |

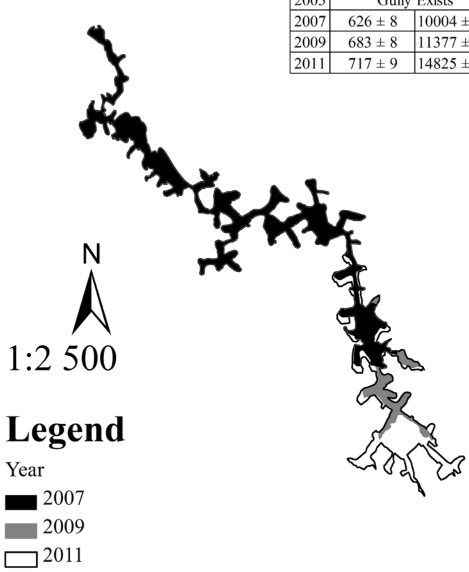



Figure 5. Gully r06 was absent on the 1972 air photography. The first observations of gully development were recorded in 2005. Gully r06 main axis development between 2007 and 2009 was 14 ± 3 m y$^{-1}$ and 17 ± 3 m y$^{-1}$ in 2010–2011.

| Year | Length (m) | Area (m$^2$) |
|---|---|---|
| 1999 | Gully Initiation | |
| 2007 | 720 ± 7 | 23131 ± 430 |
| 2009 | 748 ± 8 | 25007 ± 447 |
| 2011 | 835 ± 8 | 27762 ± 471 |

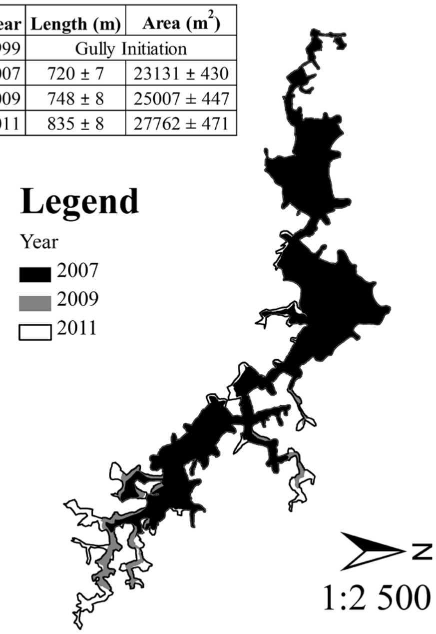



Figure 6. Gully r08p was expanding simultaneously in six distinct axes (light gray and white on the figure). While the overall length of r08p was smaller than other gullies, its area was large due to complete degradation of eroded polygons (baydjarakhs).

older, stabilized parts of the gully. The channel upstream near the gully head was ~8 m wide and ~3 m deep. The channel near the stabilized older sections of the gully in the outlet area was ~3 m wide and ~1 m deep. The gully was actively enlarging during the 2007–2011 period, although slower than the first nine years following its initiation. The gully r08p enlarged during the 2007–2011 period at a rate of 23 ± 4 m $y^{-1}$ (main axis) and 872 ± 83 $m^2$ $y^{-1}$ of overall eroded area, making this gully one of the most dynamic in the valley.

## Development Rates of Thermo-Erosion Gullies

Two of the thermo-erosion gullies covered in this study (r05, r16) initiated and developed before 1958 and have been nearly stable since then. The other three, which initiated at least after 1972 (n04, r06) or more recently (r8p, 1999), were all developing very actively. Consequently, no major gully enlargement was observed between 1958 and 1972 in the valley.

The five gullies studied in the present paper were among the largest found in the valley of Glacier C-79. These thermo-erosion features had distinctive characteristics relative to their depositional environment.

*Gullies formed in aeolian and colluvial depositional environments*

Gullies formed in colluvial and aeolian depositional environments shared interesting similarities. Channel cross-sections for these gullies were larger and deeper near the outlet than at the head, in opposition to those observed in an organic depositional environment. Their geometry and size were similar. These two types of gullies were characterized by a nearly linear main channel with very few (and small) secondary branches. The overall length and area of these two types of gullies were very similar, with a length of approximately 500 m and an area varying between ~4,500 and 6,500 $m^2$. The linear character of these gullies was reflected by a much smaller eroded surface compared to multi-channel gullies formed in an organic depositional environment. The relationship between linearity and overall eroded surface is clear when the 2007–2011 erosion rates of n04 and r08p are compared. For similar main channel erosion rates (n04 = 25 ± 3 m $y^{-1}$ and r08p = 23 ± 4 m $y^{-1}$), there was 10 times more eroded surface in the multi-channels gully r08p than in n04 (n04 = 353 ± 53 $m^2$ $y^{-1}$ and r08p = 872 ± 83 $m^2$ $y^{-1}$). The linear character of the gullies can potentially be explained by the high removal rates of sandy material of aeolian and colluvial deposits. Gullies formed in colluvial deposits, however, had a few sinkholes and tunnels which are more like gullies formed in organic depositional environments.

*Gullies formed in organic depositional environment*

Gullies formed in organic depositional environments were usually longer (~700–900 m in length) than gullies in other depositional environments. They had several channels, which is reflected in a larger eroded surface area (from ~15,000 to 29,000 $m^2$ eroded per gully). Active gullies were also characterized by a large and deep channel near their gully head area, varying from ~2 to 4 m deep and 3 to 8 m wide. Recent (2007–2011) rates of erosion for the main channels varied between 17 ± 3 and 23 m ± 4 $y^{-1}$, with 306 ± 49 and 872 ± 83 $m^2$ $y^{-1}$ of area eroded. These rates of gully development for 2007–2011 were within the same order of magnitude as the erosion rates estimated for the 1972–2007 period, which, in all cases, were much higher than 1958–1972 rates.

Organic depositional environments were characterized by well-developed ice wedges and cohesive silty peat material, enabling the formation and the relative sustainability of forms resulting from thermo-erosion such as sinkholes, tunnels, and sharp, angular gully walls and channels.

Many of the baydjarakhs observed, especially in r06 and r08p, were remnants of a sustained phase of relatively recent thermo-erosion and a rapid development rate. Gullies that developed one or more baydjarakhs were often larger than nearly linear gullies. Many water streams and/or branches were required for enabling the erosion of all sides of ice-wedge polygons.

A fluvial thermo-erosion system has been studied on the Lena River in Siberia (Are 1983), where the river eroded ice complexes (yedoma). Ablation rates of almost pure ice for the Lena River during the flood season varied from 19 m $y^{-1}$ up to 40 m $y^{-1}$, which is of the same order of magnitude as the most active gullies in the valley of Glacier C-79. This suggests that ground ice is a dominant factor in thermo-erosion rates.

## Processes of Gully Development and Stabilization

The gully r16, located near the coast, was eroded and enlarged by tidal currents and river flow over the last 30 years. This changed the base level in the gully, modified the outlet location, and reduced net gully dimensions. For gullies connected to the river, the combination of tidal currents entering the gullies and high pro-glacial river level at the end of the summer contributed to accelerated gully and terrace erosion.

Gullies found in organic depositional environments were the largest observed in the valley and had higher observed development rates. With measured expansion of 50 m in main axis length since 1958, gully r05 was one of the longest, largest, and possibly oldest gullies studied. It was the only gully nearly stabilized. This indicates that several decades are required to achieve gully slope (wall) stabilization and adjacent polygonal landscape equilibrium.

Positive feedback such as thermal denudation following a tunnel collapse, active retrogressive thaw slumps, unstable permafrost thermal regime following denudation, streams flowing through gully heads, and sinkhole enlargement contributed to the accelerate development rate.

Negative feedback such as plant growth, active layer drainage, slope equilibrium, and subsequent ground cooling favored gully stabilization. Feedback effects were therefore central to gully activity. They contributed to acceleration of thermo-erosion (positive feedback) near the gully head and to stabilization (negative feedbacks) in older areas of the gullies.

## Conclusions

Following gully initiation, development rates were very high. For instance, during the 1999–2007 period, gully r08p had an average main axis length development rate of ~80 m $y^{-1}$. It was observed that several years to decades are necessary for gully stabilization.

Gullies formed in aeolien and colluvial depositional environments shared common characteristics such as material erodability, gully size, and gully geometry.

Gullies developed faster during the 1972–2011 period than during the 1958–1972 period. Three new gullies initiated during the 1972–2011 period. Two of these (r06 and r08p) were among the largest in the valley and experienced the highest erosion rates.

Thermo-erosion gullies are long-lasting features in the periglacial landscape. They impact the local hydrology, water availability for vegetation, and therefore plant distribution and assemblages. Ground loss due to permafrost erosion resulting from gullying implies a change in the sedimentary balance of the river system downstream.

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