PERMAFROST AND PERIGLACIAL PROCESSES
Permafrost and Periglac. Process. **20**: 173–184 (2009)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/ppp.642

Origin and Polycyclic Behaviour of Tundra Thaw Slumps, Mackenzie Delta Region, Northwest Territories, Canada

S. V. Kokelj,[1]* *T. C. Lantz,*[2] *J. Kanigan,*[3] *S. L. Smith*[4] *and R. Coutts*[5]

[1] Renewable Resources and Environment, Indian and Northern Affairs Canada, Yellowknife, NT, Canada
[2] Centre for Applied Conservation Research, University of British Columbia, Vancouver, BC, Canada
[3] Lands and Operations, Indian and Northern Affairs Canada, Yellowknife, NT, Canada
[4] Geological Survey of Canada, Natural Resources Canada, Ottawa, ON, Canada
[5] Ardent Innovation Inc., Calgary, AB, Canada

ABSTRACT

In tundra uplands east of the Mackenzie Delta, retrogressive thaw slumps up to several hectares in area typically develop around lakes. Ground temperatures increase in terrain affected by slumping due to the high thermal conductivity of exposed mineral soils and deep snow accumulation in winter. Mean annual temperatures at the top of permafrost were several degrees warmer in thaw slumps (-0.1°C to -2.2°C) than beneath adjacent undisturbed tundra (-6.1°C to -6.7°C). Simulations using a two-dimensional thermal model showed that the thermal disturbance caused by thaw slumping adjacent to tundra lakes can lead to rapid near-surface lateral talik expansion. Talik growth into ice-rich materials is likely to cause lake-bottom subsidence and rejuvenation of shoreline slumping. The observed association of thaw slumps with tundra lakes, the absence of active slumps on the shores of drained lakes where permafrost is aggradational and depressions in the lake bottom adjacent to thaw slumps provide empirical evidence that thermal disturbance, talik enlargement and thawing of subadjacent ice-rich permafrost can drive the polycyclic behaviour (initiation and growth of slump within an area previously affected by slumping) of lakeside thaw slumps.

KEY WORDS: landscape evolution; permafrost; polycyclic retrogressive thaw slumps; talik; thermokarst; tundra lakes; disturbance

INTRODUCTION

Thermokarst processes are of geomorphic and ecological significance because thawing of ice-rich ground affects terrain stability, hydrology, and the chemical composition of soils and surface waters and can alter terrestrial and aquatic ecosystems (Mackay, 1970; Kokelj *et al*., 2002, 2009; Jorgenson *et al*., 2006; Mesquita *et al*., 2008; Lantz *et al*., 2009). Thawing of ice-rich sediments in sloping terrain can lead to the development of retrogressive thaw slumps (Figure 1), which comprise a steep headwall and footslope of lower gradient (Burn and Lewkowicz, 1990). Thawing turns ice-rich permafrost into a mud slurry that falls to the base of the exposure to form the scar area. Over the course of a single thaw season a slump headwall can retreat by several metres (Lewkowicz, 1987a). Slumps can remain active for a number of years, impacting hectares of terrain prior to stabilising (Figure 1). In this paper, we refer to slump initiation and growth within an area of previous slumping as polycyclic behaviour (Figure 1) (Lewkowicz, 1987b).

* Correspondence to: S. V. Kokelj, Water Resources Division, Indian and Northern Affairs Canada, 3rd Floor Bellanca Building, P.O. Box 1500, Yellowknife, NT, X1A 2R3, Canada.
E-mail: kokeljsv@inac.gc.ca

Received 15 August 2008
Revised 20 February 2009
Accepted 28 February 2009

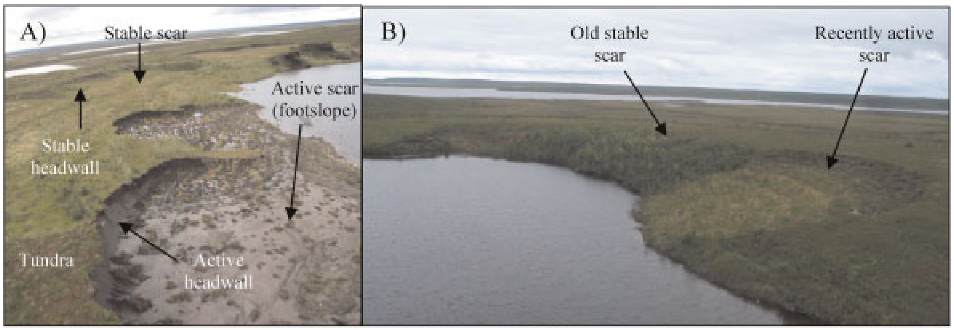

Figure 1 A) Large retrogressive thaw slump adjacent to a small tundra lake, Mackenzie Delta region (69°07′04″N; 134°10′59″W). An active slump in the foreground is developing within an older, stable slump scar, illustrating polycyclic activity. The headwall of the active slump is 3 to 4 m in height. Total disturbed area is greater than 5 ha. B) Multi-aged retrogressive thaw slumps north of Noell Lake, Mackenzie Delta region (68°36′26″N; 133°34′52″W). The total slump affected area is approximately 1 ha.

The renewal of oil and gas exploration in the Mackenzie/Beaufort area and the proposal to develop a Mackenzie Valley natural gas pipeline make it important to understand the spatial and temporal characteristics of geomorphic processes in this region. Lantz and Kokelj (2008) mapped over 500 thaw slumps adjacent to tundra lakes in a 3370 km^2 upland area east of the Mackenzie Delta, defined by a 12 km buffer around the proposed pipeline infrastructure north of Inuvik (Figure 2) (Imperial Oil Resources Ventures Limited, 2004). Lakeside thaw slumps, which constitute virtually all landslide activity in this area, commonly initiate at the shoreline within an existing disturbance and grow up- or cross-slope, progressing into the adjacent undisturbed tundra (Figure 1) (Lewkowicz, 1987b; Lantz and Kokelj, 2008). Polycyclic thaw slump activity yields disturbances which include active, recently stabilised, and older vegetated scar areas (Figure 1) (Burn, 2000; Lantuit and Pollard, 2008; Lantz and Kokelj, 2008).

In the Mackenzie Delta region, a significant increase in slump activity since the 1950s has coincided with warming summer air and mean annual ground temperatures (Smith *et al*., 2005; Kanigan *et al*., 2008; Lantz and Kokelj, 2008). However, with the exception of thermal erosion in high energy shoreline and fluvial environments, the processes leading to slump initiation and polycyclicity are not well understood (Lewkowicz, 1987b; Dyke, 2000; Wolfe *et al*., 2001). The influence of thaw slumps on the ground thermal regime of permafrost (Burn, 2000) and the association between polycyclic slumps and small to medium-sized tundra lakes (Lantz and Kokelj, 2008) suggest that slump dynamics may be associated with talik growth into ice-rich permafrost.

This paper describes the influence of thaw slumping on ground thermal conditions in tundra environments and examines the role of warming permafrost on talik enlargement as a mechanism driving the polycyclic behaviour of lakeside thaw slumps (Figure 1). We hypothesise that an increase in permafrost temperatures in response to slumping can result in lateral talik growth causing lake-bottom and shoreline settlement, leading to slump re-initiation. To test this hypothesis, snow, active-layer and ground temperature conditions were assessed in lakeside slumps and adjacent undisturbed terrain in the upland tundra east of the Mackenzie Delta (Figure 2). These data defined the boundary conditions for a two-dimensional geothermal model that was used to examine the effects of ground warming on talik geometry. The potential effects of wind-induced wave erosion on slump initiation and polycyclicity were also assessed by measuring the orientations of more than 500 thaw slumps in our study region (Figure 2). The linkage between polycyclic thaw slump activity and talik expansion was investigated by: 1) examining the frequency of association between active slumps and areas of previous disturbance; 2) describing lake-bottom bathymetry adjacent to slumped shorelines; and 3) assessing the geomorphic status of slumps along shorelines of drained lakes where permafrost is aggrading.

STUDY AREA

The focus of this paper is the tundra uplands east of the Mackenzie Delta (Figure 2). The surficial materials are glaciogenic, dominated by hummocky and rolling moraine. Near-surface sediments consist of fine-grained tills, interspersed with areas of coarser glaciofluvial and finer lacustrine deposits (Rampton, 1988; Aylsworth *et al*., 2000). Continuous permafrost

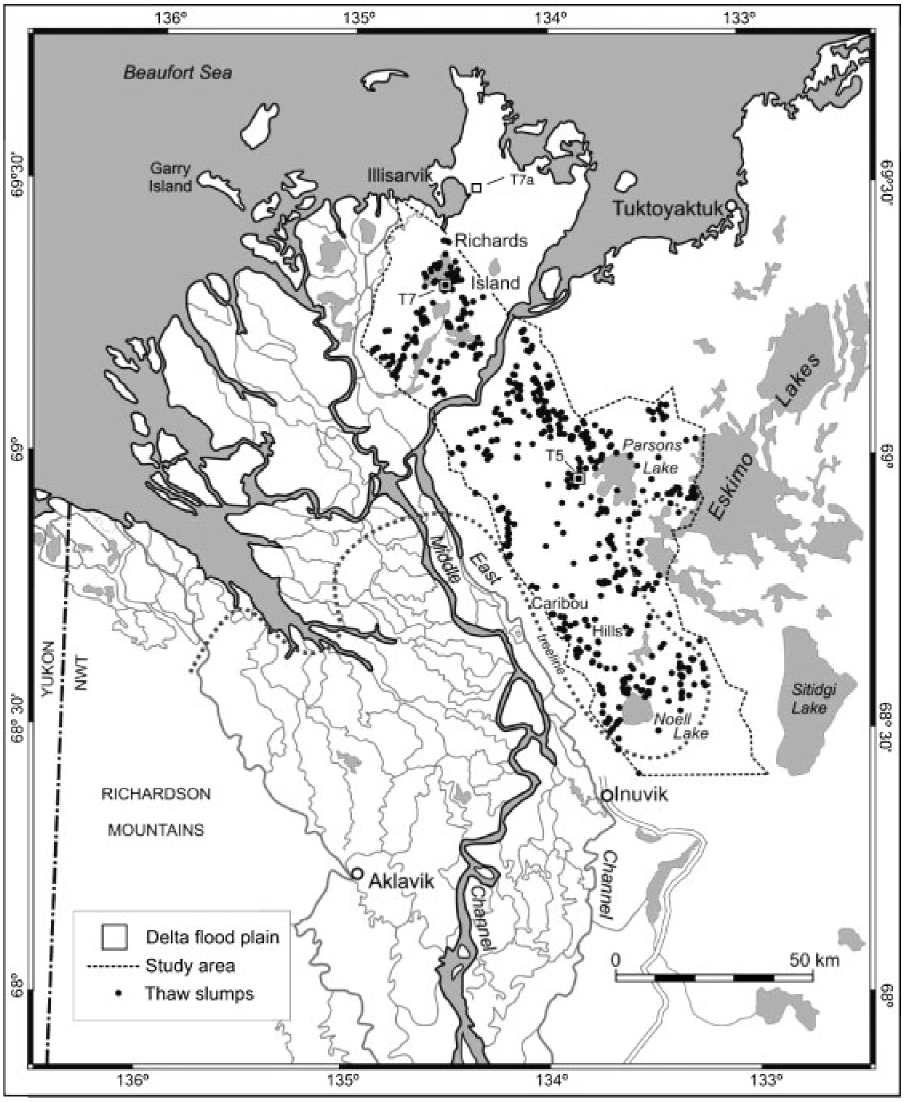

Figure 2 Study area east of the Mackenzie Delta, NWT. T5, T7 and T7a are ground temperature monitoring sites. Treeline indicated on the map is from Mackay (1963).

is up to several hundred metres thick and mean ground temperatures range from about −4°C to −9°C (Taylor *et al*., 1996; Burgess and Smith, 2000). These sediments host large volumes of ground ice including near-surface aggradational ice, ice-wedge ice, massive segregated ice and buried glacier ice that may extend to depths of 10 m or more (Mackay, 1971; Pollard and French, 1980; Kokelj and Burn, 2003; Murton, 2005). Surface expressions of thawing ground ice, including collapsed pingo scars, high-centred polygons and retrogressive thaw slumps, are common throughout the region (Mackay, 1963, 1992; Lantz and Kokelj, 2008).

The delta uplands are also lake-rich, containing over 4500 water bodies within the 3370 km^2 study area (Kokelj *et al*., 2009). Lakes and ponds deeper than the thickness of winter ice are underlain by taliks, the geometry of which is a function of the diameter and age of the water body, lake-bottom and adjacent permafrost temperatures and the thermal properties of the earth materials. Burn (2002) estimated that under equilibrium conditions on Richards Island, lakes with a radius of greater than 180 m are likely underlain by a through talik.

Thaw slumps in the study area are almost exclusively associated with slopes immediately

DOI: 10.1002/ppp

adjacent to the shorelines of tundra lakes (Lantz and Kokelj, 2008). Individual slumps frequently cover several hectares of terrain (Figure 1), and average slump size is approximately 1.4 ha (Lantz and Kokelj, 2008). Slump headwalls can be up to several metres high, but their morphology is a function of ground ice volume and the nature of the slope (Lewkowicz, 1987a; Lantuit and Pollard, 2005).

METHODS

Environmental Conditions in Thaw Slumps and Undisturbed Tundra

Topography, active-layer thickness and depth of snowpack were examined in several active and stable slumps as well as in nearby undisturbed tundra between Parsons Lake and the Beaufort Sea coast (Figures 2 and 3). Between August 2005 and August 2007, ground surface temperatures were measured in the central areas of recently active and stable slumps and hummock tops on the adjacent tundra near Parsons Lake (T5) and on Richards Island (T7 – stable; and T7a – active) (Figure 3). Measurements were made at 2-h intervals with thermistors (Onset Computing, HOBO^{TM}, TMC6-HA) connected to data loggers (Onset Computing, HOBO^{TM}, H08-006-04) providing accuracy of $\pm$ 0.5°C and a precision of $\pm$ 0.41°C. Thermistors were positioned at a depth of 5 cm and 100 cm by attaching them to a dowel inserted into the ground. Ground temperatures to depths of 10 m were measured in two stable vegetated slumps and on adjacent undisturbed tundra at T5 and T7 with multi-thermistor cables installed in cased boreholes (Figure 3). Ground temperatures were recorded at 8-h intervals using eight-channel data loggers (Branker XR-420-T8). The thermistors (YSI 46004) have an accuracy of $\pm$0.1°C while the measurement system allows for a resolution of $\pm$0.01°C. Boreholes in the slumps were located at distances between 30 m and 50 m from the lakeshore. In the near-surface, thermistors were placed at 50-cm depth increments. Maximum active-layer thickness was estimated through interpolation of the maximum annual temperatures obtained from near-surface thermistors. In March 2007, snow thickness and subnivean temperatures were collected at 5 m and 10 m intervals, respectively, along transects that extended from the lakeshore to the top of the headwall of ten active and eight stable vegetated thaw slumps between Inuvik and northern Richards Island (T7a) (Figures 2 and 3). Snow depths and subnivean temperatures were also collected along four transects on the adjacent undisturbed tundra. In the summer of 2007, slump topography was surveyed using a Trimble R3 Differential GPS system, which consisted of Pro XT receivers connected to Ranger field computers.

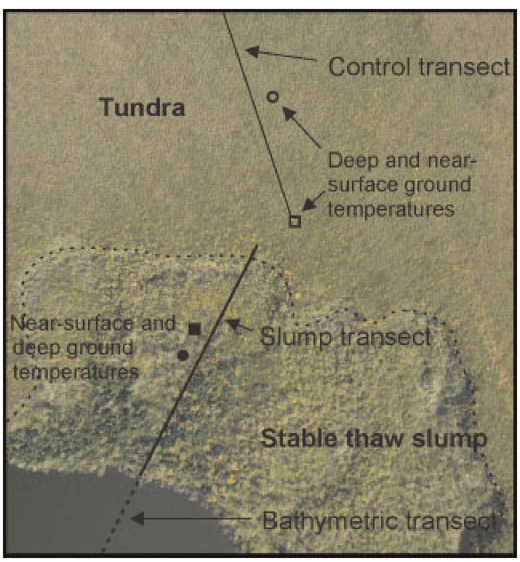

Figure 3 Aerial photograph of site T7 showing locations of transects, near-surface (■□) and deep (○●) ground temperature instrumentation on undisturbed tundra and in a stable thaw slump. The bathymetric transect extending from a disturbed shoreline is also shown. The thin dashed line outlines the scar area.

Thermal Modelling

A two-dimensional finite element geothermal model (TEMP/W Release 7.03, 2007) was utilised to investigate the relative effects of warming permafrost temperatures due to retrogressive thaw slumping on talik geometry. Ground surface boundary conditions were determined from field investigations. Simple, cylindrical model geometry was assumed with a lake radius of 300 m and tundra conditions from the lakeshore to a distance of 2000 m from the centre of the lake. The model took advantage of the symmetry associated with a round lake, and focused on a wedge-shaped vertical section with the left boundary corresponding to a vertical axis at the centre of the lake and as such was a zero-flux boundary in the model. The right boundary was sufficiently far from the lakeshore to also be specified as zero-flux. The lower boundary of the model was at 700 m below ground surface and a geothermal gradient of 0.015°C/m was applied (Taylor *et al*., 1996). Permafrost was assumed to consist of fine-grained clayey silt with 50 per cent

DOI: 10.1002/ppp

Table 1 Thermal properties of earth materials for tundra uplands of the Mackenzie Delta region. The unfrozen materials (uf) were saturated clayey silt tills and the frozen materials (f) were supersaturated.

Property	Estimated value
Volumetric water content (uf)	0.39 m^3/m^3
Volumetric water content (f)	0.72 m^3/m^3
Unfrozen thermal conductivity	105.4 kJ/day/m/°C
Frozen thermal conductivity	185.1 kJ/day/m/°C
Unfrozen heat capacity	3760 kJ/m^3/°C
Frozen heat capacity	1630 kJ/m^3/°C

excess ice content. The modelling used unfrozen moisture content as a function of temperature representative of local clayey silt till (Kokelj and Burn, 2003, Figure 3). We assumed that unfrozen sediments consisted of similar materials in a saturated state. The thermal properties of the materials (Table 1) were determined following Johansen (1975) and Farouki (1981). In the modelling, seasonal variability in surface boundary conditions was simplified by only considering the mean annual temperature beneath the lake and at the top of permafrost. It is important to note that although the use of a mean annual ground surface temperature boundary condition eliminates the freeze-thaw cycle of the relatively shallow active layer from the model, it does account for the overall heat transfer through the system and is thus valid for modelling the talik at greater depths relative to the active layer. Furthermore, it should be noted that latent heat effects and differences between frozen and unfrozen material properties associated with talik enlargement were included in the modelling.

Using mean surface boundary conditions from field data, equilibrium ground temperatures were computed using steady-state analyses. These results were used as initial conditions for subsequent transient sensitivity analyses, which involved the imposition of warmer mean annual ground temperatures on the modelled surface adjacent to the water body. The objectives of the sensitivity analyses were to examine the rate at which the talik might expand laterally under changing surface conditions caused by retrogressive thaw slumping. The thermal influence of slumping was investigated by applying mean annual ground surface temperatures representative of disturbed terrain in a step fashion 100 m inland from the shoreline of the lake to represent cold and warm slump surfaces. In each simulation, the change in talik configuration was examined at 10, 20, 40 and 100 year elapsed times. Talik growth in ice-rich terrain would likely cause subsidence and lake expansion, thereby modifying surface conditions and accelerating slump growth (West and Plug, 2008), but these effects were not addressed in our modelling. Consequently, our results likely represent conservative estimates of talik expansion.

Assessment of Aerial Photographs and Lake-bottom Bathymetry

Simulated results were compared with slump behaviour in the study region by examining 530 of the discrete disturbances mapped by Lantz and Kokelj (2008) on 1:30 000 digital aerial photographs acquired in 2004 (Figure 2). To assess the relative frequency of thaw slump polycyclicity, each disturbance was classified as either 1) single or 2) multiple aged. Distinct variations in slump vegetation and compound surfaces and lobes (Figure 1) were diagnostic of multiple disturbance events. Within individual disturbances, the minimum relative age of slump activity was estimated by classifying slumps as: 1) active – bare areas and a well-defined headwall; 2) stable – completely vegetated with well-defined boundaries; or 3) ancient – subdued headwall relief with scar covered in tundra vegetation.

Aerial photographs were also used to assess the activity of slumps around 174 drained lakes identified in a database supplied by Dr Philip Marsh (National Water Research Institute, Environment Canada) (Marsh *et al*., 2009). Drained lakes with shorelines affected by slumping were tallied and classified as active or stable based on the criteria described above. Where possible, the aerial photographic interpretations were corroborated by field inspection.

We also used aerial photographs to determine the orientation of slumps mapped by Lantz and Kokelj (2008). Orientations of all thaw slumps in the study area were measured normal to the line connecting the two points of intersection between the disturbance edges and the lakeshore. To test the hypothesis that the direction of slump initiation is random, we divided slump orientation into four classes (N, E, S, W) and used a chi-squared test for equal proportions (SAS, 2004, PROC GENMOD). Multiple comparisons were performed using a Bonferroni corrected least square means procedure (SAS, 2004). The chi-squared test was used again to determine if the orientations of active slumps differed from the orientations in the entire slump population.

In winter 2007, bathymetry measurements were obtained at 10 m intervals along transects perpendicular to eight disturbed (Figure 3) and eight undisturbed shorelines. Water depth was measured by lowering a weighted, calibrated cable through a hole in the ice to the lake bottom.

RESULTS

Thaw Slumps: Physical and Thermal Characteristics

Slump scars typically extend 50 to 150 m upslope from lakeshores with slope angles of 1° to 20°. Step-like features in stable slumps likely indicate headwalls associated with polycyclic activity (Figure 4). The headwall in an active slump can be several metres high if deep thawing of massive ice has occurred (Figure 1A), whereas shallower slumps usually occur in near-surface aggradational ice (Figure 1B) (Mackay, 1971; Burn, 1997). Stable slumps are colonised by grasses and forbs, which are typically succeeded by green alder and willows that may grow to heights exceeding 3 m (Figure 1B) (Lantz, 2008). Lake bathymetry adjacent to slumps is steeply sloping, with average depths about four times greater than those on the opposite, undisturbed shorelines of the same lakes (Figure 5).

Late winter snow depths on slump surfaces were greater than on the adjacent tundra (Figure 6). Drifts over 1 m thick accumulate immediately below headwall scarps and near shorelines. Snow cover therefore tends to be thicker on the slumps than on the adjacent undisturbed tundra with the thickest snow occurring on shrub-dominated stable slumps (Figure 6). In late March 2006, subnivean temperatures were coldest in undisturbed tundra where the snow depth was typically less than 40 cm. In stable thaw slumps, mean subnivean temperatures ranged from −10°C to −13.5°C and were up to 12°C higher than temperatures measured on the adjacent tundra surface (Lantz *et al.*, 2009).

The seasonal variation from 2005 to 2007 in near-surface ground temperatures for undisturbed terrain and slumps near Parsons Lake (T5) and on Richards Island (T7 and T7a) is shown in Figure 7. The most rapid decrease in near-surface temperatures occurred at the undisturbed tundra sites where minimum temperatures dropped below −20°C during the winter. Winter cooling was delayed in the slumps by several weeks in comparison with upland tundra (Figure 7). Minimum ground temperatures at 5-cm depth ranged from −4.8°C in January 2006 at the inactive slump near Parsons Lake to −24.2°C in February 2007 on undisturbed tundra of Richards Island (Figure 7). Thaw depths of up to 200 cm developed in mineral soils of vegetated slumps, exceeding those on the undisturbed tundra (Figure 8A). The average late

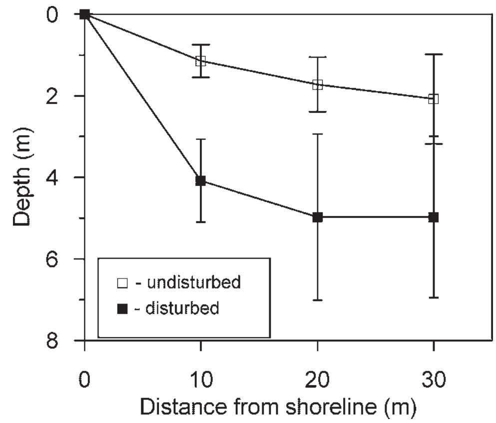

Figure 5 Mean lake depths along transects perpendicular to shorelines of lakes affected by slumping (n = 8) and undisturbed shorelines (n = 8). Error bars indicate the 95 per cent confidence interval of the mean.

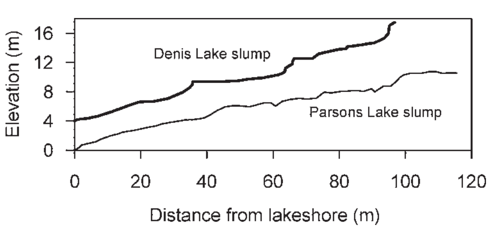

Figure 4 Topographic profiles of thaw slumps at Parsons Lake (T5) and Denis Lake (T7). The arbitrary lake level is 0 m for the Parsons Lake slump and 4 m for the Denis Lake slump.

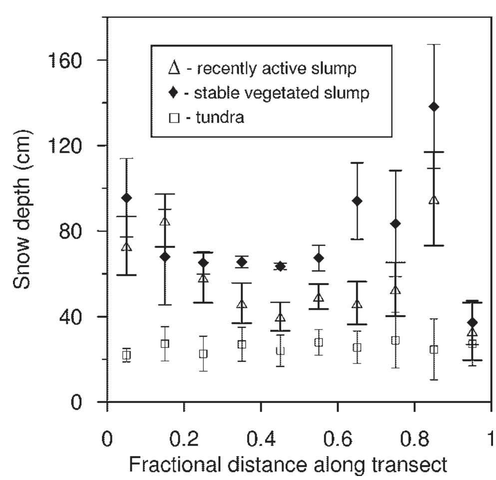

Figure 6 Mean snow depths along transects in recently active (n = 10) and stable (n = 8) thaw slumps, and in adjacent undisturbed tundra (n = 4). Data are plotted for fractional distances along transects with zero corresponding to the shoreline. Error bars show the 95 per cent confidence interval of the mean.

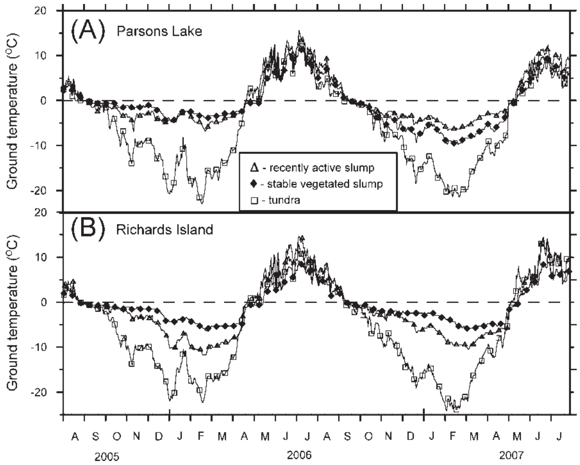

Figure 7 Ground surface temperatures (August 2005 to August 2007) at 5-cm depth for recently active and stable thaw slumps, and undisturbed tundra at A) T5 near Parsons Lake and B) T7 (stable and undisturbed tundra) and T7a (recently active) on Richards Island. The data are daily averages and symbols are plotted at 12-day intervals.

summer thaw depths for the adjacent undisturbed tundra were less than 60 cm, but there was some variation associated with hummocky micro-topography (Kokelj *et al.*, 2007).

In 2005–06, the mean annual temperatures at the top of permafrost in hummocky tundra were −6.1°C near Parsons Lake (T5) and −6.7°C on Richards Island (T7) (Table 2). In contrast, mean temperatures at

Table 2 Mean annual ground temperatures (°C) at 100 cm depth for undisturbed tundra and recently active and stable slump surfaces near Parsons Lake (T5) and Denis Lake (T7 and T7a), 2005–06.

Location	Tundra	Active	Stable
Parsons Lake	−6.1	−0.1	−0.4
Denis Lake	−6.7	−2.2	−1.5

100-cm depth in active slumps ranged from −0.1°C at Parsons Lake to −2.2°C on northern Richards Island (Table 2). The mean tundra ground temperatures at 10-m depth of −6.4 and −5.4°C were slightly higher than near-surface temperatures, whereas in thaw slumps the mean temperatures at 10-m depth ranged from −2.4°C to −2.9°C and were lower than near-surface temperatures (Table 2; Figure 8B). In slumps, the mean annual ground temperature from 3 m to 10-m depth decreased by about 0.1°Cm^{-1}, indicating that ground warming at depth is ongoing (Figure 8B).

Near-surface Talik Adjustments to Warming Permafrost

Talik configuration of a medium-sized tundra lake (600-m diameter) was simulated to assess response to permafrost warming caused by slumping. Initial ground thermal conditions were simulated using a mean annual permafrost temperature of −6.0°C (Figure 8) and a lake-bottom temperature of 4.0°C

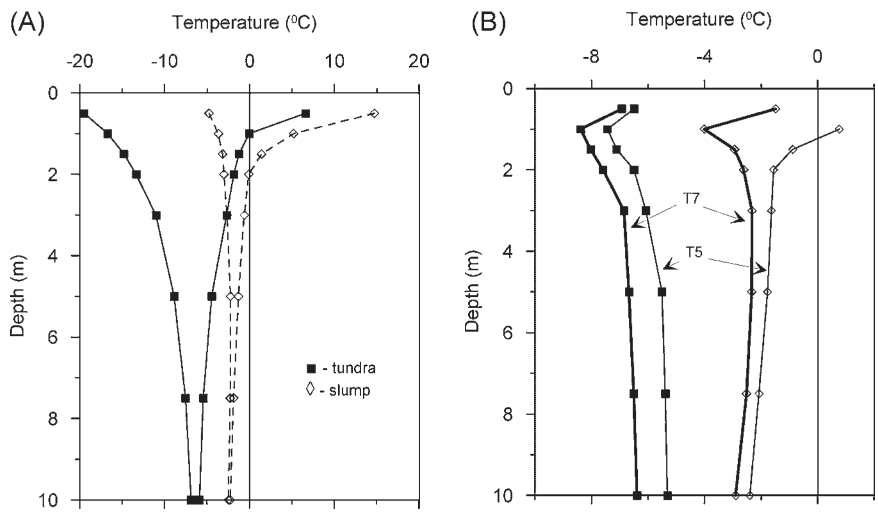

Figure 8 A) Maximum and minimum ground temperature profiles for undisturbed tundra and a stable vegetated slump surface, T7, Richards Island. B) Mean annual ground temperature profiles for undisturbed tundra and stable slump surfaces at T5 near Parsons Lake, and at T7 on Richards Island. Data are for August 2006 to August 2007.

DOI: 10.1002/ppp

(Burn, 2002). The undisturbed modelled permafrost thickness was more than 400 m with a through talik beneath the lake. These results are within the measured range of permafrost thicknesses (Taylor *et al.*, 1996) and estimated talik configurations beneath medium-sized lakes in the study region (Burn, 2002).

In the cold slump simulation, the mean annual temperature at the top of permafrost was increased in step fashion from −6.0°C to −3.0°C from the shoreline to 100 m inland. The talik at 5-m depth migrated laterally and vertically from the initial position by about 1.0 m over 40 years and by more than 2.0 m over a century of elapsed time (Figure 9A). The modelled near-surface talik adjustments with a warm lakeside slump (mean annual temperature at the top of permafrost increasing to −0.5°C) (Table 2) were more rapid, causing the 0° isotherm at 5-m depth to shift laterally by about 3.5 m and vertically by more than 2 m over 40 years (Figure 9B). Transient conditions were modelled to year 100, over which time the talik growth was limited to the top 20 m of permafrost, with growth rates decreasing with depth. Significant near-surface thawing occurred under warm slump conditions, but the imposition of a constant mean temperature at the top of permafrost condition for the slumped terrain with a static shoreline position led to the formation of a talik concavity beneath the lakeshore (Figure 9B).

Slump Activity and Orientation

Ninety-seven per cent of the 530 slumps assessed were multi-aged and more than 20 per cent of all disturbances showed evidence of recent activity (Figure 1; Table 3). The distribution of slump orientations was significantly different from random ($\chi^2_{0.05,\ 3} = 28.56$, $p < 0.0001$), with fewer slump headwalls facing to the S and the greatest proportion of headwalls facing N, E and W (Figure 10). In other words, the slumps were preferentially located on the S, W and E shores of the lakes. The distribution of orientation directions of the 113 slumps active in 2004 did not differ from the distribution of the entire population ($\chi^2_{0.05,\ 3} = 3.078$, $p = 0.38$) (Figure 10).

Of the 174 drained lakes examined, a total of 32 or 18 per cent had shoreline slumping (Table 3). All of the disturbances were well vegetated and there was no evidence of contemporary or recent slumping. However, active slumps were evident along shorelines of residual ponds within larger drained basins (Figure 11A). Active shoreline slumps also occur in association with deep holes in the littoral terraces of partially drained lakes (Figure 11B).

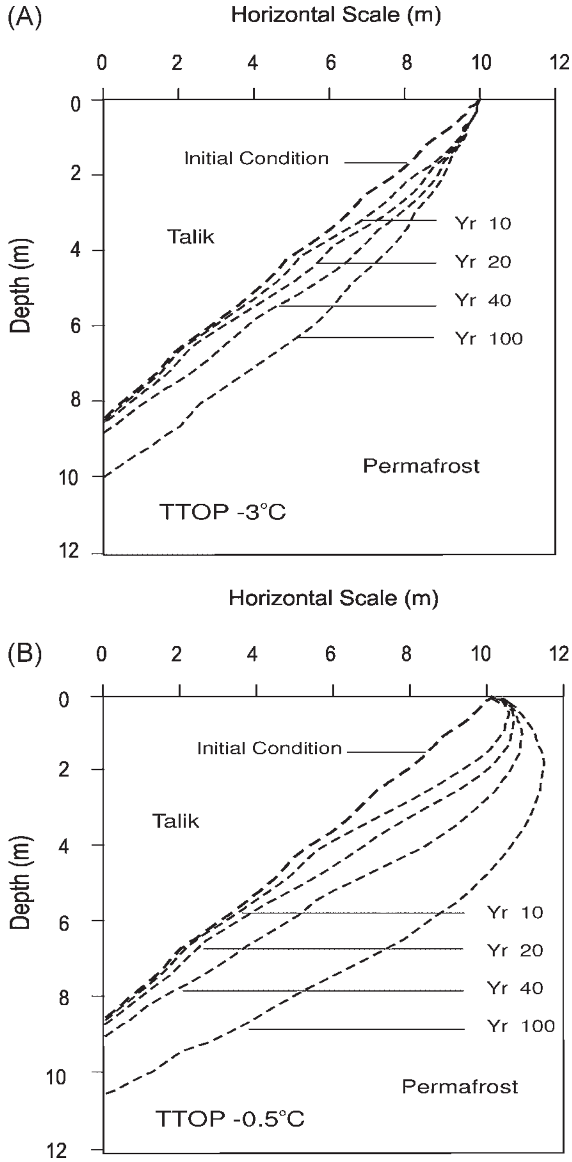

Figure 9 Modelled near-surface talik configuration for a 600-m diameter lake with an adjacent: A) cold (mean annual temperature at the top of permafrost, (TTOP −3.0°C)); and B) warm (mean annual temperature at the top of permafrost, (TTOP −0.5°C)) retrogressive thaw slump extending 100 m from the lakeshore. The modelled surface or zero on the vertical scale represents the lake bottom or top of the permafrost.

DISCUSSION

Slump Activity and Thermal Characteristics

Virtually all thaw slump areas in the study region were characterised by multiple-aged surfaces and more than

DOI: 10.1002/ppp

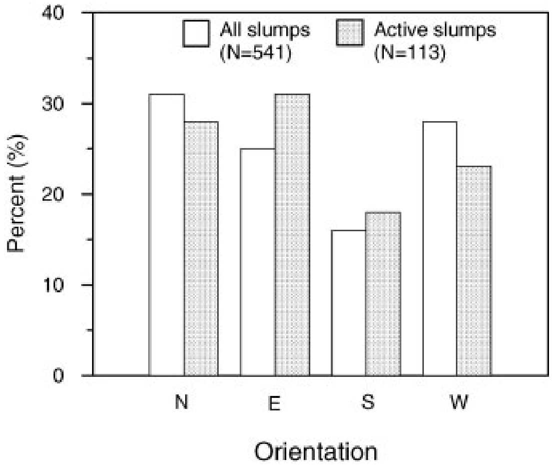

Figure 10 Headwall orientations of lakeside slumps in the study region. Orientations are plotted for all slumps in the study area (white bars) and for active slumps (stippled bars) mapped by Lantz and Kokelj (2008). The preferential location of slumps is on the S, W and E shores of the lake.

20 per cent of the slumps were active in 2004 (Table 3). Slump area has increased significantly since the 1950s and activity from 1970 to 2004 has been greater than from 1950 to 1973 (Lantz and Kokelj, 2008). The majority of this slump growth was associated with the activity of existing slumps rather than the initiation of new ones. Widespread evidence of polycyclicity, the rarity of ancient disturbances, maximum green alder age of 84 years on stable portions of 14 slumps in the study region (Lantz *et al.*, 2009), and the fact that at least 20 per cent of all slumps in the study area are currently active suggest that these disturbances rejuvenate at time-scales of less than a century (Table 3).

Retrogressive thaw slumping dramatically alters affected terrain causing a significant thermal disturbance which persists for decades after stabilisation (Figures 7 and 8; Table 2) (Burn, 2000). The removal of the insulating surface organic cover increases ground warming in summer and enhances active-layer thaw in a manner similar to effects following forest fire

Table 3 Tally and status of all slumps in the study region and drained lakes with shorelines impacted by slumping. A total of 174 drained lakes in the uplands east of the Mackenzie Delta were examined.

	Disturbances	Active	Inactive	Single aged	Multi-aged
All slumps	530	113	417	8	522
Drained lakes	32	0	32		

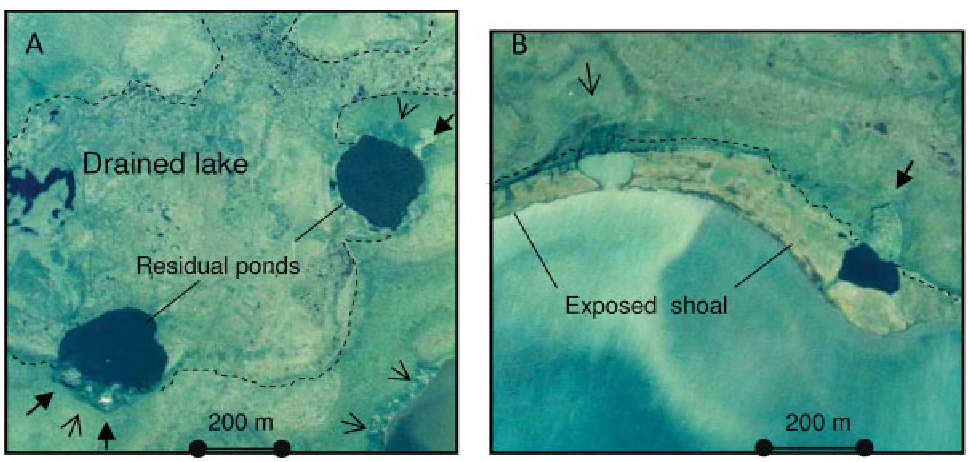

Figure 11 Aerial photographs of: A) a drained lake basin where active retrogressive thaw slumps (shown by bold arrows) and inactive slumps (shown by thin arrows) are restricted to shorelines of residual ponds; and B) a lake in which water levels have dropped, exposing a littoral terrace. Active and inactive thaw slumps shown by arrows are associated with the deep ponds. The dashed lines on A) and B) indicate former shorelines. The images are 1:30 000 aerial photographs taken by the Mackenzie Delta and Valley Airphoto Mapping Program, 2004, Indian and Northern Affairs Canada (INAC).

DOI: 10.1002/ppp

(Mackay, 1995). Although deep snow in the slumps delays surface warming in spring, the increased snow cover reduces heat loss from the ground in winter, resulting in higher minimum temperatures than in undisturbed terrain (Figure 7). These summer and winter surface energy flux perturbations lead to the development of a thick active layer and warmer permafrost relative to the undisturbed tundra (Figures 7 and 8; Table 2) (Burn, 2000).

Stable slump surfaces are rapidly colonised by grasses and forbs, which are subsequently replaced with tall shrubs (Figure 1) (Lantz, 2008). Ground shading by the dense shrub canopy and accumulation of surface litter on older slumps (Lantz *et al*., 2009) can reduce the ground heat flux in summer, but increased snow accumulation due to topography of the slump and trapping by tall shrubs likely causes the thermal disturbance to persist (Figures 6–8).

Origin and Polycyclicity of Lakeside Slumping

The results of the thermal modelling showed that permafrost warming adjacent to lakes can result in near-surface talik growth, which, for ice-rich sediments, can lead to lake-bottom and shoreline subsidence (Figure 9). The occurrence of subsidence is corroborated by lake-bottom depressions proximal to shorelines disturbed by slumping (Figures 5 and 11) and is consistent with observations of shoreline slump re-initiation. Large-scale perturbations such as fire or climate warming can have major impacts on the ground thermal regime or lake temperatures, which may also cause lateral talik growth, lakeside slumping and potentially lead to the enlargement of thermokarst lakes (Heginbottom, 1972; Smith *et al*., 2005).

In the simulations, a step change in near-surface ground temperatures from tundra conditions to those encountered in a warm slump resulted in several metres of near-surface talik migration over four decades (Figure 9B). The constant temperature conditions imposed in the models, assumptions of a static shoreline and exclusion of thaw consolidation processes likely make the estimates of lateral talik growth conservative. However, even this amount of talik growth, if it occurred in ice-rich sediments, would result in thaw subsidence that could stimulate shoreline slumps to re-initiate.

The lateral and vertical talik adjustments predicted by the model also offer a process-oriented explanation for the multi-decadal polycyclic behaviour of lakeside slumps (Figures 1 and 9; Table 3). Talik expansion and subsidence are a mechanism for shoreline slump re-initiation that is consistent with the frequent occurrence of depressions in the lake-bottom adjacent to areas impacted by slumping (Figures 5 and 11B). The association between these deep pools and slumping is also noticeable on shallow littoral terraces underlain by permafrost on northern Richards Island (C. R. Burn, personal communication, 2008). The proposed association between talik dynamics, ice-rich permafrost and slump activity is further supported by the absence of active slumping along previously disturbed shorelines of drained lake basins where the permafrost is aggradational rather than degradational, and is corroborated by the persistence of active slumps around some residual ponds (Table 3; Figure 11A).

Modelling and field results support the hypothesis that talik expansion causes re-initiation of lakeside slumps, but the mechanisms driving thaw slump origin are less clear. A correspondence between bias in the proportion of slumps oriented northwards and westwards (Figure 10) and the direction of the strongest summer winds from the N and W suggests that wave-induced erosion may contribute to the origin of lakeside retrogressive thaw slumping (Côté and Burn, 2002). Although wave-induced thermal erosion may lead to the initiation of new lakeside slumps, it is unlikely that wind-generated waves or currents could remove sediments from disturbed shorelines of small lakes at rates large enough to account for frequent rejuvenation of existing slumps (Figure 1; Table 3). The absence of thermo-erosional niches along disturbed shorelines of small lakes further supports the idea that wave erosion is subordinate to other processes in the re-activation of lakeside slumps.

The feedbacks between physical and thermal disturbance suggest that where the permafrost is ice-rich, lakeside polycyclic thaw slumping may be sustained for centuries. Deep holes in lake bottoms adjacent to thaw slumps (Figures 5 and 11) likely evolve in association with gradual lake enlargement, talik expansion and thawing of deeper ground ice over centennial to millennial time-scales (West and Plug, 2008). Sediment cores obtained from the centres of several small lakes affected by thaw slumping were characterised by thick mineral substrate in contrast with the organic-rich bottoms of nearby undisturbed lakes, suggesting that a terrestrial sediment source has been maintained for long periods of time (M. F. J. Pisaric, personal communication, 2008).

CONCLUSIONS

Based on the preceding results and discussion we draw the following conclusions:

1. Retrogressive thaw slumps can impact several hectares of terrain and constitute a major thermal

disturbance to permafrost conditions in the tundra environment. Removal of surface organic cover enhances heat flow into the ground and thaw penetration in summer and greater snow accumulation in winter inhibits ground heat loss, resulting in net warming of the permafrost.

2. Geothermal modelling suggests that the surface thermal disturbance associated with lakeside slumping can cause several metres of near-surface talik enlargement to occur over decadal timescales. Feedbacks between slumping, modification of ground thermal conditions, talik enlargement and potential thaw subsidence of the lake-bottom and shoreline suggest a mechanism that can drive the polycyclic activity of lakeside retrogressive thaw slumps.
3. The association between thaw slumps and tundra lakes, deep lake-bottom holes adjacent to polycyclic thaw slumps and the absence of active slumps along the shorelines of drained lakes where permafrost is aggrading provides empirical support for model indications that talik enlargement and thawing of subadjacent ice-rich permafrost drive the polycyclicity of lakeside thaw slumps.

ACKNOWLEDGEMENTS

The work was supported by funds received through the Northern Energy Development Initiative of the Department of Indian Affairs and Northern Development, Natural Resources Canada, the Northern Science Training Program, Global Forest Research, the Canon National Parks Science Scholars Program, the Killiam Trusts, the Inuvialuit Joint Secretariat, the Natural Sciences and Engineering Research Council of Canada, and the Aurora Research Institute. Field and lab assistance from Sarah Bogart, Douglas Esagok, Robert Jenkins, Michael Palmer, Megan Thompson, Rufus Tingmiak and Matt Tomlinson is gratefully acknowledged. We thank C. R. Burn and S. A. Wolfe for helpful discussions and comments, and two anonymous reviewers for providing suggestions that improved the manuscript.

REFERENCES

Aylsworth JA, Burgess MM, Desrochers DT, Duk-Rodkin A, Traynor JA. 2000. Surficial geology, subsurface materials, and thaw sensitivity of sediments In *The Physical Environment of the Mackenzie Valley: A Baseline for the Assessment of Environmental Change*, Dyke LD, Brooks GR (eds). Geological Survey of Canada, Bulletin 547: 41–48.

Burgess MM, Smith SL. 2000. Shallow ground temperatures In *The Physical Environment of the Mackenzie Valley, Northwest Territories: A Baseline for the Assessment of Environmental Change*, Dyke LD, Brooks GR (eds). Geological Survey of Canada, Bulletin 547: 89–104.

Burn CR. 1997. Cryostratigraphy, paleogeography, and climate change during the early Holocene warm interval, western Arctic coast, Canada. *Canadian Journal of Earth Sciences* **34**: 912–925.

Burn CR. 2000. The thermal regime of a retrogressive thaw slump near Mayo, Yukon Territory. *Canadian Journal of Earth Sciences* **37**: 967–981.

Burn CR. 2002. Tundra lakes and permafrost, Richards Island, western Arctic coast, Canada. *Canadian Journal of Earth Sciences* **39**: 1281–1298.

Burn CR, Lewkowicz AG. 1990. Retrogressive thaw slumps. *Canadian Geographer* **34**: 273–276.

Côte MM, Burn CR. 2002. The oriented lakes of Tuktoyaktuk peninsula, western arctic coast, Canada: a GIS-based analysis. *Permafrost and Periglacial Processes* **13**: 61–70. DOI:10.1002/ppp.407

Dyke LD. 2000. Stability of permafrost slopes in the Mackenzie Valley. In *The Physical Environment of the Mackenzie Valley, Northwest Territories: A Baseline for the Assessment of Environmental Change*, Dyke LD, Brooks GR (eds). Geological Survey of Canada, Natural Resources Canada, Bulletin 547: 177–186.

Farouki O. 1981. Thermal Properties of Soils. CRREL Monograph 81-1. US Army Cold Regions Research and Engineering Laboratories, Hanover, New Hampshire, 135p.

Heginbottom JA. 1972. Some effects of a forest fire on the permafrost active layer at Inuvik, N.W.T. In *Mackenzie Delta Area Monograph*, Kerfoot D. 22nd International Geographical Congress, Brock University Press: St. Catherines, Ontario, Canada; 149–156.

Imperial Oil Resources Ventures Limited. 2004. Environmental Impact Statement for the Mackenzie Gas Project, Vol. 1: Overview and Impact Summary. www.ngps.nt.ca/applicationsubmission/EIS.html [June 2008].

Johansen Ø. 1975. Thermal conductivity of soils. PhD thesis, Trondheim, Norway. (CRREL Draft Translation 637, 1977.).

Jorgenson MT, Shur YL, Pullman ER. 2006. Abrupt increase in permafrost degradation in Arctic Alaska. *Geophysical Research Letters* **33**: L02503.

Kanigan JCN, Burn CR, Kokelj SV. 2008. Permafrost response to climate warming south of treeline, Mackenzie Delta, Northwest Territories, Canada. In *Proceedings of the Ninth International Conference on Permafrost (Vol 1)*, Kane DL, Hinkel KM (eds). Institute of Northern Engineering, University of Alaska at Fairbanks: Fairbanks, Alaska; 901–906.

Kokelj SV, Burn CR. 2003. Ground ice and soluble cations in near-surface permafrost, Inuvik, Northwest Territories. *Permafrost and Periglacial Processes* **14**: 275–289. DOI:10.1002/ppp.458

Kokelj SV, Smith CAS, Burn CR. 2002. Physical and chemical characteristics of the active layer and permafrost, Herschel Island, western arctic coast, Canada. *Permafrost and Periglacial Processes* **13**: 171–185. DOI:10.1002/ppp.417

Kokelj SV, Burn CR, Tarnocai C. 2007. The structure and dynamics of earth hummocks in the subarctic forest near Inuvik, Northwest Territories, Canada. *Arctic, Antarctic and Alpine Research* **39**: 99–109.

Kokelj SV, Zajdlik B, Thompson MS. 2009. The impacts of thawing permafrost on the chemistry of lakes across the subarctic boreal-tundra transition, Mackenzie Delta region, Canada. *Permafrost and Periglacial Processes* **20**: 185–199. DOI: 10.1002/ppp.641

Lantuit H, Pollard WH. 2005. Temporal stereophotogrammetric analysis of retrogressive thaw slumps on Herschel Island, Yukon Territory. *Natural Hazards and Earth Systems Science* **5**: 413–423.

Lantuit H, Pollard WH. 2008. Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada. *Geomorphology* **95**: 84–102.

Lantz TC. 2008. Relative influence of temperature and disturbance on vegetation dynamics in the Low Arctic: an investigation at multiple scales PhD dissertation, University of British Columbia, Vancouver.

Lantz TC, Kokelj SV. 2008. Increasing rates of retrogressive thaw slump activity in the Mackenzie Delta region, N.W.T. Canada. *Geophysical Research Letters* **35**: L06502.

Lantz TC, Kokelj SV, Gergel SE, Henry GHR. 2009. Relative impacts of disturbance and temperature: persistent changes in microenvironment and vegetation in retrogressive thaw slumps. *Global Change Biology.* In press. DOI: 10.1111/j.1365-2486.2009.01917.x

Lewkowicz AG. 1987a. Headwall retreat of ground-ice slumps, Banks Island, Northwest Territories. *Canadian Journal of Earth Sciences* **24**: 1077–1085.

Lewkowicz AG. 1987b. Nature and importance of thermokarst processes, Sand Hills moraine, Banks Island, Canada. *Geografiska Annaler* **69A**: 321–327.

Mackay JR. 1963. The Mackenzie Delta area, N.W.T Geographical Branch Memoir 8, Department of Mines and Technical Surveys, Ottawa, Canada, 202p.

Mackay JR. 1970. Disturbances to the tundra and forest tundra of the western Arctic. *Canadian Geotechnical Journal* **7**: 420–432.

Mackay JR. 1971. The origin of massive icy beds in permafrost, western Arctic Coast, Canada. *Canadian Journal of Earth Sciences* **8**: 397–422.

Mackay JR. 1992. Lake stability in an ice-rich permafrost environment: examples from the western Arctic coast. In *Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management*, Robarts RD, Bothwell ML (eds). N.H.R.I. Symposium Series 7. Environment Canada: Saskatoon, Saskatchewan, Canada; 1–25.

Mackay JR. 1995. Active layer changes (1968 to 1993) following the forest-tundra fire near Inuvik, N.W.T., Canada. *Arctic and Alpine Research* **27**: 323–336.

Marsh P, Russell M, Pohl S, Haywood H, Onclin C. 2009. Changes in thaw lake drainage in the Western Canadian Arctic from 1950 to 2000. *Hydrological Processes* **23**: 145–158.

Mesquita PS, Wrona FJ, Prowse TD. 2008. Effects of retrogressive thaw slumps on sediment chemistry, submerged macrophyte biomass, and invertebrate abundance of upland tundra lakes. In *Ninth International Conference on Permafrost (Vol 2)*, Kane DL, Hinkel KM (eds). Institute of Northern Engineering, University of Alaska Fairbanks: Fairbanks, Alaska; 1185–1190.

Murton JB. 2005. Ground-ice stratigraphy and formation at North Head, Tuktoyaktuk Coastlands, western Arctic Canada: a product of glacial-permafrost interactions. *Permafrost and Periglacial Processes* **16**: 31–50. DOI:10.1002/ppp.513

Pollard WH, French HM. 1980. A first approximation of the volume of ground ice, Richards Island, Pleistocene Mackenzie Delta, Northwest Territories, Canada. *Canadian Geotechnical Journal* **17**: 509–516.

Rampton VN. 1988. Quaternary geology of the Tuktoyaktuk Coastlands, Northwest Territories Geological Survey of Canada, Memoir 423.

SAS. 2004. *SAS Version 9.1.3 Help and Documentation*. SAS Institute: Cary, North Carolina.

Smith SL, Burgess MM, Riseborough D, Nixon FM. 2005. Recent trends from Canadian permafrost thermal monitoring network sites. *Permafrost and Periglacial Processes* **16**: 19–30. DOI:10.1002/ppp.511

Taylor AE, Dallimore SR, Judge AS. 1996. Late Quaternary history of the Mackenzie-Beaufort region, Arctic Canada, from modelling of permafrost temperatures. 2. The Mackenzie Delta-Tuktoyaktuk Coastlands. *Canadian Journal of Earth Sciences* **33**: 62–71.

TEMP/W. 2007. TEMP/W Release 7.03. www.geo-slope.com [June 2008].

West JJ, Plug LJ. 2008. Time-dependent morphology of thaw lakes and taliks in deep and shallow ground ice. *Journal of Geophysical Research* **113**: F01009. DOI: 10.1029/2006JF000696.

Wolfe SA, Kotler E, Dallimore SR. 2001. Surficial characteristics and the distribution of thaw landforms (1970 to 1999), Shingle Point to Kay Point, Yukon Territory Geological Survey of Canada. Open File 4088.