Retrogressive thaw slumps: From slope process to the landscape sensitivity of northwestern Canada.

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
Retrogressive thaw slumping is an important driver of geomorphic change in ice-rich, glaciogenic landscapes. Here we summarize research on the processes of thaw slump development, with focus on studies from northwestern Canada. In the Peel Plateau, individual slumps commonly exceed 20 ha in area. These “mega slumps” displace downslope up to 10^6 m^3 of previously frozen materials, reconfigure drainage networks, and significantly increase stream sediment and solute loads. The significant acceleration of slump activity has caused this process to become a dominant driver of geomorphic change in several ice-rich environments across the western Arctic. Landsat satellite imagery (1985 to 2011) and high frequency climatic and photographic time-series from the Peel Plateau indicate that an increase in rainfall has accelerated downslope sediment flux from slump scar zones, perpetuating slump activity and intensifying this disturbance regime. Increasing summer rainfall is likely the main factor driving recent geomorphic change. Remotely sensed mapping of slump-impacted terrain across a 1, 275, 000 km^2 area of northwestern Canada indicates the close association with ice-rich hummocky moraine landscapes deposited at the margins of the former Laurentide Ice Sheet. This mapping provides a quantitative basis for evaluating the potential for climate-driven landscape change and assessing the spatial distribution of ice-cored permafrost across northwestern Canada.

RÉSUMÉ
Les glissements régressifs de dégel représentent un processus thermokarstique dynamique et influencent la géomorphologie des environnements circumpolaires d’origine glaciaire. Les glissements présents sur le plateau de la rivière Peel, affectent fréquemment des superficies excédant 20 ha. Ces «méga-glissements» déstabilisent jusqu’à 10^6 m^3 de sédiments, reconfigurent le drainage et augmentent la charge de transport des cours d’eau en aval. Une augmentation de leur activité est observée dans les environnements de pergélisol riche en glace de l’ouest de l’arctique. Les données satellitaires Landsat (de 1985 à 2011) ainsi que les imageries et reconstitution climatique à hautes fréquences indiquent qu’une augmentation des précipitations sous forme de pluie accélère le taux de transport sédimentaire en provenance de zones des parois d’instabilités. Ce mécanisme empêche la stabilisation naturelle des parois et intensifie le processus de glissement régressif. Une cartographie par télédétection des zones affectées par des glissements régressifs sur une superficie de 1, 275, 000 km^2 du Nord-Ouest Canadian indique une forte association entre la présence de glissements et les moraines frontales riches en glace de l’inlandsis laurentien. Cette cartographie, considérée conjointement avec les processus de formation des glissements, permet une évaluation quantitative des changements géomorphologiques liés au climat, ainsi qu’une mesure de la distribution géographique des zones de pergélisol riche en glace du Nord-Ouest Canadian.

1 INTRODUCTION

Retrogressive thaw slumping is a dynamic form of thermokarst slope disturbance that couples thermal and geomorphic processes to rapidly degrade ice-rich permafrost (Fig. 1) (Burn and Lewkowicz, 1990). The process can modify slope morphology and transport large volumes of thawed materials downslope to lakes, valley bottoms and coastal zones. In ice-rich permafrost environments, thaw slumping can be the dominant driver of landscape change (Lewkowicz, 1987a; Lacelle et al., 2010; Lantuit et al., 2012). Mounting evidence suggests that this disturbance regime has intensified across a range of environments, increasing terrain and fluvial impacts (Kokelj and Jorgenson, 2013).

In this paper we consider the processes and feedbacks associated with thaw slump development, linkages with climate, and the factors that control the distribution of these disturbances. The broad goal of this research is to understand the climate change sensitivity of permafrost environments. The focus on thaw slumps has been stimulated in part by the concerns raised by land users, and environment and infrastructure managers who have reported that the magnitude of slumping and landscape impacts has intensified in northwestern NWT. Our specific objectives are to: A) summarize the processes contributing to thaw slump development, and document their environmental impacts; B) evaluate the drivers that intensify thaw slump activity across a range of western Arctic landscapes; and C) examine the broad-

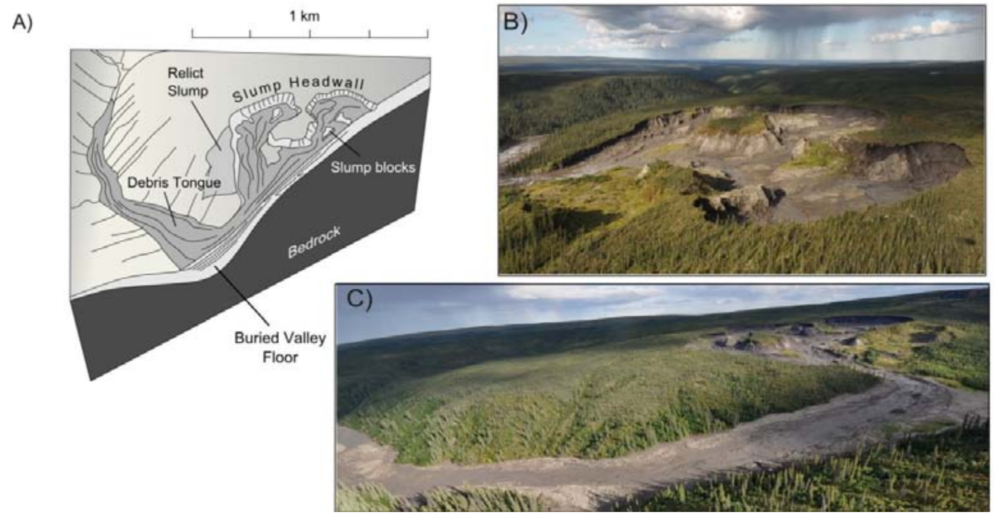

Figure 1. Thaw slump photo montage. A) Schematic cross-section of a large thaw slump. B) Scar zone and headwall of a "mega slump" on the Peel Plateau. C) The same slump viewed to show the extent of the debris tongue deposit. The total disturbance area is approximately 39 ha and the headwall is up to 25 m high. The disturbance has been on the landscape since the 1950s. Intensified thermokarst activity in the past 2 decades has resulted in rapid headwall retreat and an increase in scar area driven by an acceleration of scar zone sediment flux and the deposition of a large debris tongue.

scale patterns of thaw slump distribution across northwestern Canada. Based on these results we have refined a conceptual model linking climate conditions with slump intensification, which informs our understanding of the sensitivity of permafrost landscapes.

2 STUDY AREA AND METHODS

2.1 Field-based and local-scale mapping studies: Slump dynamics and change with time

A series of collaborative mapping and field-based studies were initiated on the Peel Plateau, northwestern NWT in 2010 to investigate the distribution and development of thaw slumps, and to determine the environmental impacts of this disturbance regime (Fig. 2). The Peel Plateau is a fluvially-incised, ice-rich morainal landscape that extends along the eastern margins of the Richardson Mountains and northeastern Mackenzie Mountains. Permafrost depths are greater than 100 m (Mackay, 1967) and the mean annual ground temperatures are relatively warm (< -2.5°C) due to atmospheric temperature inversions in winter (O'Neill et al., 2015). Terrain stability on the Peel Plateau is of broad interest because it constitutes a major sediment source for numerous tributaries of the Peel River and Mackenzie Delta (Kokelj et al., 2013), it is traversed by the Dempster Highway, which links western Arctic Canada with the south (Gill et al., 2014), and it lies at the heart of Gwich'in traditional lands (Slobodin, 1981).

A range of field techniques were implemented to investigate the processes and feedbacks of slump growth. These included terrain surveys, deployment of remote cameras to track slump sediment transport, collection of automated climatic data and compilation of historical climate records to investigate drivers of scar zone sediment flux (Kokelj et al., 2015). The geochemistry of permafrost, slope runoff and streams were evaluated by sampling across a range of slump impacted and unimpacted streams. Selected streams were also monitored with data loggers to evaluate patterns of variation in water levels, chemistry and sediment flux (Malone et al., 2013; Kokelj et al., 2013; Lacelle et al., 2015). Aerial photograph interpretation, and novel analysis of Landsat satellite images from 1985 to 2011 were undertaken to determine the distribution of slumps, landscape associations and their change over time (Brooker et al., 2014, Lacelle et al., 2015; Kokelj et al., 2015).

Thaw slump distribution and rates of growth were documented using historical air photographs in the Peel Plateau and three additional study areas across the western Arctic (Fig. 2). The goal of this analysis is to assess landscape and climate factors that contribute to regional variation in slump characteristics and rates of change.

2.2 Broad-scale mapping: The distribution of slump impacted terrain across northwestern Canada

The objective of this study was to evaluate the broad-scale distribution of terrain affected by retrogressive thaw slumping across the western and central regions of Subarctic and Arctic Canada, including portions of the Yukon, Northwest Territories, and Nunavut (Fig. 2). This project was made possible by the compilation of georeferenced SPOT 4 and 5 orthomosaics from 2005-2010 (http://www.geomatics.gov.nt.ca/sdw.aspx). To map the areas impacted by active retrogressive thaw slumps, a 15 x 15 km grid system was developed to cover the1,274,625 km^2 study area (Fig. 2). Trained technicians assessed disturbance and landscape attributes for each

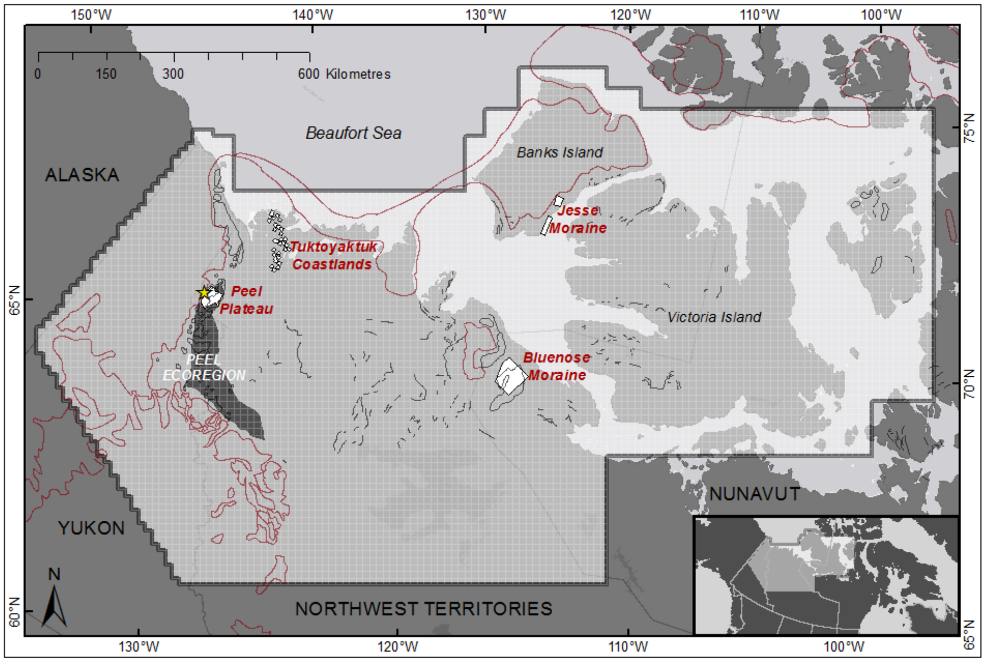

Figure 2. Broad-scale mapping study area in Northwestern Canada, including the western Arctic and subarctic Northwest Territories, northern Yukon and central eastern Nunavut. The star indicates the Peel Plateau, small white blocks indicate areas of air photograph analysis for slump change. The lighter coloured landscape delineated by a solid line indicates the 1,275,000 km^2 broad-scale slump mapping project area. The red line indicates the Wisconsinan Glacial extent and ice front positions and the grey lines are major moraine features from Fulton (1995). The inset map at the bottom right shows the position of the study area in northern Canada.

grid cell by viewing the georeferenced SPOT 5 and SPOT 4 orthomosaics. A classification scheme described in Segal et al., (2015) provided a systematic basis for assessing each grid cell and populating all required attribute fields which included: 1) the slump density; 2) primary and secondary slump-landscape associations (valley, lakeside, coastal); and 3) area of the largest slump.

The SPOT imagery used a pixel size of 10 m, and was viewed at a scale of 1:20 000 to 1:30 000 and mappers were able to confidently identify disturbances as small as 0.75 ha. To ensure that slumps were mapped accurately, each grid cell was examined by at least one trained observer and one expert reviewer. Stable slump scars were not considered in this analysis because of challenges associated with their consistent identification across a range of landscapes using the SPOT imagery. As such, the map products represent conservative estimates of slump distribution.

3 RESEARCH RESULTS AND DISCUSSION

3.1 Thaw slump processes, Peel Plateau

Retrogressive thaw slumping is an important driver of geomorphic change in landscapes underlain by ice-rich permafrost, and it is the most common form of mass wasting on the Peel Plateau (Fig. 1) (Lacelle et al., 2015). In this environment, thaw slumps are initiated when ground ice is exposed by mechanical and thermal erosion due to fluvial activity (Kokelj et al., 2015), thermally driven subsidence along lakeshores (Kokelj et al., 2009a), or mass wasting triggered by extreme thaw or precipitation (Lacelle et al., 2010). Active thaw slumps are comprised of an ice-rich headwall, a low-angled scar zone consisting of thawed slurry and in some cases a periodically mobile tongue of debris that develops as the saturated materials flow downslope (Figs. 1, 3). Surface energy fluxes, ground ice and headwall characteristics (size and orientation) influence ablation of ground ice and rates of thaw slump enlargement (Lewkowicz, 1987b; Lacelle et al., 2015). Gravity-driven flow and collapse move thawing materials to the base of the headwall. Meltwater and debris are transported from the slump headwall by fluvial processes and shallow and deep-seated mass flows (Kokelj et al., 2013, 2015). The nature and rate of downslope sediment removal from the slump scar zone is a function of slope, soil characteristics and the moisture content of the thawed materials (Kokelj et al 2015). A thaw slump can enlarge for decades until the exposed ground ice is covered by an accumulation of thawed sediments (Fig. 3b) (Burn and Lewkowicz, 1990). Vegetation colonization on the nutrient-rich scar zone occurs when material accumulation has stabilized the disturbance (Lantz et al., 2009).

Our research on thaw slump processes and environmental impacts has been focused on large, valley-side slumps in the Peel Plateau. The high relative relief of fluvially-incised slopes and ice-rich permafrost provide favourable conditions for the development of extremely large thaw slumps now common in the Peel Plateau (Fig.

1) (Lacelle et al., 2015). These “mega slumps” grow beyond the break of slope, thaw thick layers of ice-rich permafrost and translocate large volumes of sediment downslope, reconfiguring slopes and depositing debris in valley bottoms (Figs. 1, 3, 4). As thaw slumps enlarge they tend to increase in geomorphic complexity to include different modes and intensities of downslope sediment displacement, which operate across a range of temporal and spatial scales (Kokelj et al., 2015). These processes include: (1) exposure of, and ablation of large massive ice bodies, backwasting of the headwall by retrogressive failure and supply of sediments and meltwater to a low-angled scar zone; (2) evacuation of debris from the slump scar zone facilitated by a combination of diurnal, meltwater driven fluvial transport, intermittent rainfall-induced mass wasting (gravitational collapse, slumps, torrents, plug-like debris flow), and quasi-continuous fluidized mass flows; (3) base-level erosion, or evacuation of outlet detritus; and (4) valley-confined downstream aggradation of debris derived from the scar zone, leading to cascading effects including development of debris damned lakes and enhanced valley-side erosion and development of secondary slumps. These processes and feedbacks can prolong slump activity over periods of several decades to produce disturbances that are tens of hectares in area.

3.2 Intensification of slumping, feedbacks and cascading effects

Thaw slump activity has increased across a range of landscapes in northwestern Canada (Lantz and Kokelj, 2008; Lacelle et al., 2010; Kokelj et al., 2015). Warmer air temperatures and increasing rainfall can influence thaw slump initiation. Around lakes, rising permafrost and water temperatures can alter talik configuration and thaw ice-rich sediments subadjacent to lakeshores causing lake-bottom subsidence, shoreline collapse and thaw slump initiation (Kokelj et al., 2009a). Deeper seasonal thaw or higher rainfall can also cause active-layer detachment slides. The intensification of precipitation regimes and high summer streamflow events can accelerate thermoerosion along flow tracks and channels, exposing ground ice and leading to slump initiation.

Several climate factors can intensify the processes of thaw slump development. On the Peel Plateau, a major increase in the number and size of active slump surfaces and debris tongue deposits since the mid-1980s (Table 1) has occurred in concert with a statistically significant increase in the magnitude and intensity of rainfall (Kokelj et al., 2015). Air temperature and precipitation interact to influence the moisture regime of slump soils and downslope sediment transport from the slump scar zone. Diurnal pulses of ground ice meltwater drive high frequency, low magnitude surficial-sediment movement, and intense rainfall events stimulate major mass flows and downslope debris tongue enlargement (Kokelj et al., 2015). These lower-frequency high magnitude rainfall-induced flows evacuate sediments from the slump scar zone (Fig. 3c). Where the floor of the slump scar is underlain by ice-rich permafrost or massive ground ice,

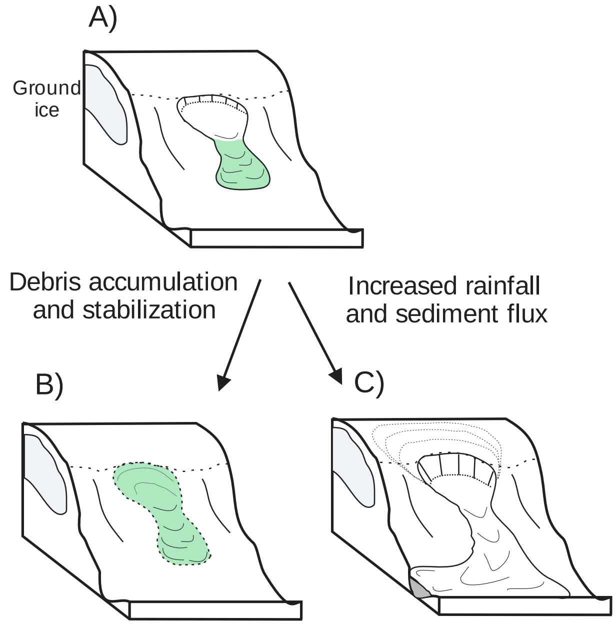

Figure 3. A) Schematic showing a valley-side slump, headwall, scar area and vegetated debris tongue (green). B) Stabilization of the slump can occur when slump grows to the upper slope and when materials accumulate to insulate exposed ground ice. The green shaded scar and debris tongue indicate the establishment of vegetation cover. C) The influence of accelerated sediment flux from the scar zone on headwall height and debris tongue development. The dotted lines upslope of the headwall indicate the increased upslope growth potential of the disturbance.

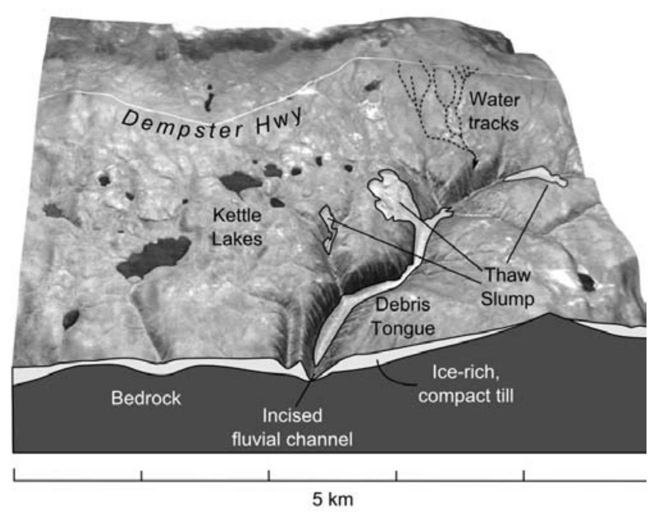

Figure 4. An active disturbance regime is evident in glacially-conditioned, ice-rich terrain on the Peel Plateau. Fluvial incision and thermal erosion have exposed ice-rich sediments, which has led to the development of large retrogressive thaw slumps and debris tongues within the network of incised valleys in the Plateau. Kettle lakes suggest ice-cored terrain, which is confirmed by the ice-rich permafrost at least 25 m thickness exposed in the nearby slumps.

meltwater runoff and downslope removal of debris can contribute to further thaw settlement of the slump floor or polycyclic behaviour (Lantuit et al., 2012). Together, these processes help maintain a headwall of exposed ground ice and inhibit slump stabilization (Fig. 3c).

The enlargement of thaw slumps can strengthen feedbacks that amplify this disturbance regime. At decadal timescales, large slumps retreat more rapidly than small ones because they are less likely to accumulate sufficient debris to arrest headwall retreat (Lacelle et al., 2015). The exposure to incoming solar radiation and rate of ground ice ablation also increase with headwall height and length so that large slumps may grow upslope more rapidly than smaller disturbances. More rapid ablation of these large headwalls produce saturated scar zone soils preconditioned for the occurrence of rainfall-induced mass flows (Kokelj et al., 2015). As thaw slumps enlarge so do their hydrological contributory areas, which can enhance the soil moisture regime and further accelerate sediment removal from the scar zone.

These feedbacks accelerate scar zone sediment flux and debris tongue progradation, which can in turn intensify fluvial impacts and disturbance of adjacent slopes (Fig. 1, 3, 4). Debris tongue deposits can raise the base level of the trunk stream causing the formation of debris-damned lakes and channel diversions. Lateral stream displacement commonly initiates valley-side thermoerosion and slumping of adjacent slopes to produce localized areas of high disturbance intensity (Kokelj et al., 2015).

An increase in the frequency and magnitude of thaw slumps can elevate the supply of sediments and solutes to fluvial and lacustrine environments (Kokelj et al., 2009b, 2013). Sediment and solute concentrations in slump-impacted streams are several orders of magnitude greater than in undisturbed streams (Kokelj et al., 2013; Malone et al., 2013). Hundreds of small to medium sized watersheds on the Peel Plateau are impacted by thaw slumps (Brooker et al., 2014). A significant rising trend in SO_4 concentrations and the SO_4/Cl ratio in the Peel River between 1960 and 2012 suggest that the acceleration of thaw slump activity has increased the weathering of glaciogenic materials and altered the geochemical flux of this 70, 000 km^2 watershed (Kokelj et al., 2013). The rapid downstream responses to thaw slump enlargement highlight the efficacy of this process in mobilizing previously frozen glaciogenic materials from slope storage to the fluvial system (Fig. 1, 3c). This disturbance regime and the geomorphic consequences described here can be expected to increase as glacially conditioned, ice-rich permafrost landscapes adjust to a rapidly changing climate. These observations highlight the importance of understanding spatial variability in the landscape susceptibility to this disturbance regime.

Table 1. Summary showing differences in large active disturbance surface areas between 1985-1990, and 2011 as determined by using Landsat imagery to map 14 slump affected study areas each 100 km^2 in area. This table was derived from data presented in Table 1 in Kokelj et al., 2015.

Disturbance and date		N	Mean *A* and Stdev (ha)	*A*(ha)/100km^2
Total slump	1985	41	3.8 (*3.7*)	11.2
Debris tongue	1985	14	3.2 (*2.9*)	3.2
Total slump	**2011**	**68**	**9.9 (*11.2*)**	**47.9**
Debris tongue	**2011**	**31**	**6.6 (*4.3*)**	**14.6**

3.3 Broad-scale mapping of thaw slumps: Relationships with the distribution of massive ground ice and glacial legacy

A review of ground ice and surficial studies suggests an association between thaw slumps and ice-rich glaciogenic deposits (Lewkowicz, 1987a; Rampton, 1988; St-Onge and McMartin, 1999; Dyke and Savelle, 2000; Lacelle et al., 2015). Development of large retrogressive thaw slumps requires the presence of ice-rich permafrost indicating that these disturbances may be a valuable indicator of ice-cored or ice-rich terrain. An online mosaic of SPOT imagery enabled the mapping of the distribution of thaw slumps across northwestern Canada (Fig. 2).

Preliminary results indicate that retrogressive thaw slumps are widely distributed throughout northwestern Canada. Grid cells with terrain impacted by slumps totaled about 140 000 km^2 or about 11% of the entire mapped area (Table 2). As an example, mapping results from Banks Island show that the distribution of thaw slump affected terrain is clearly bounded by the extents of the Sandhills and Jesse Moraines (Fig. 5). Other notable areas impacted by slumping include the Peel Plateau (Lacelle et al., 2015), the Yukon Coastal Plain to Herschel Island (Rampton, 1982, Lantuit et al., 2012), the Tuktoyaktuk Coastlands (Rampton, 1988), the Bluenose Moraine (St Onge and McMartin, 1999) and moraines on Victoria Island, including the Wollaston Peninsula (Dyke and Savelle, 2000). The final map produced for this project illustrates the broad-scale association between slump affected terrain and ice-rich moraine deposits bounded by the maximum westward extent of late Wisconsinan glaciation.

This mapping project also showed that slumps are much more widespread in fluvial and lake environments than in coastal settings (Table 2), where they typically have been studied (Lewkowicz, 1987a; Lantuit et al., 2012). Coastal slumping was abundant along the Yukon coastal plain, throughout the Tuktoyaktuk Coastlands and along the Jesse Moraine on eastern Banks Island, although dominant landscapes impacted on Banks Island were inland (Fig. 5; see inset). Lakeside slumps were common in impacted areas across the study region, except in the fluvial landscapes of the Peel Plateau and eastern foothills of the Mackenzie Mountains. These regions, in addition to eastern Banks Island, were dominated by valley-side slumps that impacted streams and rivers.

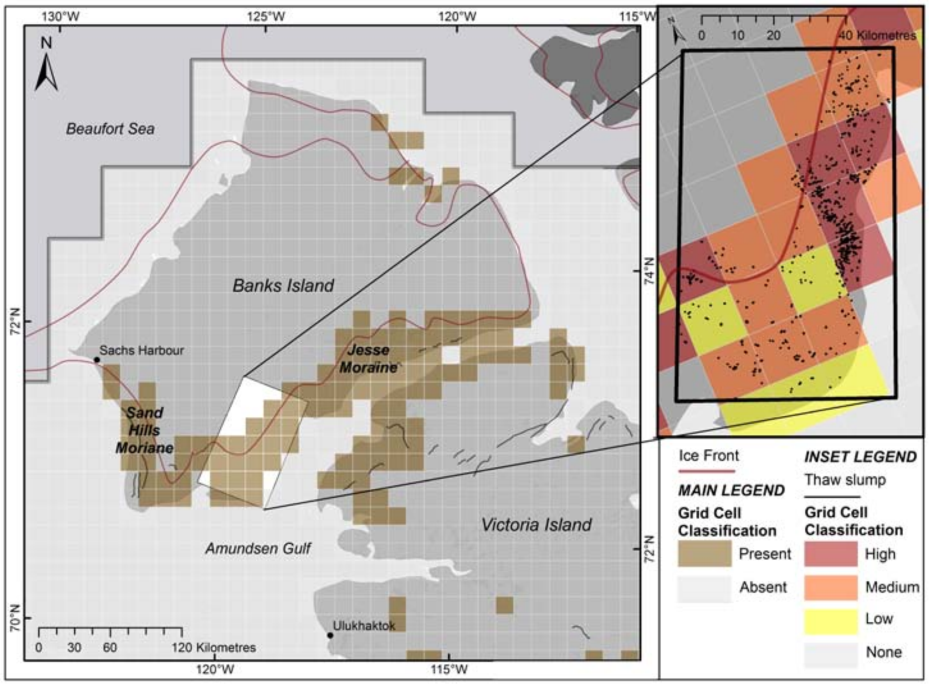

Figure 5. Broad-scale slump mapping results for Banks Island and adjacent Victoria Island. The inset on the right shows an area of south-eastern Banks Island where a detailed assessment of thaw slump distribution was conducted using a combination of air photographs and SPOT imagery. The coloured grid cells indicate relative disturbance intensity based on the broad-scale assessment and black dots are individual thaw slumps determined by detailed mapping.

Table 2. Summary showing the grid cell area affected by thaw slumping for different geomorphic environments. Note that proportional areas are calculated on the basis of a total terrestrial area of 1,274,625 km^2. In some cells thaw slumps occur in association with more than one type of environment.

Geomorphic environment impacted by slumping	Grid cell area (km^2)	% of slump affected area	% of total area mapped
Coastal	14,850	10.7	1.2
Lake	76,725	55.4	6.0
Fluvial, valley-side	81,675	59.0	6.4
Slump totals	138,375	100.0	10.9

4 CONCLUSIONS

Thaw slumping is a dominant driver of geomorphic change in ice-rich glaciogenic landscapes. This process can rapidly degrade thick layers of ice-rich permafrost and release vast quantities of glaciogenic materials downslope to fluvial, lacustrine and coastal environments. Since thaw slumping involves the coupling of geomorphic and thermal processes this disturbance regime is particularly sensitive to climatic variation. Recent research demonstrates that an increase in rainfall has accelerated slump activity in the Peel Plateau, and may be an important factor contributing to increased slump activity in many parts of the Arctic and subarctic of northwestern Canada. Enhanced moisture regimes can increase rates of downslope sediment removal from the slump scar zone inhibiting slump stabilization, perpetuating processes of slump growth and increasing the magnitude and duration of downstream impacts.

Slumps are widespread across subarctic and Arctic regions of northwestern Canada. Their distribution is largely constrained to ice-rich moraine deposits bounded by the maximum westward extent of late Wisconsinan glacial ice. Permafrost has preserved thick layers of relict ground ice and glaciogenic sediments, making these glacially-conditioned landscapes particularly susceptible to thaw slump disturbance, and inherently sensitive to climate driven geomorphic change (Kokelj et al., 2015). Broad-scale mapping of slumps provides a spatial basis for evaluating the distribution of ice-cored permafrost, and the terrain sensitivity of northwestern Canada.

5 ACKNOWLEDGEMENTS

This work was supported by the NWT Cumulative Impact Monitoring Program, the Aurora Research Institute and the Northwest Territories Geological Survey, Government of the Northwest Territories, Natural Sciences and Engineering Research Council of Canada and the Polar Continental Shelf Project. Institutional support from the Gwich'in Tribal Council, Gwich'in Renewable Resources Board and the Tetlit Gwich'in Renewable Resources Council and field assistance from several residents of Fort McPherson is gratefully acknowledged. The authors thank Rebecca Segal for producing figures 1 and 5.

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