

Retrogression rate of thaw slumps in permafrost – an update from the latest monitoring data

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ABSTRACT

This paper provides an update on the latest monitoring results of retrogression rates of 18 thaw slumps in the Mackenzie Valley, Northwest Territories, Canada. The thaw slumps were monitored from 2007 to 2009. The first year monitoring data was published when the data became available, which demonstrated a correlation between thaw slump retrogression rate and scarp wall height. The additional two year data enhanced the initial findings that the retrogression rate of the thaw slumps increases with increase in height of the scarp wall. An updated correlation between the retrogression rate and scarp wall height is presented. The effect of slope orientation on thaw slump retrogression was further verified. The data continue to confirm that retrogressive thaw slumps have no preference over slope orientation.

RÉSUMÉ

Le présent document contient une mise à jour des derniers résultats de surveillance des taux de rétrogression pour 18 glissements dus au dégel dans la vallée du Mackenzie, dans les territoires du Nord-Ouest, au Canada. Un suivi des glissements dus au dégel a été effectué de 2007 à 2009. Les données recueillies pendant la première année de surveillance ont été publiées lorsqu'elles ont été disponibles. Elles démontraient un lien entre le taux de rétrogression attribuable à des glissements dus au dégel et la hauteur des escarpements. Les données recueillies au cours de deux années supplémentaires ont permis d'améliorer les premières constatations, à savoir que le taux de rétrogression augmente avec la hauteur de la paroi. Nous présentons ici une mise à jour de la corrélation entre le taux de rétrogression et la hauteur de l'escarpement. L'effet de l'orientation de la pente, comme facteur pouvant causer des glissements régressifs dus au dégel, a été étudié de façon plus approfondie. Les données continuent de confirmer que les glissements dus au dégel ne sont pas liés à l'orientation de la pente.

1 INTRODUCTION

Retrogressive thaw slumps are common failures of permafrost slopes of fine-grained soils. According to the definition of the Multi-Language Glossary of Permafrost and Related Ground-Ice Terms compiled by the IPA's Terminology Working Group (Everdingen 2002), retrogressive thaw slumps consist of a steep headwall that retreats in a retrogressive fashion due to thawing, and a debris flow formed by the mixture of thawed sediment and meltwater that slides down the face of the headwall and flows away. Such slope failures constantly occur in the Mackenzie Valley, Northwest Territories, Canada. Wang et al. (2005) reported 97 active thaw slumps counted during a single site reconnaissance trip to the northern part of the Mackenzie Valley in June 2005. The majority of those slides were retrogressive thaw slumps. Figure 1 shows a typical example of such slope failures. The scarp wall retrogresses as melting continues in summer, stops in winter and reactivates the next summer. The cycle repeats and the size of the slump grows every year until the ice-rich scarp is covered or ice-poor material is encountered. Such slumps may

start from a slope failure as small as a few meters diameter and retrogress over a distance as large as a few hundred meters. They alter local landforms and cause damage to facilities, e.g., pipelines or highways (Ma et al. 2006). Understanding the failure processes and documenting the retrogression rate are important for developing appropriate mitigation measures.

A field monitoring program was started at the Geological Survey of Canada (GSC) in 2007 to investigate the retrogression behaviour of the thaw slumps in the Mackenzie Valley. A total of 13 thaw slump sites were monitored during the first year 2007. Survey stakes were installed at locations near the scarp walls. The distances of the scarps from the stakes were measured at the beginning and end of the summer thawing season. The first year (2007) monitoring data demonstrated promising trend and was published (Wang et al. 2009). The monitoring program continued for two more years in 2008 and 2009. An additional five thaw slumps were monitored in 2008 and 2009 for a total of 18 slumps. This paper presents an update of the monitoring results from 2008 and 2009.

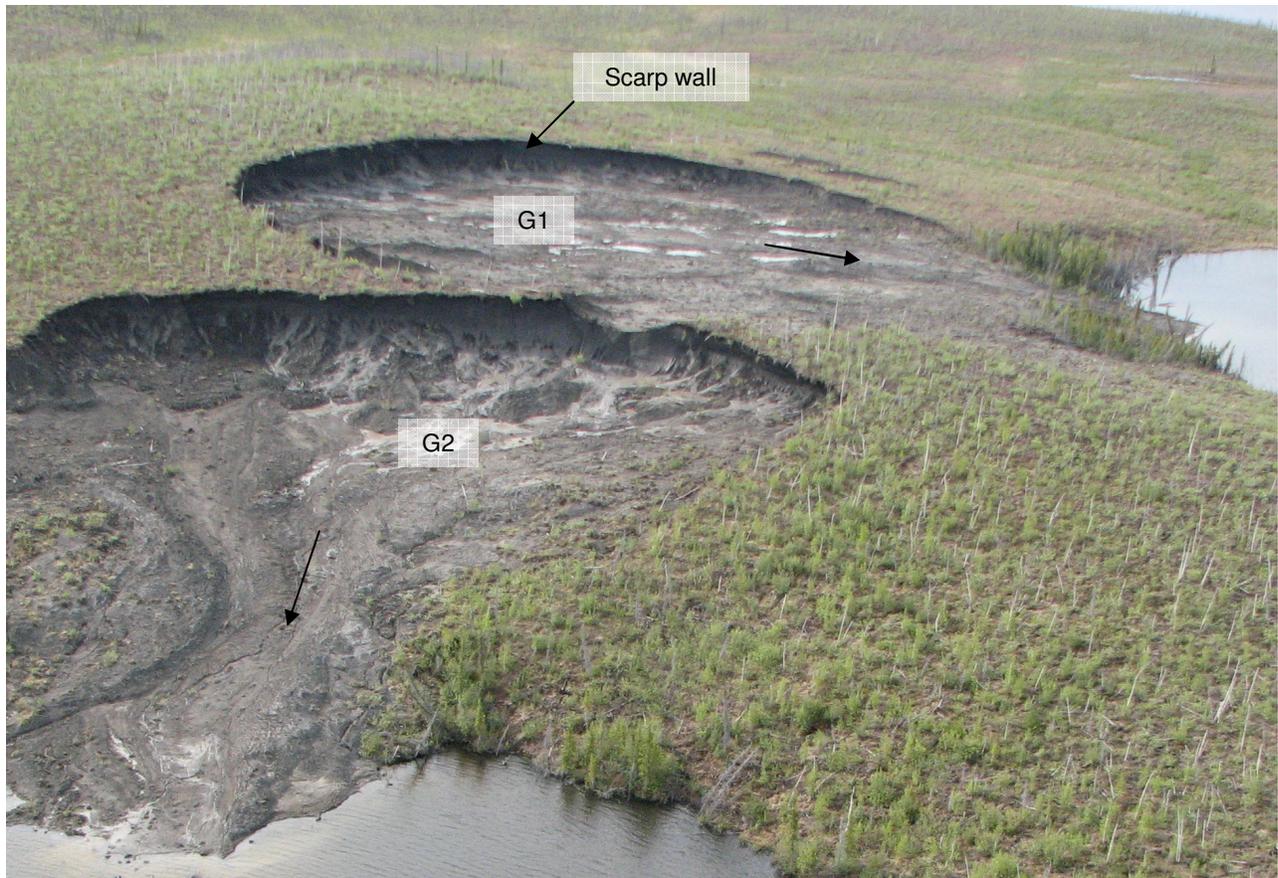


Figure 1. Typical thaw slumps (G1 and G2 correspond to locations on Figure 2. Photo taken June 2009.)

2 SITE DESCRIPTIONS

Figure 2 shows the locations of the 18 retrogressive thaw slumps monitored from 2007 to 2009. These sites were selected as they are representative of the typical retrogressive thaw slumps observed in the region. Seven of the sites were to the north of Inuvik, and 11 were to the south of Inuvik. The northern sites are in Inuvialuit Settlement Region and are depicted as I1 to I5. The southern sites are in Gwich'in Settlement Region and are depicted as G1 to G12. Two locations at site I1 and 3 locations at site G1 were monitored. Some survey stakes installed in 2007 were destroyed later due to expansion of the slumps.

Vegetation in the two study regions were different. The northern sites (I1 to I5) were covered by tundra vegetation with little or no trees. The ground in this region is typically covered by a layer of organic mat of about 15 to 30 cm thick (locally thinner or thicker) that consists of roots or moss. The subsurface materials exposed in the scarps of the slumps are clayey silt or silty clay with trace sand and gravel and occasional

cobbles (glacial till deposit). The active layer is about 0.5 m thick underlain by ice-rich permafrost.

The southern sites (G series) are in forest areas. Most of the sites are in burned areas where trees and vegetation were destroyed by relatively recent forest fires about a decade ago. There was no sign of any recent fire activity at sites G4 and G8 where mature trees were observed. The soil materials from the landslide scarps are mostly silty clay. The active layer is about 1 m thick in the burned areas and thinner in the unburned area where undisturbed vegetation provided better insulation to the subsurface soils.

All the sites monitored are in continuous permafrost region, where permafrost extends to a great depth (in the order of hundred meters according to Taylor et al. 2000, and Smith and Burgess 2002). The fine-grained permafrost soils are usually ice-rich.



Figure 2. Site location map (dots with notation I1 to I5 and G1 to G12 indicate study sites)

3 WEATHER CONDITIONS

Weather stations are available in Inuvik, which are about 30 km from the nearest site in the north and about 90 km from the nearest site in the south. Historical weather data recorded in Inuvik from 1958 to 2009 were obtained from Environment Canada (2011). The minimum and maximum Mean Annual Air Temperature (MAAT) and air thawing indices (I_{at}) are provided in Table 1. The MAAT and I_{at} for the study years of 2007, 2008 and 2009 are given in Table 2.

As noted in Tables 1 and 2, the air temperature conditions in 2007, 2008 and 2009 were close to the historical normal conditions. The MAAT was slightly lower by 0.1°C for 2008 and 2009 than for 2007. The I_{at} was also slightly lower for those two years. However, the

differences are marginal compared to the historical variations shown in Table 1.

Table 1. Historical mean annual air temperatures (MAAT) and air thawing indices (I_{at}) in Inuvik (1958-2009)

Description	MAAT (°C)	I_{at} (°C-day)
Minimum	-11.8	939
Average	-8.8	1,309
Maximum	-4.5	1,822

Table 2. Air temperatures of 2007 to 2009 in Inuvik

Description	MAAT (°C)	I_{at} (°C-day)
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2007	-7.6	1,376
2008	-7.7	1,212
2009	-7.7	1,306

4 FIELD MEASUREMENTS

The selected thaw slumps were monitored with survey stakes installed at one or more locations ahead of the scarps. The distance between the survey stakes and the scarp walls were measured with measuring tapes twice a year: once at the beginning of the summer thaw season and another at the end of the thaw season in 2007, 2008

and 2009. Most of the survey stakes were installed at the higher locations above the scarp walls, whilst some of them were installed at lateral locations towards which the scarps were retrogressing. Also measured were the heights of the scarp walls where and when the distances to the survey stakes were measured. The slope orientation or the scarp wall dipping direction at each location was measured as well. Table 3 provides the measured data from the three years.

Table 3. Field measurements

Site-Location	Scarp Dipping Direction	2007		2008		2009	
		Scarp Height (m)	Scarp Retrogression (m/year)	Scarp Height (m)	Scarp Retrogression (m/year)	Scarp Height (m)	Scarp Retrogression (m/year)
I1-STK1	N50°E	9.1	7.0	2.2	4.0	-	-
I1-STK2	N50°E	9.1	6.0	2.2	3.0	1.7	0.0
I1-STK4	N52°E	-	-	-	-	1.7	1.0
I2-STK4	N164°E	-	-	2.5	4.3	1.7	0.4
I2A-STK1/STK5	N196°E	-	-	6.0	10.0	6.0	8.8
I3-STK1A	N0°E	2.5	1.8	2.5	0.8	1.5	0.3
I3A-STK1	N60°E	-	-	2.5	1.2	2.0	0.1
I4-STK1	N80°E	13.0	8.0	13.0	14.3	10.0	11.7
I5-STK1	N100°E	6.6	5.6	8.1	8.4	5.5	4.1
G1-STK1/STK2	N253°E	7.0	9.3	8.0	15.1	6.0	14.1
G1-STK3	N180°E	6.0	9.0	6.0	11.0	-	-
G1-TP2	N343°E	5.0	6.7	5.0	6.0	-	-
G2-STK1	N0°E	5.8	9.0	10.6	11.0	-	-
G3-STK1	N241°E	4.0	6.5	4.0	12.2	-	-
G4-STK1/STK2	N30°E	15.0	8.8	15.0	9.4	14.0	8.8
G5-STK1/STK2	N290°E	8.2	7.0	4.7	11.4	4.8	10.0
G6-STK1/STK2	N18°E	6.4	6.5	6.0	9.1	5.0	8.1
G7-STK2	N56°E	2.2	4.7	1.9	3.7	2.5	0.0
G8-STK1/STK2	N0°E	14.5	9.7	14.5	10.8	12.0	8.6
G9-STK1/STK2	N190°E	7.0	7.6	4.4	11.3	4.0	7.2
G10-STK1	N22°E	-	-	7.5	9.8	7.7	10.1
G12-STK1	N117°E	-	-	4.6	4.9	-	-

5 RETROGRESSION CORRELATION

A correlation between the thaw slump retrogression rates and the heights of the scarp walls was identified by Wang et al. (2009) based on the 2007 monitoring data. Continued monitoring during the subsequent two years in 2008 and 2009 enhanced the data. The three-year monitoring results of retrogression vs. scarp height are plotted in Figure 3. As noted from this figure, the distribution of the later 2008-2009 data follows the same pattern established by the 2007 data. The upper limit of the data has been pushed higher from about 10 m/year for the 2007 data to about 15 m/year for the 2008 and 2009 data. The three-year data are more scattered than the first year data. The increased scattering was expected with more data becoming available.

As noted in Section 3 above, the average air temperatures for 2008 and 2009 are remarkably close to that of 2007. It is therefore unlikely that the air temperature contributed to the increase of the upper limit of the data. As a matter of fact, based on the slightly lower air thawing indices in 2008 and 2009 (Table 2), the retrogression rates should have dropped slightly, which was actually not the case. The increase of the upper data limit should therefore be considered as normal data scattering.

Nevertheless, given the three-year duration of measurements and normal air temperature conditions, the retrogression rates collected are believed to be representative of normal rates in the region. Based on this set of data, the earlier correlation (Wang et al. 2009) has been updated as follows:

$$R = a - b * e^{(-H/c)}$$

[1]

(m); and a , b , and c are fitting constants with values given in Table 4.

Where R denotes distance of scarp wall retrogression per year (m/year); H is height of scarp wall

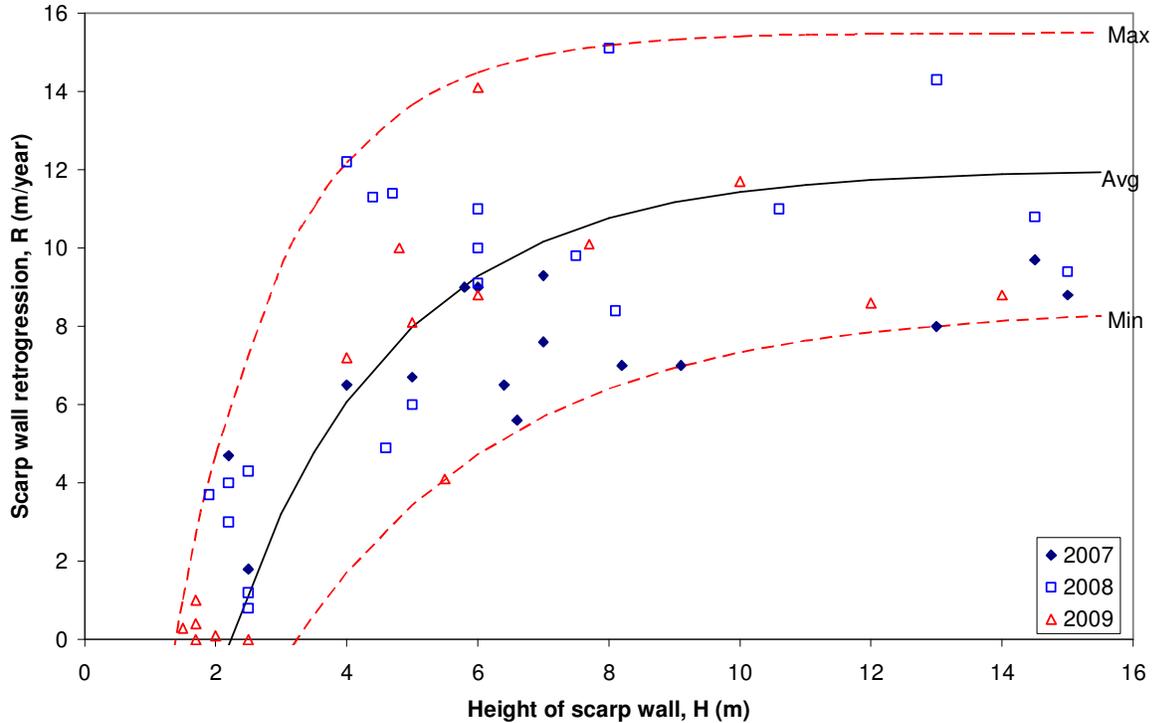


Figure 3. Thaw slump retrogression rate vs. height of scarp wall

Table 4. Constants for correlation between retrogression rate and scarp wall height (Eq. 1)

Constant	Lower Bound	Average	Upper Bound
a	8.5	12.0	15.5
b	22.0	28.5	35.0
c	3.4	2.6	1.7

A correlation between thaw retrogression and slope angle was presented in Wang et al. (2009). However, it was pointed out that the correlation with slope angle was less meaningful than that with scarp wall height. The new data confirmed this point. Further correlation with slope angle was not found.

Thaw retrogression is associated with melting of ice-rich permafrost exposed. Ablation continues along the scarp wall in summer as long as there is enough ice-rich material in the wall. Depending on the water content, the ablated materials build up at the toe of the wall covering part or the entire ice-rich surface as illustrated in Figure 4. Scarps of lower height tend to retreat more slowly because in most of these cases, the ice-rich materials are covered or partially covered by the debris. The materials from the active layer have lower water content

compared to those from the permafrost where soil contains high water/ice content. The ice-rich soil behaves like a “slurry” when melted and flows away relatively quickly from the scarp (Wang et al. 2005). When the “slurry” is mixed with the materials fallen off from the upper active layer, its fluidity decreases resulting in a decreased flow rate of the debris. This causes the debris to aggrade at the toe of the scarp. The debris build-up reduces the amount of ice-rich permafrost being exposed and therefore a reduced amount of “slurry” generated. This further decreases the fluidity of the “slurry mix” and hence more aggradation. On the other hand, as the debris builds up, its weight increases. When the build-up is high enough, the mass slides away driven by its own weight. Thus, the covered ice-rich permafrost along the toe of the wall is re-exposed, and melting is accelerated until it is covered again. This process is illustrated in Figure 4. The cycle repeats throughout the summer.

6 EFFECT OF SLOPE FACING DIRECTION

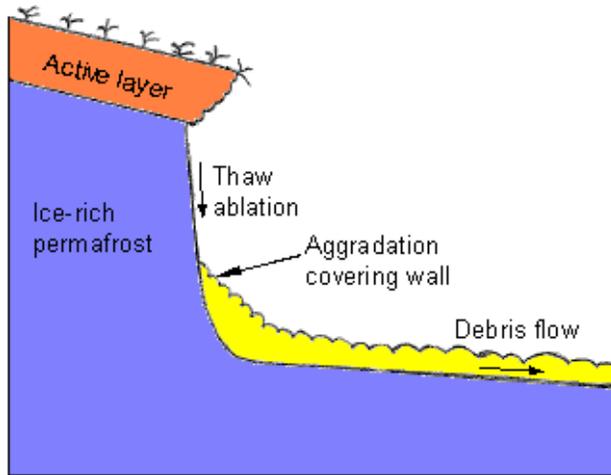


Figure 4. Illustration of thaw slump process

In summary, the retrogression rate is higher with higher scarp walls. The reasons are: (a) the accumulating debris cannot build up high enough at the toe of the scarp wall to block the ice-rich permafrost from melting; (b) the materials falling off the scarp wall may have overall higher water content and, therefore, can flow more easily. This can be due to a higher ratio of ice-rich permafrost to active layer (about 0.5 to 1 m thick in the study region) materials in the mixed mass. This process explains that once the scarp wall reaches a certain height, ablation is at its full potential throughout the summer and a maximum retrogression occurs. Figure 3 indicates that the maximum retrogression may occur for scarp walls higher than about 6 m.

The relationship between thaw slump retrogression and slope orientation for the three-year monitoring period is shown in Figure 5. A trajectory drawn from the coordinate origin to any data point indicates the direction and distance of retrogression at that point. As indicated by Wang et al. (2009), the retrogression was not influenced by the slope orientation observed from the first year (2007) data. This conclusion was strongly supported by the extended monitoring data from 2008 and 2009. As shown in Figure 5, the retrogression rates are fairly evenly distributed in all directions.

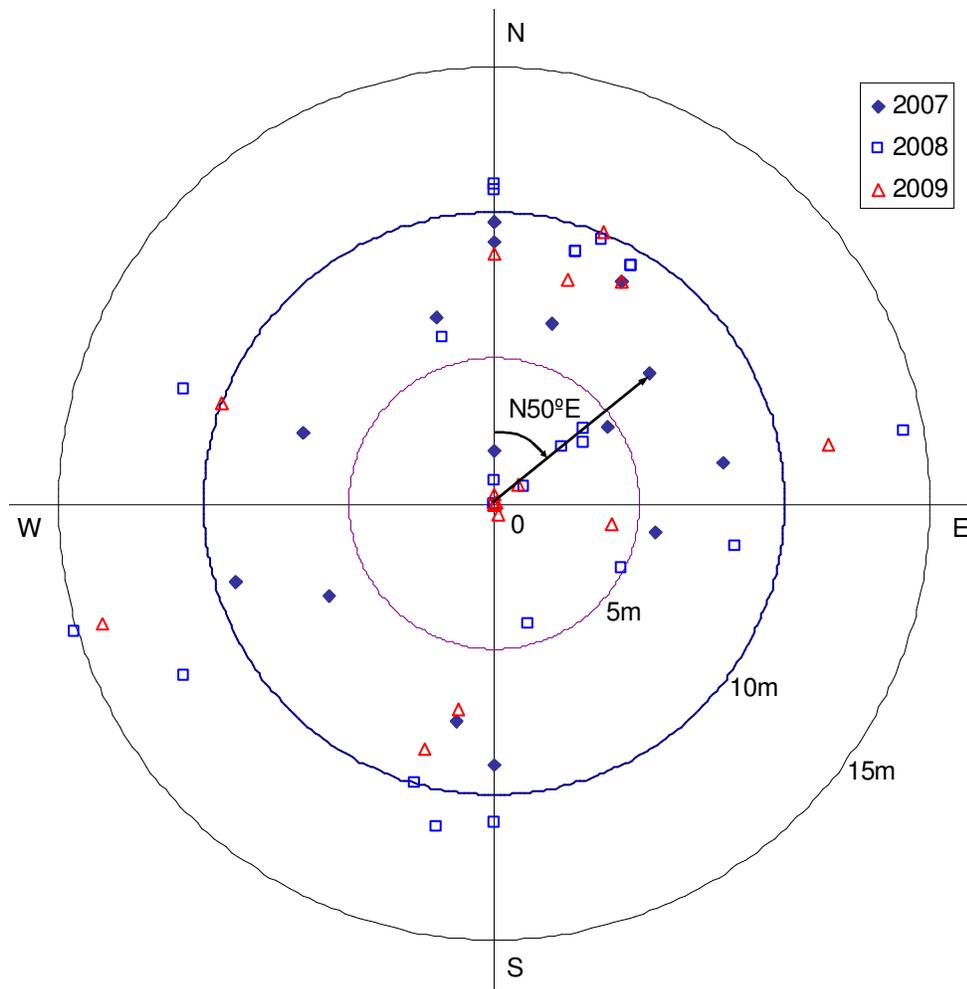


Figure 5. Distribution of scarp wall retrogression rates and scarp facing directions

7 CONCLUSIONS

Continued monitoring of 18 thaw slumps in the Mackenzie valley was carried out to further study the retrogression behaviour of those slope failures and to validate the initial findings reported by Wang et al. (2009). The new monitoring data confirmed the initial findings that thaw slump retrogression rate increases with the increase of scarp wall height. The retrogression rate starts to reach its maximum when the scarp wall is about 6 m or higher. The maximum retrogression can be as high as 15 m/year. The average air temperatures during the three monitoring years were very close to the historical average conditions. The three-year monitoring data are believed to be representative. The correlation between the retrogression rate and scarp wall height has been updated.

The new monitoring data continued to support the findings that the thaw slump retrogression has no preference over slope facing direction. There is strong evidence proving that north facing slopes do not necessarily retrogress slower than those facing south.

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