Landslides on ice-rich slopes – a geohazard in a changing climate

Ryan R. Lyle, P.Eng.
Cementation Canada Inc., North Bay, Ontario, Canada
Marc-André Brideau, PhD.
BGC Engineering Inc., Vancouver, British Columbia, Canada
Panya Lipovsky, P.Geo.
Yukon Geological Survey, Whitehorse, Yukon, Canada
D. Jean Hutchnson, PhD., P.Eng., FEIC
Department of Geological Sciences and Geological Engineering – Queen's University, Kingston, Ontario, Canada

ABSTRACT
Slopes in warm discontinuous permafrost have long been recognized as a potential hazard to development. Both human and natural disturbance of such slopes can lead to instability with the exposure of ice-rich sediments. This paper provides a case study of the Little Salmon Lake area in central Yukon where an acceleration of natural landslide processes has taken place in the past two decades. Ice-rich permafrost has played an integral role in three large recent landslides with distinct processes. These provide an example of the geohazard of ice-rich permafrost slopes in a changing climate.

RÉSUMÉ
Les pentes en pergélisol discontinu chaud ont longtemps été identifiées comme risque potentiel au développement. Les perturbations anthropogéniques et naturelles de telles pentes peuvent mener à l'instabilité avec l'exposition des sédiments riches en glace. Cet article fournit une étude de cas d'une région dans le Yukon central où une accélération des processus naturels d'éboulement a eu lieu dans les deux dernières décennies. La dégradation du pergélisol chaud et riche en glace a joué un rôle intégral dans trois grands éboulements récents avec des processus distincts. Ceux-ci fournissent un exemple de georisque associé avec les pentes pergélisol riches en glace dans un climat changeant.

1 INTRODUCTION

As northern regions continue to develop, slopes underlain by warm, ice-rich permafrost present a challenging geohazard that is further complicated by climate change. This paper presents 10 years of observations of naturally-occurring permafrost-related landslides located near Little Salmon Lake, in central Yukon. The goal of this work has been to improve our understanding of landslide processes in permafrost terrain to help guide future development or land use in the region.

Three large (>1 Mm^3 displaced) landslides in the study area illustrate three distinct mass wasting processes. The Magundy River Landslide, initiated in 1996, is a retrogressive thaw slump dominated by the exposure and ablation of ice-rich permafrost forming viscous debris flows. The YT Landslide is a complex landslide, displaying deep-seated rotational, translational and toppling behaviour. Though active for decades, it greatly accelerated and expanded in the past decade. The Little Salmon Lake Landslide has a complex history beginning with a prehistoric bedrock slump; frozen colluvium and relict landslide debris were subsequently reactivated in a large debris flow/avalanche triggered by intense rainfall in 2008. In 2009, forest fires triggered many new shallow slides, which have the potential to develop into larger slides.

Many of these landslides share important characteristics, including: naturally-occurring initiation on gentle to moderate slopes (<25°), rapid growth, and prolonged or renewed activity that has impacted very large areas. The slides provide a warning of what can be expected if slopes underlain by ice-rich permafrost are subjected to disturbance of ground thermal and/or hydrogeological regimes. Anthropogenic disturbances also have the potential to trigger landslides on permafrost slopes and any new development in these areas must therefore consider these hazards. This work highlights the need for detailed permafrost mapping, landslide susceptibility mapping, and subsurface geotechnical characterizations on or below slopes underlain by permafrost prior to any development.

2 BACKGROUND

The Magundy River Landslide was noted by the Yukon Geological Survey (YGS) while undertaking regional mapping in the Glenlyon area in 2002 (Bond and Plouffe, 2003). The YGS suggested that the Little Salmon Lake region was an excellent study area for Geographic Information System (GIS) based geohazard research being undertaken at Queen's University in Kingston, Ontario. Lyle (2006) undertook a graduate thesis in landslide susceptibility mapping in discontinuous permafrost for the Little Salmon Lake area. Prior to this research, there had been very little study of landslides in the central Yukon, with the exception of the Surprise

Rapids Landslide on the MacMillan River (Ward et al.,1992), the Pelly River Landslide (Mollard and Janes, 1984) and the retrogressive thaw slumps near Mayo (Burn 2000). Lipovsky and Huscroft (2007) have subsequently studied the Ten Mile Creek landslide near Carmacks and performed an inventory of landslide activity in the Pelly River Watershed.

Terrain evaluation studies were carried out using a variety of existing data including: airphotos, Landsat satellite imagery, and maps displaying topography, bedrock geology (Colpron, 2000; Campbell, 1967), surficial geology (Ward and Jackson, 2000; Campbell, 1967), geological processes (Mougeot and Walton, 1996), forest cover and forest fire inventories. Follow up field work was completed in 2004 and 2005.

From this terrain evaluation, over 80 sites of past and present landslide activity were identified in the project area (Lyle, 2006). The failure modes noted included permafrost related skin flows (active layer detachments), bi-modal flows (retrogressive thaw slumps) and complex slides, as well as slide activity unrelated to permafrost degradation such as debris flows and rock slumps. For the data collected during the inventory phase of the work, landslide attributes such as slope angle, slope aspect, surficial sediment type, depth of overburden and sometimes geomorphic processes were captured (Bichler et al., 2004). Further analysis was performed to map causal factors, such as slope angle, surficial material, and permafrost distribution (based on permafrost distribution relationships established for the central Yukon by Côté, 2002). The final phase of the analysis resulted in the production of landslide susceptibility maps as found in Lyle, 2006.

The research also included in-depth case study characterizations of the Magundy and YT landslides, and to a lesser degree, the Little Salmon Lake Landslide.

Following completion of Lyle's 2006 thesis, YGS continued monitoring headscarp retreat and ground deformation at the Magundy and YT landslides from 2006-2009. Survey monuments were installed in 2006 and differential GPS surveys were conducted until 2007. Interferometric Synthetic Aperture Radar (InSAR) analysis was also performed at both sites during this period in partnership with CCORE Engineering and the European Space Agency (CCORE, 2007). Although the technique showed some promise, the results were not highly consistent with the surveyed displacements due to challenges with poor RadarSAT image coherence and resolution.

In late August 2008, the Little Salmon Lake Landslide reactivated and mobilised following a period of higher than normal precipitation. An in-depth study of this reactivation was performed by Simon Fraser University (Brideau et al, 2010).

In late summer 2009, forest fires swept the slopes on the south side of Little Salmon Lake for the first time since before 1946. Over 40 small landslides, generally shallow skin flows, were triggered within 1 month of the fire (observed from a reconnaissance flight over the area on Sept. 25, 2009). Although no systematic landslide inventory or survey has been completed since the forest fire, no new large scale landslides have been observed as of 2013, though there is still potential for landslides to develop.

3 LITTLE SALMON LAKE SETTING

3.1 Physiography

Little Salmon Lake is located along the Robert Campbell Highway between the villages of Carmacks and Faro (Figure 1). Local physiographic features are shown on a satellite image in Figure 2. Little Salmon Lake lies at an elevation of 609 m within the Yukon Plateaus region, a broad uplands area consisting of rolling hills and some mountain ranges (Ward and Jackson, 2000). The Little Salmon Lake area contains some of the highest peaks on the Plateaus, with elevations exceeding 1700 m. The Little Salmon Lake valley occupies a glacially scoured and over-deepened U-shaped valley (Campbell, 1967).

Figure 1. Map of the Yukon showing location of the Little Salmon Lake Project Area

During the most recent glaciation (Wisconsinan McConnell), the Selwyn lobe of the Cordilleran Ice Sheet covered the Little Salmon Lake area (Ward and Jackson, 2000). Glacial flow was generally in a northwest direction. Glacial retreat occurred very rapidly through ice sheet down-wasting and stagnation. Variable thicknesses of till cover the valley sides and plateau summits. Mixed glaciofluvial, till and glaciolacustrine sediments are found in the valley bottoms. Post-glacial lacustrine, fluvial, organic and colluvial deposits of Holocene age are also widespread in the valley bottoms.

3.2 Climate and Permafrost

The Little Salmon Lake area is within the sub-arctic continental climate zone, which is characterized by long, cold winters, short, warm summers, low relative humidity, and low to moderate precipitation. Sporadic climate data are available from 1970 to 2007 for the Drury Creek

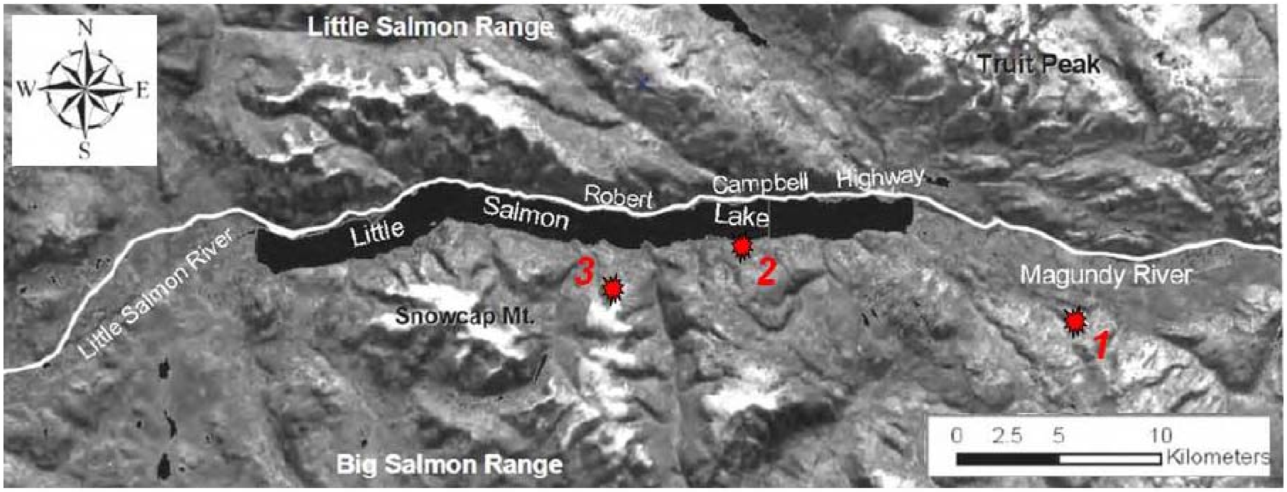

Figure 2: Physiography of the Little Salmon Lake area. Select landslide locations: 1 – Magundy River Landslide; 2 – YT Landslide; and 3 - Little Salmon Lake Landslide.

meteorological station located at the east end of Little Salmon Lake. Continuous climate records are available from the nearby Carmacks station since 1964 (see Figure 1 for Carmacks Location relative to Little Salmon Lake).

Average annual air temperatures are plotted for both stations in Figure 3. The Carmacks data from 1964 to 2013 show an overall warming trend of 0.5 °C / decade. The trend from the patchy Drury Creek data is even more dramatic with a warming rate of nearly 1 °C / decade; however, this is likely exaggerated as many of the gaps in these data are from colder years recorded in the Carmacks data.

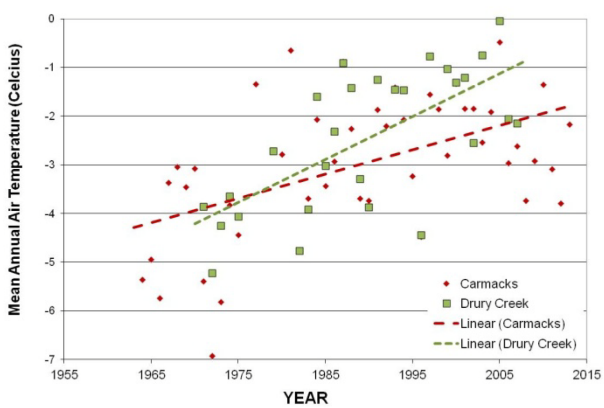

Figure 3**:** Average annual air temperature for Drury Creek and Carmacks stations (data from Environment Canada)

The Little Salmon Lake area is within the zone of extensive discontinuous permafrost (Bonnaventure et al, 2012). Primary controls on permafrost distribution include slope aspect, elevation, surficial material type and age, vegetation cover and drainage conditions. Local climatic effects such as snow depth variation and temperature inversions may also control permafrost distribution. In general, permafrost is thicker and more widespread on north-facing slopes where hill-slope shading, thick vegetative mats and poor drainage conditions exist.

4 LANDSLIDE DESCRIPTIONS

4.1 Magundy River Landslide

The Magundy River Landslide (MRL), shown in Figure 4, is located at 62°08.5'N latitude and 134°11.4'W longitude on a 10-20° north-facing slope. The top of the failure stands at an approximate elevation of 975 m elevation. It was previously classified as a bi-modal flow (Lyle et al. 2005) following the classification of McRoberts and Morgenstern (1974) and Tart (1996). Harris (1987) describes bi-modal flow as a landslide that can be divided into two distinct morphological sectors – an upper headscarp, where ablation and erosion releases sediment (Figure 4b), which slides, flows or falls down into a gently inclined mudflow lobe, where it flows away (Figure 4c). Bi-modal flows are termed 'retrogressive thaw slump' by van Everdingen (1998). Two other landslides in the Central Yukon: the Surprise Rapids Landslide (Ward et al., 1992) and Pelly River Landslide (Ward and Jackson, 2000; Mollard and Janes, 1984) share similar morphology and process as the MRL.

The MRL was observed in the field in 2002, 2004-2007 and 2009. Satellite imagery from 2013 indicates a much slower rate of ablation since 2009. Only south and northwest facing scarps were active during field visits. Scarps in these areas are very steep - from 40° to near-vertical, often with an overhanging organic mat, and range from 5 to 10 m in height. Massive ice was found in all of the active areas, and is believed to provide the moisture to form the debris flows. Ice lenses and veins composed up to 50% of the soil volume in the scarp exposures.

It is believed that the slide was initiated in 1996 as a small failure less than 10 m wide. Descriptions from local residents indicate that it was a piping type failure. Figure 5 shows the rapid growth of the MRL. The 1996 location and size is estimated from eyewitness accounts, the 1998 outline was taken from airphoto coverage and the 2004 and 2006 data are based upon field GPS mapping. The

Figure 4: Magundy River Landslide: a) overview looking south (top scarp is 350 m wide, elevation change from top scarp to depositional area is about 350 m; total runout is 1.8 km to toe of lower depositional fan) b) active thaw slump area – north scarp (note 4th author for scale); and c) active debris flow (channel width is approximately 1 m across) d) footprint of the MRL in 1996 (black), 1998 (orange) and 2004 (light grey). Upper zone was mapped in 2006 (pink line). (photographs R.Lyle, August 2004)

impacted area of the slide has not changed dramatically since 2006.

Two substantial channels, with distinct depositional areas (Figure 4c) have been eroded by the debris flow. There are two surficial units, with similar texture, exposed in the landslide: a colluvial layer of variable thickness overlying denser glacial diamicton (till). The colluvium consists of reworked till, and is thin or absent in some areas. Multiple organic horizons, separated by diamicton layers, were found in one active scarp, suggesting previous debris flow activity.

Headscarp retreat rates for retrogressive thaw slumps have been reported by Burn and Lewkowicz (1990) and are shown in Table 1. Retreat rates for three different scarps at the MRL have been estimated based on a 1998 airphoto and the 2004 scarp location (Table 1). The southeast and southwest scarps retreated at rates consistent with those observed elsewhere (12-16 m/yr). The north scarp has retreated 30-40 m per year. This high rate is likely due to the south-facing aspect of the slope (increased solar radiation), down slope retreat of the scarp, and lateral ablation. In addition, this landslide is further south than any of the slides noted in Table 1. The rates are relatively short term and have dropped off since about 2007.

The primary causal factor for the MRL is not readily apparent. Forest fire activity, active layer detachments, and fluvial and shoreline erosion are considered to be the primary triggers of retrogressive thaw slumps (McRoberts, 1978; Lewkowicz, 1988; Dyke, 2000). No forest fire activity has been noted in the 50 years prior to landslide initiation and there are no lakes/rivers for hydraulic erosion. Eyewitness accounts describe landslide initiation in a piping-type failure (see Lyle, 2006). As discussed by Tart (1996), the low permeability of frozen ground can make it an ideal cap for piping to occur. Debris flows are most often controlled by meteorological events, usually heavy rainfall or rapid snowmelt (Bell, 1999) though long-term climatological change may have a control on thaw-related flow in permafrost regions. Climatological data from the Drury Creek Meteorological station, which is 12 km away, indicate that 1996 was colder than average. However, the summer of 1995 was one of the warmest on record. Perhaps more importantly, the maximum recorded monthly precipitation (snow and rain) fell in March 1996, which was followed by the maximum recorded monthly rainfall in April 1996. These record spring precipitation conditions, coupled with the post-Little Ice Age warming trend, likely led to the hydrogeological and thermal conditions conducive to landslide initiation.

Table 1: Headscarp retreat rates for various retrogressive thaw slumps (data from Burn and Lewkowicz, 1990) compared with the MRL.

Location	Rate (m/yr)
Ellef Ringness Island, Nu	7-10
Ellesmere Island, Nu	9-14
Melville Island, Nu	7-8
East Banks Island, NWT	7-10
South Banks Island, NWT	10-15
Tuktoyaktuk Peninsula, NWT	7
Mackenzie Delta, NWT	1.5-4.5
Mayo, YT	14-16
MRL, North Scarp, 1998-2004	30-40
MRL, Southwest Scarp, 1998-2004	13-16
MRL, Southeast Scarp, 1998-2004	12-15

5 YT LANDSLIDE

The YT Landslide (YTL) is located on a north-facing slope, along the south shore of Little Salmon Lake (Figure 5). It is situated at a latitude of 62°10.7'N and a longitude of 134°30.7'W and an elevation of 700 m (at the top of the failure). Overall, the YTL is thought to be a rotational soil slump. However, much of the documented movement is translational with both toppling and flow behaviour occurring at the lake's edge and where massive ice is exposed. The slump has put ice-rich sediments in contact with the lake; the resulting thermal erosion accelerates the overall movement. Given the variety of processes, the YTL is classified as a complex landslide in surficial sediments. More recently it appears to be widening to the west, this process has accelerated since forest fires destroyed the surrounding forest cover in 2009.

Figure 5. YT Landslide – overview showing significant changes from 2004 (top) and 2010 (bottom) (Photographs by D.J. Hutchinson and J. Koch)

The YTL was first documented in 2004 by Lyle (2005). A temporal analysis of the landslide was completed using aerial photos from 1949, 1967, 1989 and 1998, as well as observations and airphotos from 2004-2011. Some evidence of slope deformation is evident on the 1949 and 1967 photos. Scarp development becomes apparent in the 1989 airphoto and by 1998, the main scarp was developed. A small dark area appeared along the shoreline at the centre of the slide in 1989. This may be the early development of the translational movement and the lake-side scarp, and the beginning of thermal erosion of ice-rich sediments. This feature is much larger in the 1998 airphoto.

In plan, the landslide is approximately 250 m long, from the lake shore to the top scarp (Figure 5). An elevation change of nearly 100 m over the length of the landslide yields an overall angle of 20°. The slide continues to an unknown depth below the lake surface. In 2004 the upper scarps measured 350 m across from the west end of the top scarp to the east end of the main scarp. The landslide then covered a land area of approximately 80 000 m^2. Subsequently, the YTL appears to have widened to the west about 350 m based on a 2011 photograph (this requires field verification). The overall depth of the landslide is not known, as no subsurface exploration has been conducted.

Figure 6 illustrates theoretical failure planes (dashed lines) along a cross section through the landslide. It is thought that YTL is moving in a rotational manner based on the curved upper scarps and pattern of deformation noted on historical airphotos. The movement noted in the short term (such as between field seasons) indicates a more translational movement of intact blocks of frozen sediment downward to lake level (i.e., the smallest blocks indicated on Figure 6. The material that has moved rapidly during the past ten years appears to be very ice-rich. No significant excess ice has been noted in the sediments exposed in the upper scarps, but massive ice was present in the lower scarps (Figure 7). The ice-rich material is thermally eroded by the lake water. Undercutting of the ice-rich material causes the toppling of large blocks of frozen sediment into the lake. Melting of ground ice above lake level also enables sediment to fall or flow into the lake. A topple of a large frozen block (estimated to be 1200 m^3) was witnessed in August 2004. The block remained coherent and rolled out into the lake approximately 40 m before disappearing. This toe unloading contributes to accelerating landslide movement.

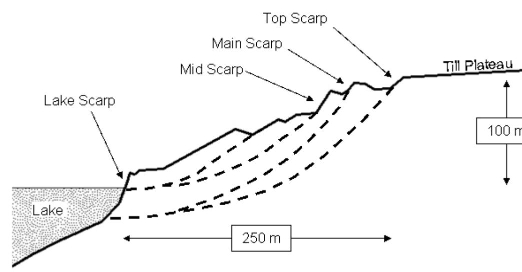

Figure 6. Schematic cross-section of the YT Landslide in 2004, looking east. Failure planes are theoretical (no subsurface data exists). (from Lyle 2006).

Figure 7. Massive ice found in the lower blocks of the YT Landslide (Photograph by D.J. Hutchinson, August 2004)

The site stratigraphy is partially exposed in the numerous scarps and extensional cracks, but reconstruction of a detailed stratigraphic section is hampered by the extensive surface disturbance. The following units were described in detail by Lyle (2006). A thin layer of organic material and/or a colluvial veneer overlies much of the slope surface. The top scarp exposes the edge of a very gently sloping till plain (over 10 m thick). This is underlain by an ice contact sequence (greater than 15 m thick) of dense (apparently unfrozen) glaciofluvial and frozen glaciolacustrine sediments containing mm-scale ice lenses. The majority of the glaciofluvial material is highly oxidized. Underlying these McConnell-aged sediments is a diamicton interpreted to be a pre-glacial debris flow or colluvial apron, dated at >47,000 years BP. Many massive ice lenses were found in this unit. Clasts found in the diamicton are composed of poorly sorted, angular psammitic schist and/or quartzite (likely local bedrock). The sediment exposed at the lake margin is a colluvial mass derived from the described stratigraphy. It contains greater than 50 percent ice by volume, mostly in massive ice lenses (Figure 7).

The origin of the massive ice found in the lower portion of the YT Landslide is open to debate. Most evidence points to segregated/intrusive ice, as such ice can form in any orientation and dimension. The presence of massive ice at the bottom of the slope within highly permeable glaciofluvial sands and gravels showing signs of groundwater flow, beneath a less permeable cap (till and permafrost), is highly indicative of an open system pingo environment, common in other parts of the Yukon and central Alaska (Mollard and Janes, 1984). Sand and gravel inclusions and other impurities were found in the massive ice which indicates expulsion of impurities during two-sided freezing when water is injected into permafrost.

Initiation of the YTL is not well understood. However permafrost creep likely played a key role. French (1996) suggests that permafrost creep is most prevalent in ice-rich soils on steep warm permafrost slopes (like at Little Salmon Lake). Deformation is promoted at warmer temperature by the increasingly plastic nature of ice and the high unfrozen water content. Greater deformation is expected with warmer permafrost and higher ice contents. These conditions exist in the lower portion of the slope at the YTL. Climate warming, either longer term, post Little Ice Age or recent warming trends noted in Figure 3, likely played a role in accelerating permafrost creep. McRoberts (1978) theorized that creep movements may occur in ice-rich permafrost slopes. Warming temperatures have potential for creep acceleration which could result in the long-term creep rupture of the frozen soil. This would produce a landslide form that would resemble block slides, like those of the original blocks at the YTL.

6 LITTLE SALMON LAKE LANDSLIDE

The Little Salmon Lake Landslide (LSLL) is a deep-seated slump block in highly fractured rock that reactivated as a debris avalanche and debris flow in August 2008. It is situated at a latitude of 62°09.6'N and a longitude of 134°38.8'W and 1200 m elevation (at the top of the failure). The LSLL is located on a moderately steep (15-25°) north-facing slope on the south side of Little Salmon Lake (Figs. 2 and 8). The landslide was previously described by Lyle et al. (2005), Lyle (2006) and Brideau et al. (2010). Lyle (2006) used aerial photographs to document an early phase of renewed activity at the LSLL between 1949 and 1989 and provided a field characterization of increased activity since 1989, indicated by rockfall.

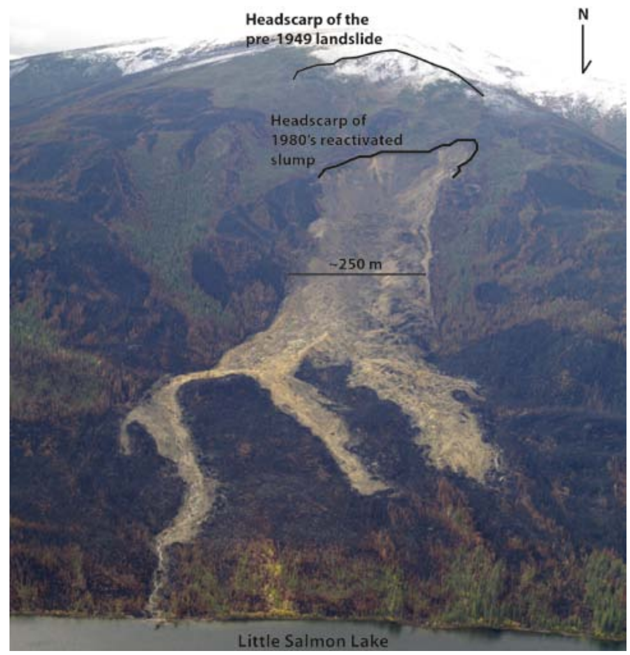

Figure 8. Overview photograph of the Little Salmon Lake Landslide after the 2009 fire (Photograph P. Lipovsky September 25, 2009).

The debris-avalanche and debris-flow reactivation of the LSLL occurred between August 22 and 28, 2008 following a period of higher than normal precipitation. This most recent reactivation involved little additional material from the 1980's headscarp, which is located 250 m below the pre-1949 headscarp (Fig. 8). Instead, bedrock slump blocks and colluvial surficial materials located below the 1980's headscarp were mobilized in the debris flow and debris avalanche. In total the landslide travelled a horizontal distance of 2050 m and over 515 m in elevation difference between the 1980's headscarp and the shore of Little Salmon Lake, *i.e.* a ΔH/L ratio of 0.25. A conservative estimate of the material volume involved is on the order of 1 Mm^3, assuming a 2 m deposit thickness across a 400 000 m^2 area. No displacement wave was reported in association with the landslide material entering the lake.

The bedrock material associated with the pre-1949 slope failure and 1980's reactivation is part of the Snowcap Assemblage, which regionally consists of psammitic schist, quartzite, dark grey carbonaceous schist, calc-silicate rocks of Devonian age and older (Colpron, 2000). Lyle (2006) noted that the surficial material in the immediate surroundings of the LSLL consisted of a colluvial veneer.

6.1.1 Description of the deposit and its properties

The LSLL can be divided in three parts based on their morphology. The upper part consists of large (10 m high x 10 m long x 20 m wide) slump blocks with vegetation still present on them. Two sag ponds were observed between back-rotated slumped blocks. The second part of the deposit in the middle of the landslide consists of hundreds of conical mounds of distinctly variable colour and varying in height from 0.3 m to 10 m (Fig. 9). The majority of the mounds are composed of disintegrated bedrock with a single constituent lithology, including yellow quartzite, grey schist and dark grey graphitic schist while others were composed of brown gravel-size surficial material. Where the material in the mounds is derived from two lithologies, the contact between them is sharp. A thin layer of tephra is observed in the soil layer still present on top of some mounds. The materials comprising the mounds are generally clast-supported, although occasionally consist of exclusively fine-grained clay-rich material. The clasts primarily consist of medium gravel to small cobbles, with occasional larger cobbles up to 50 cm. The average slope angle of the conical features is between 35^o and 37^o. These correlate well with the previously reported values for gravelly material (e.g. Rahn, 1969; Burgess, 2002). The third part of the landslide consists of the channelization of the debris in its lower parts (Figure 8). Occasional mounds were found in these sections but they were less frequent than in the central portion. The characteristics of the deposit were more typical of debris flows, where the grain-size distribution of the deposit was finer (matrix-supported in some cases) with woody debris and levees lining the sides of the channel.

Figure 8. Overview of mounds in the middle section of the Little Salmon Lake Landslide (Photograph M-A Brideau July 2009).

6.2 Permafrost and Ground Ice

An initial visit was made by the YGS to the LSLL after the August 2008 debris-avalanche and debris-flow reactivation. At this time, frost probing in the adjacent mature spruce forest revealed an active layer that varied in thickness from 51 to 65 cm. Large angular blocks of ice-rich stratified colluvium up to 11 m in height were also noted in the landslide deposit. Clasts from these blocks were observed to be actively ravelling as they rapidly thawed. The ravelling fragments were accumulating at the base of the frozen blocks in a conical form. Segregated ice content was visually estimated to be 50% in an approximately 9 m tall colluvium block. Frozen blocks were not observed when the site was visited in August 2009 (Brideau et al., 2010) but a solid ice lens approximately 10 cm thick was identified in a fractured bedrock slump block found in the upper part of the deposit.

6.3 Formation of conical mounds

The presence of conical mounds in large landslide deposits has long been noted in landslide research, and the features are commonly referred to as molards or hummocks. Several mechanisms for the formation of these landforms have been reviewed in Brideau et al. 2010. A laminar or plug emplacement mechanism is proposed to explain formation of the LSLL mounds based on several observations made at the site, including: the presence of tephra caps on some of the mounds; their dominantly single lithology composition, or sharp contact between geological units in the cases where two lithologies are present; and the preservation of internal structures in mounds composed of surficial material. The mechanism we suggest for the formation of the conical mounds at the Little Salmon Lake landslide is summarised in Figure 9.

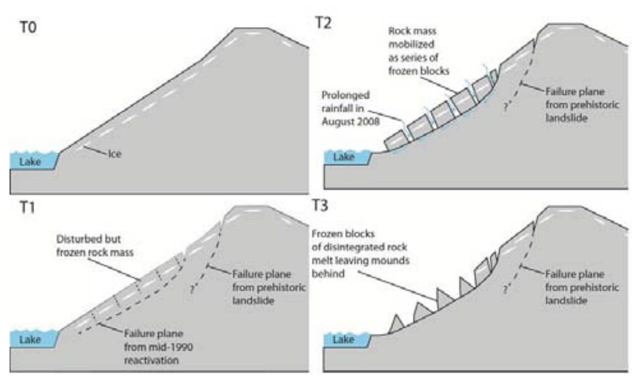

Figure 9. Mechanism for the formation of mounds in the middle section of the Little Salmon Lake Landslide

The strength of the rock mass was initially reduced by the pre-1949 bedrock slump (T1 in Fig. 9). During the 1980's to July 2008 the highly fractured rock mass on the slope was further degraded by renewed slumping activity (T2 in Fig. 9). The permafrost in the ground was providing an "effective" cohesive strength to the surficial material and disintegrated rock mass. In August 2008, these frozen blocks of soil and rock were mobilized by high pore water pressure in the surrounding saturated sediments. These blocks were rafted downslope in the main body of the landslide (T3 in Fig. 9). Following deposition, ice within these blocks subsequently melted and/or dried to form the conical features. In this proposed mechanism, the ice would provide the cohesion in a fashion similar to the wet sand in the physical models of Shea and van Wyk de Vries (2008). Conical mounds in landslides within permafrost regions have previously been reported by Dahl-Jensen et al. (2004) in Greenland, Geertsema et al., (2009) in the Northwest Territories, and observed by the second author in the Kluane Ranges of the Yukon. It is suggested that the same formation process could be applied to these other sites.

7 SUMMARY OF LANDSLIDE ACTIVITY AT LITTLE SALMON LAKE

Over 80 sites of past and present landslide activity were identified in an initial landslide inventory in the Little Salmon Lake area (Lyle, 2006). The failure modes evaluated include skin flows, debris flows, rock slumps, bi-modal flows and complex slides. It is estimated that less than half of the area is underlain by permafrost and correspondingly, permafrost does not play a role in many of these landslides. However, permafrost does play a role in the largest, most active slides in the area (MRL, YTL, LSLL). These slides all started, re-activated and/or accelerated within the last two decades. Permafrost degradation has played a role in most of the new landslides in the area.

Three large distinct landslide processes active in the Little Salmon Lake area have been described in the previous sections. Of the three large landslides, two (YTL and MRL) are directly related to melting and/or creep of massive ground ice. In addition, the relatively impermeable frozen ground may have contributed to high groundwater pressures that also play a role in the mass wasting processes.

Permafrost and ground ice are not primary causal factors for the LSLL. However the frozen ground and ground ice influenced the failure process by keeping large blocks intact and likely providing moisture (as ground ice melts) that contributes to the mobility of the landslide debris. Low permeable frozen ground could also have played a role in developing high groundwater pressures that may have aided the reactivation of the landslide.

The August 2009 forest fire that swept the slopes south of Little Salmon Lake adds an interesting dynamic to the current slope stability of the area. Forest fires rapidly alter surface temperature and soil moisture conditions during and immediately following the fire. On permafrost slopes, active-layer depths then rapidly increase and often cause small-scale, shallow, active-layer detachment slides in the first year following the fire (Lipovsky et al., 2006; Coates, 2008). Over 40 such landslides occurred within 1 month of the 2009 Little Salmon Lake fire, Two of these slides are shown initiating in isolated burned patches in Figure 10, illustrating the strong causal relationship between the recent forest fire and landslide initiation. It remains to be seen if further large landslides will develop as a result of these disturbances. If massive ground ice, like that found at the YTL, LSLL and MRL is exposed by these small scale landslides, larger landslides may develop.

Figure 10. Small landslide activity immediately after the 2009 fire (Photograph P. Lipovsky September 25, 2009).

8 IMPLICATIONS AND RECOMMENDATIONS

The Little Salmon Lake area provides an excellent area to study natural landslide processes influenced by the presence of warm ice-rich permafrost. There are three relatively large landslide documented in this paper. Fortunately, these landslides have had little impact on human development as all infrastructure and settlement in the Little salmon Lake valley is on south facing slopes or the valley bottom where permafrost is not present or there is no gradient for mass wasting to occur. All three landslides have produced environmental impacts through increased sediment loads into the Magundy River and/or Little Salmon Lake.

As northern regions continue to develop, new infrastructure is planned in areas of warm, ice-rich permafrost slopes. In addition, climate modelling indicates that northern areas are warming faster than the mean of the world (Ford et al., 2005). Thus it is likely that these types of landslides will both become more prevalent and have more human impact. Regardless of projected future climatic trends, the existence of these slides should serve as a reminder that any activity that may disturb the thermal regime of potentially ice-rich slopes should be carefully planned and mitigated.

The impact of landslides in permafrost can be far-reaching, can remain active for decades, can occur on gentle slopes impacting large areas. They can be triggered by human and natural causes including road construction, river erosion, forest fires, heavy rainfall and confined groundwater flow. This illustrates the need for detailed permafrost mapping, landslide susceptibility mapping, and subsurface geotechnical characterizations prior to any development. In anticipation of future climate warming, land-use decisions in the area should therefore consider the possibility of the increasing occurrence of such landslides.

All of these considerations highlight the ultimate need for both regional and detailed permafrost mapping and modelling, as well as landslide susceptibility mapping, and geotechnical evaluations prior to future development projects proposed in permafrost terrain.

The Little Salmon Lake region is ideally suited for the continuing development of effectual landslide susceptibility mapping in discontinuous permafrost. Lyle

(2006) provides an inventory of landslides from an investigation in 2004-5. Landslide susceptibility mapping, using a variety of methods were also presented by Lyle (2006). Since the forest fire activity in 2009, many new landslides have developed. A new landslide inventory should be compiled and the susceptibility mapping techniques refined.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of a number of individuals to the study: Mr Jeffrey Bond of the Yukon Geological Survey first suggested the study in the project area and aided in the initial field work. Dr. Alan Gorman (Queens University) was an inspiration to the early study in the area and volunteered countless days contemplating the mysteries of the Little Salmon Lake area. T. Sivak (2009), K. Kennedy (2008), B. Lyle (2005) and Y. Preston (2004) assisted in the field. W. and G. Eberlein, residents of the Little Salmon Lake area, supported field work and have kept the authors updated on changes in the region. The authors would also like to acknowledge stimulating discussions with D. Stead, M. Geertsema, B. Ward, T. Davies, M. McSaveney, L. Dyke, R. Harrap, A. Lewkowicz, E. Hoeve, R. Trimble, C. Huscroft, N. Rosser and A. Price Jones.

Funding for research and field work over the years was provided by the Yukon Geological Survey, NSERC, Northern Scientific Training Program, GEOIDE and a Simon Fraser University graduate fellowship.

REFERENCES

Bell, F.G. 1999. *Mass Movements*. E &FN Spon, London, UK.

Bichler A., D. VanDine and P. Bobrowsky. 2004. Landslide Hazard and Risk Mapping – A Review and Classification. . *Proceedings of the 57th Canadian Geotechnical Conference*. Session 5C. pp.1-12.

Bond, J.D., and Plouffe, A., 2003. Yukon Target Geoscience Initiative, Part 2: Glacial history, till geochemistry and new mineral exploration targets in Glenlyon and eastern Carmack map area, central Yukon. In: *Yukon Exploration and Geology 2002*, Emond, D.S., Lewis, L.L., (eds.), Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, pp. 109-134.

Bonnaventure, P.P., Lewkowicz, A.G., Kremer, M., Sawada, M.C., 2012. A Permafrost Probability Model for the Southern Yukon and Northern British Columbia, Canada. *Permafrost and Periglacial Processes* 23: 52-68. DOI: 10.1002/ppp.1733.

Brideau, M.-A., Stead, D., Lipovsky, P., Jaboyedoff, M., Hopkinson, C, Demuth, M., Barlow, J., Evans, S., and Delaney, K. 2010. Preliminary description and slope stability analyses of the 2008 Little Salmon Lake and 2007 Mt Steele Landslides, Yukon. In: *Yukon exploration and Geology 2009,* MacFarlane, K.E., Weston, L.H., Blackburn, L.R., (eds.) Yukon Geological Survey, pp. 119-133.

Burgess, J.W., 2002. Material Properties, In: *SME Mining Reference Handbook*, Lowrie R.L. (Ed.), pp. 9-54.

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

Burn, C.R. and A.G. Lewkowicz. 1990. Canadian Landform Examples – Retrogressive Thaw Slumps. *The Canadian Geographer*. 34 (3): 273-276.

Campbell, R.B. 1967. R*econnaissance Geology of Glenlyon Map-Area, Yukon Territory (105L*). Geological Survey of Canada Memoir 352.

CCORE, 2007. *Satellite Monitoring of Permafrost Instability – Validation, Evaluation and Evolution*. C-CORE Report R-07-018-402 v.2.0, prepared for European Space Agency in collaboration with Yukon Geological Survey.

Coates, J., 2008. *The impact of forest fire on permafrost slopes, Klondike area, Yukon Territory*. Unpublished M.Sc. thesis. University of Ottawa, Ottawa, Canada.

Colpron, M. 2000. *Geological map of Little Salmon Lake (parts of NTS 105L/1, 2 & 7), central Yukon*. Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Open File 2000-10.

Cote, M.M. 2002. *The influence of elevation and aspect on permafrost distribution in central Yukon Territory.* Unpublished M.A. Thesis, Carleton University. Ottawa, Canada.

Dahl-Jensen, T., Larsen, L.M., Pedersen, S.A.C., Perdersen, J., Jepsen, H.F., Pedersen, G.K., Nielsen, T., Pedersen, A.K., von Platen-Hallermund, F., Weng, W., 2004. Landslide and Tsunami 21 November 2000 in Paatuut, West Greenland. *Natural Hazards* 31: 277-287.

Dyke, L.D. 2000. Stability of permafrost slopes in the Mackenzie Valley; I*n: The Physical Environment of the Mackenzie Valley, Northwest Territories: a Base Line for the Assessment of Environmental Change,* (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 177-186.

Ford, J.D., Smit, B. and Wandel, J. 2006. Vulnerability to climate change in the Arctic: A case study from Arctic Bay, Canada. *Global Environmental Change* 16: 145-160.

French, H.M. 1996. *The Periglacial Environmen*t. Addison Wesley Longman Company Essex.

Geertsema, M., Highland, L., Vaugeouis, L., 2009. Environmental Impact of Landslides. In: *Landslides – Disaster Risks Reduction*. Springer, pp. 589-607.

Harris, C. 1987. Mechanisms of Mass Movement in Periglacial Environments. In: *Slope Stability* Anderson, M.G. and K.S Richards (eds.). John Wiley and Sons. pp. 531-559.

Lewkowicz, A.G. 1988. Slope Processes. In: M.J. Clark (ed.) *Advances in Periglacial Geomorphology*. London: John Wiley and Sons. pp.325-368.

Lipovsky ,P.S., Huscroft, C., 2007. A reconnaissance inventory of permafrost-related landslides in the Pelly River watershed, central Yukon. In: *Yukon Exploration and Geology 2006*, Emond, D.S., Lewis, L.L., and Weston, L.H., (eds.), Yukon Geological Survey, pp. 181-195.

Lipovsky, P.S., Coates, J., Lewkowicz, A.G., Trochim, E., 2006. Active-layer detachments following the summer 2004 forest fires near Dawson City, Yukon. In: *Yukon Exploration Geology 2005*, Emond, D.S., Bradshaw, G.D., Lewis, L.L., Weston, L.H., (eds), Yukon Geological Survey, pp. 175-194.

Lyle, R.R., Hutchinson, D.J. and Preston, Y., 2005. Landslide processes in discontinuous permafrost, Little Salmon Lake (NTS 105L/1 and 2), South-central Yukon. *In: Yukon and Exploration Geology 2004*, D.S. Emond, L.L. Lewis and G.D. Bradshaw (eds.), Yukon Geological Survey, pp.193-204.

Lyle, R.R., 2006. L*andslide susceptibility mapping in discontinuous permafrost: Little Salmon Lake, Central Yukon.* Unpublished M.Sc. thesis, Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, Canada.

McRoberts, E.C. 1978. Slope Stability in Cold Regions. In: *Geotechnical Engineering for Cold Regions*. Andersland, O.B. and D.M. Anderson (eds.) McGraw-Hill Inc., New York, USA, 363-404.

McRoberts, E.C. and N.R. Morgenstern. 1974. *The Stability of Thawing Slopes*. Canadian Geotechnical Journal. 11: 447-469.

Mollard., J.D. and J.R. Janes. 1984. *Airphoto Interpretation and the Canadian Landscape*. Energy, Mines and Resources Canada, Hull, Canada.

Mougeot, C.M. and L.A. Walton. 1996. Yukon Geoprocess File (2002), *Geological Processes and Terrain Hazards of Glenlyon*, 105L. Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada.

Rahn, P.H., 1969. The relationship between natural forested slopes and angles of repose for sand and gravel. *GSA Bulletin* 80: 2123-2128.

Shea, T. and van Wyk de Vries, B., 2008. Structural analysis and analogue modeling of the kinematics and dynamics of rockslide avalanches. *Geosphere*, 4 (4): 657-686.

Tart. R.G. 1996. Permafrost. *In: Landslides: Investigation and Mitigation,* (eds.) K.R. Turner and R.L. Schuster. Transportation Research Board Special Report 247. pp. 620-645.

van Everdingen, R.O. (ed.) 1998. *International Permafrost Association's Multi-language glossary of permafrost and related ground ice terms.* Arctic Institute of North America, Calgary, Canada.

Ward, B.C., Jackson, L.E., 2000. *Surficial geology of the Glenlyon map area, Yukon Territory.* Geological Survey of Canada Bulletin 559.

Ward, B.C., Jackson, L.E. Jr., and K.W. Savigny. 1992. *Evolution of Surprise Rapids Landslide, Yukon Territory*. Geological Survey of Canada Paper 90-18.