# Geomorphology of thermo-erosion gullies – case study from Bylot Island, Nunavut, Canada

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ABSTRACT
In the valley of glacier C-79 on Bylot Island, snowmelt water runoff is creating thermo-erosion of permafrost wetlands. This process contributes to the rapid formation of gullies in ice-wedge polygons. One gully had been observed since 1999 and had a growth of 748 m since then. The geomorphology of this gully is characterized by an active thermo-erosion zone near the gully head, a poorly-active zone near the outlet and a moderately active zone in-between. Feedback mechanisms contribute to the erosion processes governing the development of the gully, accelerating erosion at its head and stabilizing it at its outlet. Erosion features such as sinkholes, collapses and baydjarakhs were consequently observed in the gully. Thermo-erosion processes have remained active and have had an impact on the ecosystem for more than a decade.

RÉSUMÉ
La thermo-érosion induite par la fonte du couvert nival cause la dégradation du pergélisol dans la vallée glaciaire C-79 sur l'Ile Bylot. Ce processus contribue à la formation rapide de réseaux de ravinement dans les polygones à coin de glace. L'observation d'un ravin depuis sa formation en 1999 et de son évolution jusqu'à 748 m en 2009, révèle trois types de zones d'érosion caractérisant sa géomorphologie : une zone de thermo-érosion très active en amont, une zone intermédiaire, et une zone faiblement active à proximité de l'exutoire. Les mécanismes de rétroaction amplifient l'érosion en tête de ravin et la stabilisent à l'exutoire. Des composantes géomorphologiques tels que des puits, effondrements et baydjarakhs sont conséquemment observées dans le ravin. Le déclenchement du processus de thermo-érosion souterrain exerce un impact sur l'écosystème depuis plus d'une décennie.

## 1 INTRODUCTION

In 1999, thermo-erosion processes triggered the development of a sub-kilometric sized gully network in ice-wedges polygons located in the valley of glacier C-79 (Bylot Island, NU, Canada). Development of this gully has been closely monitored since its inception (Fortier *et al.*, 2007). Several forms of erosion and permafrost degradation were observed in the gully system. It was observed that these forms evolved with time, some remained active for a number of years, other were deactivated very rapidly after a few years. For over ten years, the gully head section has migrated upstream while the gully outlet has remained stable. The geomorphology of the central section between the gully inlet and outlet has also evolved over the years. The objectives of this paper are to characterize the geomorphology of three sections of a thermo-erosion gully with different ages: 1) the head of the gully characterized by very active thermo-erosion processes 2) the central part of the gully characterized by low to moderate thermo-erosion activity and gullying 3) the outlet of the gully characterized by very low thermo-erosion activity, gullying and permafrost degradation.

## 2 STUDY SITE

The study site is located on the south-western plain of Bylot Island (73° 09'N –79° 57' W) at about 85 km north-west of the village of Mittimatalik (Pond Inlet) (Figure 1).

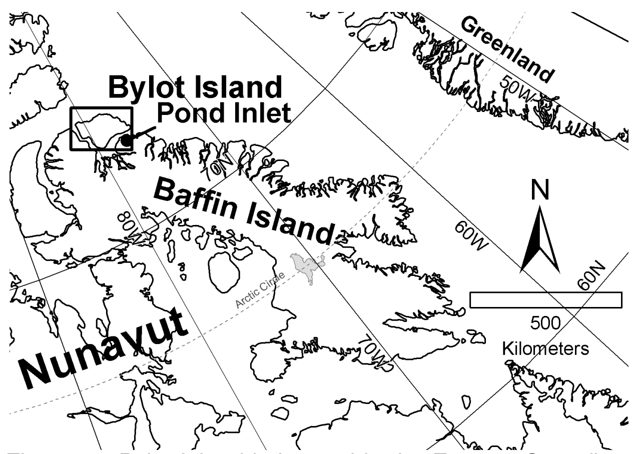


Figure 1 : Bylot Island is located in the Eastern Canadian Arctic Archipalego (Nunavut). Pond Inlet is located 85 km south-east from the study site.

Climate normal from Pond Inlet (72° 40 N, 77° 58 W) for the period 1971-2000 indicate a mean annual air temperature of -15.1°C, with 190 mm of annual precipitation, 145 mm of which falls as snow (Environment Canada, 2002). The active layer depth in peaty-silt is about 40-50 cm and is a few decimeters deeper in coarse grained materials (Fortier et al., 2006). The permafrost thickness in the area is estimated to be over 400 m (Smith et al. 2000; Young et al. 1986). The study site is located in the valley of Glacier C-79. The valley is about 15 km long and 5 km wide and oriented ENE – WSW.

Plateaus up to 500 m high form the valley walls. Two glaciers give rise to a braided river flowing down the valley (Figure 2). This river is the highest stream order in this hydrographical system and forms a delta as it ends in the Navy Board Inlet. (Horton, 1945).

Ice-wedge polygons terraces aggraded on each side of the outwash plain during the Late-Holocene (Fortier *et al*, 2004). The slopes are deeply incised and alluvial fans

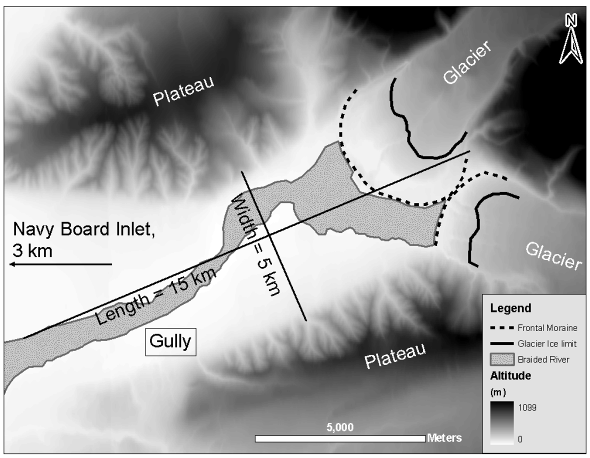


Figure 2 : A digital elevation model centered on the C-79 Glacier valley (CDED, 2003). The gully case-study is located at less than 1 km south of the braided river. The proglacial river is flowing towards the Navy Board Inlet.

are formed at the bottom of the valley walls on the terraces. Previous cryostratigraphic studies showed that the central portion of the terraces comprises 2 to 4 meters of ice-rich, fine to coarse aeolian sediments mixed with poorly decomposed peat (Fortier *et al.* 2006). Periglacial features are abundant on the terrace with well-developed ice-wedges polygons, thermokarstic ponds and lakes and about half a dozen pingos (Figure 3).

The studied gully is oriented sub-perpendicular to the proglacial river conformably to the gentle slope of the terrace. Water flow in the gully resumes with snowmelt water run-off and continues throughout the summer due to drainage of the surrounding wetlands. The gully outlet connects to a lake-discharge stream which is flowing toward the proglacial river 1 km downstream.

## 3 METHODS

During the 2009 fieldwork, a detailed survey of the gully geometry was done using a differential GPS. The unit used to characterize the gully was a Trimble DGPS (model Pathfinder Pro XRS with a TSC1 data collector). Differential correction was applied to the DGPS data using GPS Pathfinder Office v3.10 and the Thule (Greenland) base station (located 496 km from Glacier C-79 valley) as a reference. Differential correction report indicates that 99.9% of positions (x,y,z) have an effective accuracy between 0.5m and 1m. Gully contour, erosion landforms and active geomorphological processes were georeferenced in the DGPS database during 2009 survey. The gully was visited almost yearly between 1999 and 2009. Markers were installed along the boundaries of active thermo-erosion and gullying zones. The positions of the markers were georeferenced and integrated into a GIS (ESRI's ArcGIS v9.3.1). Gully metrics (e.g. area, length) were calculated directly in ArcGIS using the 'Calculate Geometry' tool. The geometry of a dozen cross-sectional transects were measured along the length

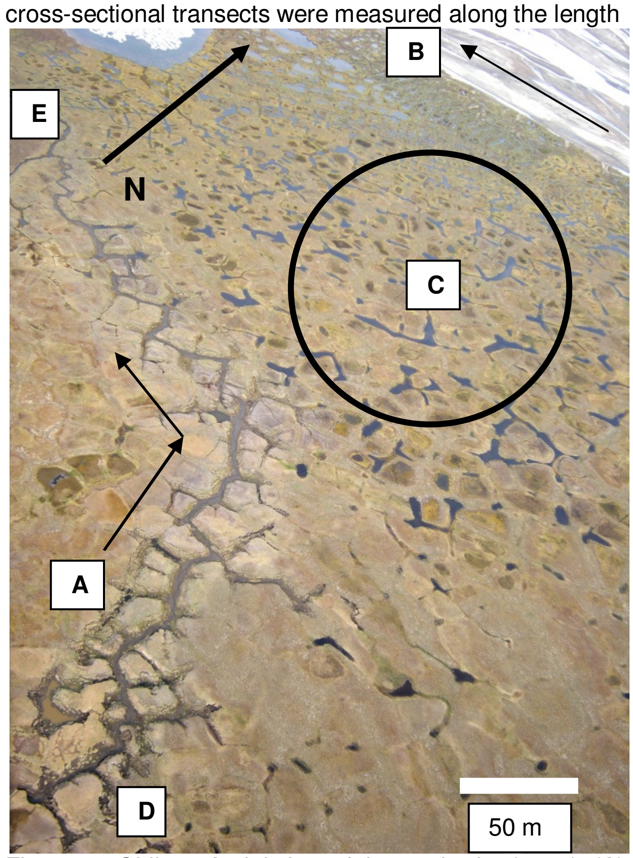


Figure 3 : Oblique Aerial view of the study site (2009). (A) Thermo-erosion gully. Flow direction in the gully is indicated by arrows. (B) The proglacial river is flowing from the glacier to the sea (arrow); (C) ice wedges polygons and ponds are widespread on the terrace. (D) Gully head (inlet); (E) gully outlet.

of the gully. A Trimble DGPS was used to make precise positional lectures of gully transect from one side to the other side of the gully channel. The distribution of transects covers the length of the gully.

## 4 RESULTS

4.1 Distribution of erosion processes and landforms in the gully.

In 2009, in the vicinity of the gully head we observed the presence of sinkholes feeding water to tunnels formed in the permafrost. Later in the summer, some tunnels collapsed and created very steep new gully walls. Several streams were flowing into the gully in this area. Active layer slumping and exposures of ground ice were widespread in these newly formed gully branches. Thermo-erosion, the process of rapid heat transfer that occurs between flowing water and frozen ground or ice, was the main process of permafrost degradation. A few thermokarstic ponds were localized on the polygonal terrace close to the margin of the gully. The gully area formed during the previous summers and located downstream of the gully-head zone was exempt of sinkholes and tunnels except at the location of a few intermittent streams flowing on the ice-wedge polygon terrace and captured after retrogressive erosion of the gully walls. Thermo-erosion in this section of the gully has a much more limited impact than in the gully head section. In this section of the gully, exposures of ground ice were rare. The gully walls were not as steep as in the gully head section and the slopes were evolving towards stabilization. Plant and mosses had colonized some of these slopes. Ground ice exposed along the gully walls the previous year commonly evolved into retrogressive thaw slumps. Thawing of ice-rich permafrost soils and melting of ground ice promoted thaw settlement, ground subsidence and eventually collapses. Sediment transport in the gully channel was significant due to high sediment input in the gully head zone.The downstream area near the outlet is the oldest part of the gully system and was formed eight to ten years ago. It is characterized by stable and low angle vegetated slopes (gully walls), drained polygon centers along the gully margin, stabilized to very weakly active retrogressive thaw slump, and very to totally (flat) degraded baydjarakhs. In enlarged sections of the gully channel, alluvial levees were formed over the years. The levees often contained small pools.

4.2 Gully geometry

The main axis of the gully is 748 m long; the cumulative length of the gully network, considering all branches and relict channels, is 2572 m. The area that was directly affected by thermo-erosion over the ten year period is 25000 $m^2$. Figure 4 shows a schematic of the gully contours and the localization of the pools within in the gully channel. The general direction of water flowing in the gully is from the head toward the outlet (NW) following a gentle slope of approximately 3 meters over 748 m (Figure 5). Water flows out of the gully in a small stream draining the terrace and ending in the proglacial river about 1 km downstream. The angular layout of the gully system is essentially due to the degradation of the ice wedges forming the polygons.The localization of three typical cross-sections of the gully is shown on Figure 4. TR1, TR2, and TR3 represent cross-sections of the gully head, central and outlet sections respectively (Figure 5). Error bars represented on each point illustrate the 1 meter ellipsoid maximum spatial error from the DGPS recording unit. Transects width is increasing from 5.2 m near the head (TR1) to 9.9 m at gully outlet (TR3). Gully depth is decreasing from 4.4 m at (TR1) to 1 m at (TR3). The intermediate transect (TR2) is having in-between values both for width and depth.

4.3 Gully evolution from 1999 to 2009

The location of the gully head for four periods (1999, 2000-2001, 2002-2005 and 2006-2009) is shown on figure 4. The development of the gully was extremely rapid during the first year (390 m) and about 50 m $year^{-1}$ (102 m total) the second and third year (2000, 2001). The progression continued to slow down considerably during the 2002-2005 (≈ 32 m $year^{-1}$) and the 2006-2009 (≈ 38 m $year^{-1}$) periods.

4.4 Gully geomorphological forms and processes

Several forms of erosion can be associated with the development and evolution of the gully over the period of observations. Some of these forms were the direct result of the thermo-erosion process (sinkholes, tunnels, gully head and surface lowering), some were triggered by permafrost degradation processes that followed thermo-erosion (retrogressive thaw-slump, tunnel collapse and active layer slumping) and others were related to fluvial processes in the gully channel (levees and pools) (Table 1).

4.4.1 Sinkholes
Sinkholes were found exclusively at gully head where the thermo-erosion processes were active. Sinkholes promoted the infiltration of streams running on the surface of the polygons into the permafrost (Figure 6). Sinkholes were connected to the gully by a tunnel network subdued to the geometry of the ice wedges.

4.4.2 Gully head
Gully head were points of active thermo-erosion where water penetrated in the gully network by way of waterfalls (Figure 8). Gully heads were essentially present in the high-erosion activity zone and to a lesser extent in the intermediate-erosion activity zone. They were absent from the low-activity zone downstream. Gully heads were deactivated during the summer when runoff became insignificant.

4.4.3 Retrogressive thaw slump (RTS)
Retrogressive thaw slumps (RTS) were observed from the gully head to the gully outlet but were more common in the intermediate zone. RTS walls were steep and arcuate (Figure 10). The ground affected by active RTS zone was chaotic and poorly drained. A general gradient of activity was observed with the more active RTS located close to the gully-head area and RTS evolving towards stabilization downstream. Stabilized RTS did not have ground ice exposure, the slopes of the valley wall had reach or were close to equilibrium, were colonized by plants and the ground was better drained than in upstream RTS zones.

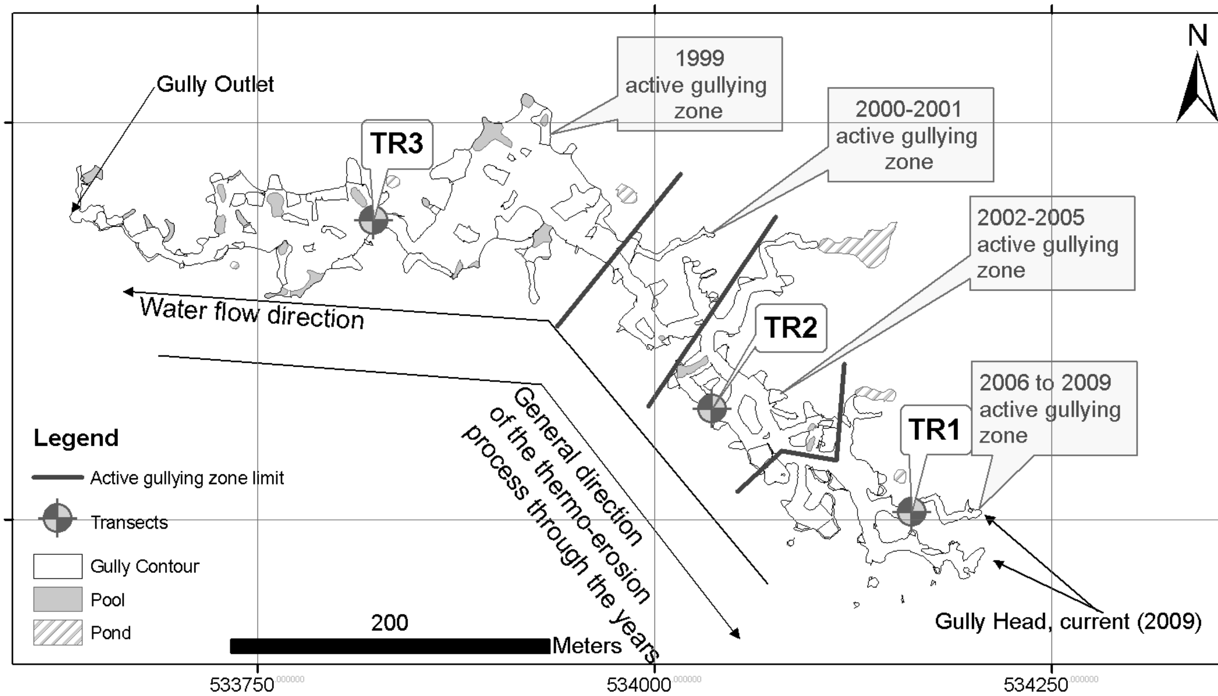


Figure 4 : DGPS-based map of the gully. The gully area is 25000 m2. The main axis of the gully is 748 m long and its cumulative length including all the branches is 2572 m. TR1, TR2 and TR3 are typical cross-sections of the gully head, central section and outlet zones respectively. Active erosion zones for four time frames are represented for 1999, 2000-2001, 2002-2005 and 2006-2009 periods.

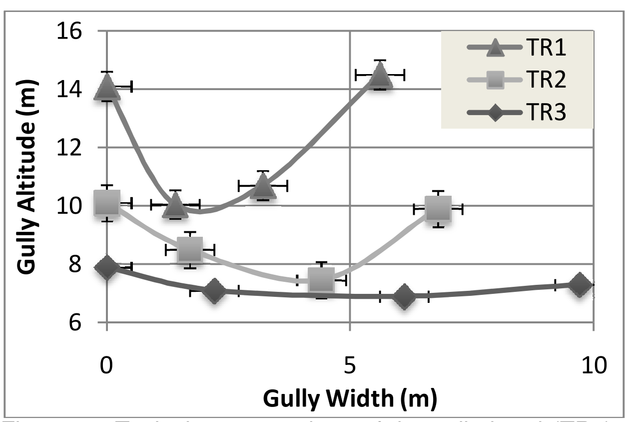


Figure 5 : Typical cross-sections of the gully head (TR1), central section (TR2), and outlet (TR3) zones (see figure 4 for localization of the cross-sections).

4.4.4 Pools

Pools were observed in the gully channel downstream of active RTS zones (Figure 9). These pools were formed and contained by the development of alluvial levees following high snowmelt water discharge in the gully.

Table 1: Geomorphological forms and processes found in the gully.

| Name | n | Area ($m^2$) | Figure |
|---|---|---|---|
| Sinkhole | 9 | 50 | 6 |
| Tunnel | 3 | N/A | 7 |
| Gully Head | 15 | N/A | 8 |
| Pool | 25 | 2350 | 9 |
| Retrogressive Thaw Slump | 135 | 4153 | 10 |
| Collapse | 11 | 1030 | 11 |
| Surface Lowering | 26 | 917 | N/A |
| Baydjarakhs | 5 | 44 | 12 |
| Ponds | 6 | 991 | 13 |

Figure 6 : Sinkhole in ice wedge polygon. The ladder to the left indicates the scale. The arrow in the stream indicates water direction toward the sinkhole.

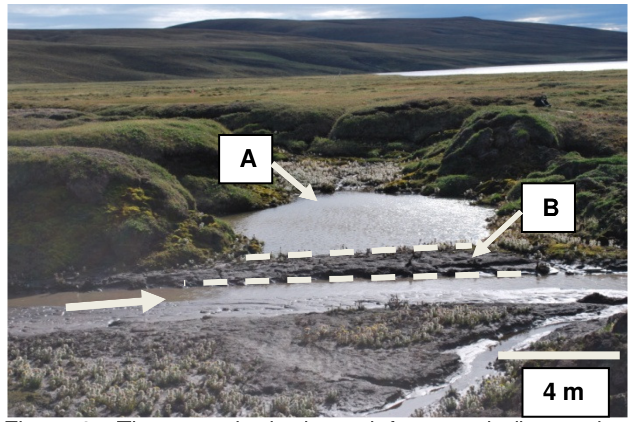


Figure 9 : The arrow in the lower left corner indicates the water flow direction in the gully. (A) Pool in enlarged portion of the gully channel. (B) An alluvial levee containing the pool.

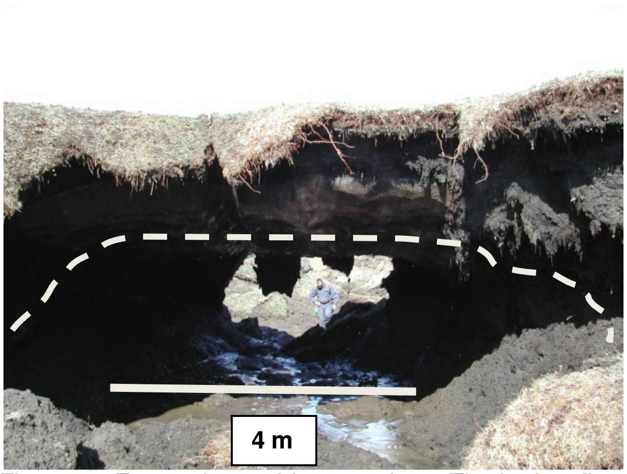


Figure 7 : Exposed tunnel in permafrost. The broken line indicates the ceiling of the tunnel.


Figure 10 : Active retrogressive thaw slump due to the degradation of an exposed ice wedge.

Figure 8 : Gully head in ice wedge polygons forming falls, (person for scale).


Figure 11 : A fresh collapse following thermo-erosion of ice wedge polygons.

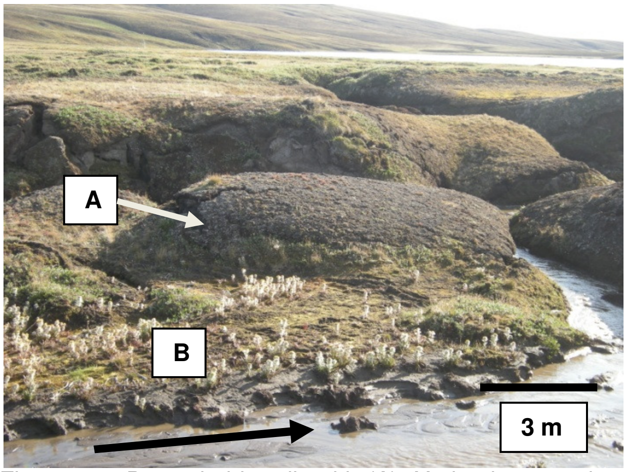

Figure 12 : Degraded baydjarakh (A). Xeric plant species such as *Cassiope tetragona* colonized the baydjarakh (B) Zone evolving towards stabilization with *Senecio congestus* plants.

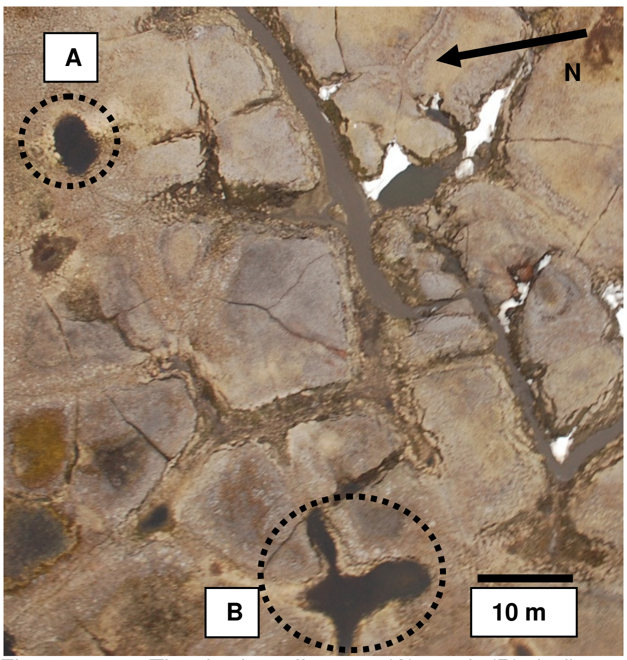

Figure 13 : The broken line at (A) and (B) indicate thermokarstic ponds near the gully network. The pond at (B) was formed at an ice wedge intersection. The arrow in the upper-right corner indicates the geographic north.

4.4.5 Surface lowering
Surface lowering consists of local terrain subsidence adjacent to the gully margins. This phenomenon was mainly due to the joint action of both conductive and convective heat transfer following water flow over the peaty surface of the polygons. Zones subject to surface lowering were lower than the surrounding ground not submitted to surface run-off and with gentle slopes conformable to the direction of the water flow. Surface lowering was not as common near the gully head in the high-erosion activity zone and the intermediate-erosion activity zone, but more frequent in the low-erosion activity zone. Drainage of low-center polygons following gully formation was very often associated with this phenomenon.

4.4.6 Collapse
Tunnel collapse and associated active layer slumps were observed essentially in the intermediate-erosion activity zone and to a lesser extent in the low-erosion activity zone (Figure 11). Collapses create baydjarakhs which became better developed with time in the low thermo-erosion activity zone.

4.4.7 Baydjarakh
The baydjarakh, also known as thermokarst mound (van Everdingen, 1998) is the result, at the study site, of thermo-erosion of the ice wedges forming the boundaries of ice wedge polygons. The polygon center, in this case composed of ice-rich material, is then exposed on all sides. The formation process of this form in the context of the current study begins when active thermo-erosion degrades one or more sides of an ice-wedge polygon under the effects of convective heat transfer. Once the polygon boundary (ice wedges) are thermo-eroded, thermo-erosion action on the baydjarakh is negligible. Baydjarakhs located in the intermediate-erosion activity zone degrade slowly by conductive heat transfer from the slopes and the top of the polygon center. Degradation of ground ice of the polygon center promotes surface subsidence. The final stage of degradation is achieved by fluvial erosion in the gully channel. There are very few baydjarakhs in the gully; those observed were in the low-activity erosion zone where water flow was negligible (Figure 12).

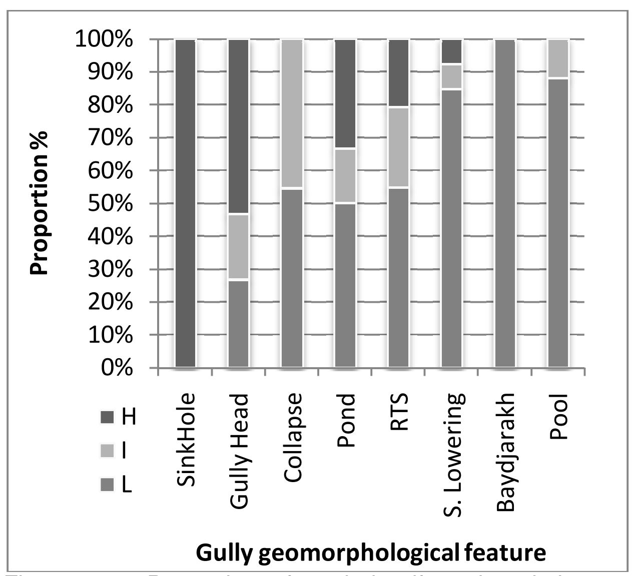

Figure 14 : Proportion of each landform in relation to zones of erosion. The erosion activity level zone in the gully is indicated by H = High, I = Intermediate, L = Low erosion activity.

4.4.8 Thermokarstic pond
Low-center polygons with ponds were observed on the terrace along some sections of the gully channel (Figure

13).Thermo-erosion and retrogressive sub-aerial erosion can lead to drainage of these ponds in the gully. This process locally and momentarily enhances gullying of the surrounding permafrost until the pond is completely drained.

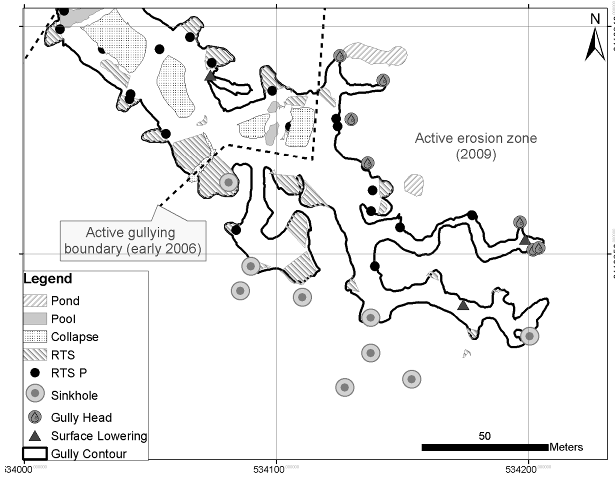


Figure 15 : Zone of high thermo-erosion where entry points to the gully for stream running on the polygon terrace are numerous: this area is characterized by sinkholes and gully heads.

## 5 DISCUSSION

### 5.1 The function of time on zonal categorization

The zones of erosion and permafrost degradation in the gully were defined by the active processes at work for a given year. As time passes, the speed and amplitude at which the processes have acted on gully features have changed. The spatial delineation of each zone is therefore dynamic and is dependent on the speed and importance of the thermo-erosion and other processes of permafrost degradation on the gully geomorphology.

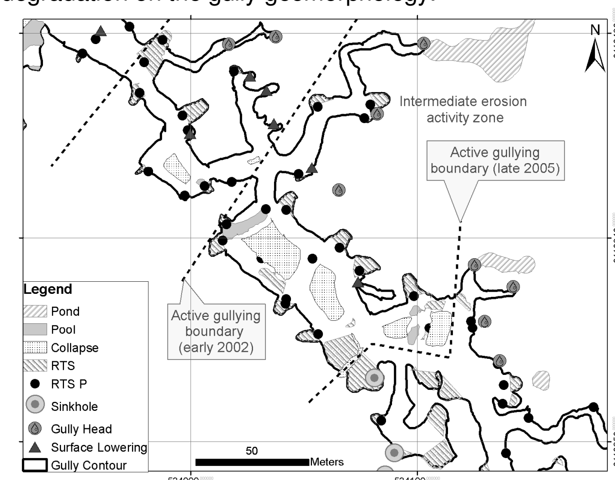


Figure 16 : The zone of intermediate thermo-erosion is dominated by tunnel collapses and retrogressive thaw slumps. Permafrost degradation in this area will eventually initiate the development of baydjarakh.

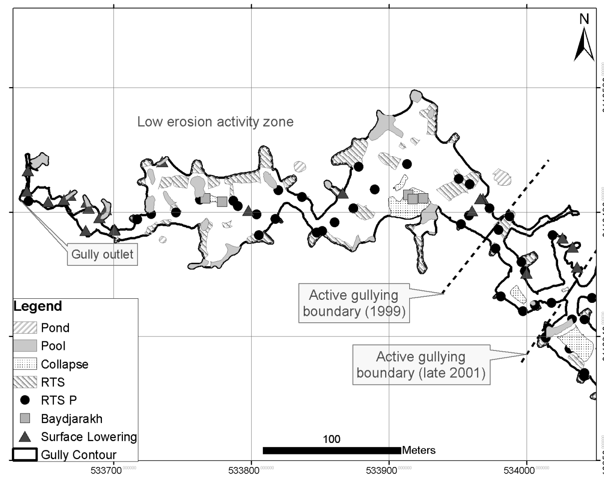


Figure 17 : The zone of low/null thermo-erosion process is the largest zone of this gully and is characterized by the presence of baydjarakhs, pools, alluvial levees, surface lowering and channel enlargement.

The delineation is also function of when the survey is accomplished, which is a snapshot of the gully system for a given moment. To illustrate this concept, we may consider that during the first year after gully initiation, the whole gully was heavily under the effect of thermo-erosion, and sinkholes and gully head were very active. On the contrary, not enough time has passed for ice-wedge polygon boundary and the polygon center to develop baydjarakhs. In the current case, ten year after gully formation, the localization of baydjarakhs is in the oldest part of the gully: the high thermo-erosion zone is progressively evolving into a low to null thermo-erosion zone, while passing by the intermediate stage.

### 5.2 Effects of positive and negative feedback processes on gully development

#### 5.2.1 Observed positive feedback mechanisms

Feedback mechanisms are an important factor in gully formation. Positive feedback mechanisms are contributing to accelerate gullying under the action of thermo-erosion, particularly in the high thermo-erosion zone and near the upstream boundary of the intermediate zone. Water infiltration in sinkholes initiates the melting of an ice-wedge polygon boundary toward the gully main axis. This new path for water in a gently sloped polygon terrace will capture water and maintain or enhance the thermo-erosion process in its immediate area. A stabilized section of the gully can experience the reactivation of the thermo-erosion processes under the effects of thermal and mechanical action of pond drainage and cause new retrogressive thaw slumps and ice-wedges exposition. A winter season where a thick snow blanket accumulates or if a rapid snowmelt happens during late spring create positive feedbacks effects due to the warmer ground temperature related to the insulating effect of snow and especially due to the above average and rapid input of water in the gully system.

5.2.2 Observed negative feedback mechanisms

On the other hand, negative feedback mechanisms are affecting the area of low thermo-erosion action near the gully outlet and the lower boundary of the intermediate zone. Retrogressive thaw slump or collapse material transported by water can be deposited near the gully outlet and can contribute to the formation of alluvial levees and meanders. Alluvial levees retain water in pools and prevent its free flowing to the active part of the gully channel. Water circulating in the meanders is at a distance to ice-rich polygons which prevent further from thermo-erosion action. Enlargement of gully walls channels by retrogressive thaw slumps decrease the possibilities of rapid thermo-erosion of walls downstream. Sediments that are not removed by water in large channels near the gully outlet contribute to deactivation of old thaw slumps and to slope stabilization. Drainage of stabilized thaw-slump and slope colonization by plants then contribute to the development of an insulation layer and eventually to permafrost recovery and final stabilization of old sections of the gully.

# 6 CONCLUSIONS

Our long term observations of the gully case-study on Bylot Island revealed that geomorphic features in the gully are function of the level of thermo-erosion currently active near these features. The quantification and localization of each geomorphic feature makes possible to characterize the gully in function of its thermo-erosion level of activity. The gully walls are steeper in active thermo-erosion zone and very gently sloped in older stabilized part. Gully evolution in the past 10 years shows that the speed of gully development is not linear and that the last few years of progression were much slower than the first year. This indicates that the threshold reached to trigger underground thermo-erosion processes during the first year can have impacts on the ecosystem for decades. Negative feedback mechanisms contribute to stabilization of old gully section whereas positive feedback mechanisms ensure reactivation of gullying processes over the years.

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