

# CONTRASTING BEHAVIOUR OF TWO RECENT, LARGE LANDSLIDES IN DISCONTINUOUS PERMAFROST, LITTLE SALMON LAKE, YUKON, CANADA

Ryan R. Lyle<sup>1</sup>, D. Jean Hutchinson<sup>2</sup> & Panya S. Lipovsky<sup>3</sup>

<sup>1</sup> BGC Engineering Inc. (e-mail: rlyle@bgcengineering.ca)

<sup>2</sup> Queen's University (e-mail: jhutchin@geol.queensu.ca)

<sup>3</sup> Yukon Geological Survey (e-mail: panya.lipovsky@gov.yk.ca)

**Abstract:** Two large active landslides involving the degradation of ice-rich sediments are found in the Little Salmon Lake region of the Yukon, Canada. Volume estimates for both slides are in excess of one million cubic metres of sediments and ice. These landslides share many key geographic, geological and climatic factors; however, their behaviours show considerable contrast. The Magundy River Landslide is an example of a large retrogressive thaw slump dominated by the exposure and ablation of ice-rich permafrost, forming viscous debris flows. The YT Landslide is a complex in displaying rotational, translational and toppling behaviour. Much of the movement is thought to be due to thermal erosion aiding in the unloading of the toe. Descriptions of these two landslides are provided in this paper along with a discussion of key causal factors. A key aspect in the initiation of these two landslides is thought to be the post-Little Ice Age and current climate-warming trends. These landslides may be indicative of future slope instability in warm discontinuous permafrost areas, given a continuing warming trend.

## INTRODUCTION

Slopes in warm discontinuous permafrost have long been recognized as a potential hazard to development. Human disturbance of such slopes can lead to slope failures with the exposure of ice-rich sediments. Natural factors can also lead to instability of slopes in permafrost. This is the case in the Little Salmon Lake region (Figure 1) of the Central Yukon where an acceleration of natural landslide processes has taken place in the last decade. Degradation of warm, ice-rich permafrost has played an integral role in two recent landslides of considerable size in the region: the Magundy River Landslide and the YT Landslide. Though found in a similar setting, these two large landslides show considerable contrast in behaviour and process.

The research reported in this paper was carried out as part of a landslide susceptibility mapping program focussed on discontinuous permafrost in the Little Salmon Lake region of the Yukon. This project resulted in publications by Lyle (2006), Lyle and Hutchinson (2006) and Lyle et al., (2005). The Yukon Geological Survey (YGS) is continuing the monitoring of the two landslides described in this paper. In cooperation with the European Space Agency and C-CORE (St. John's, NF), the YGS is currently conducting pilot studies at both landslide sites to test the application of interferometric synthetic aperture radar (InSAR) satellite monitoring for detecting centimetre-scale slope movements in permafrost regions. Several monuments placed within each landslide in 2006 are being statically surveyed biannually using a high-accuracy GPS to validate the InSAR results, and to monitor future ground movements. Kinematic GPS surveys of the slide boundaries and other prominent linear features are also being performed biannually to monitor the future expansion of the area impacted by the landslides.

This paper describes field and mapping studies carried out to provide insight into these two large, recent landslides. Large retrogressive thaw slumps have been observed previously in the Central Yukon; however, the trigger mechanism and rate of expansion of the Magundy River

Landslide appears to be unique. The other landslide described in this paper, the YT Landslide, is complex and the authors are unaware of any other documented landslide that is similar to it.



**Figure 1:** Map of the Yukon Territory indicating the location of Little Salmon Lake.

## STUDY AREA

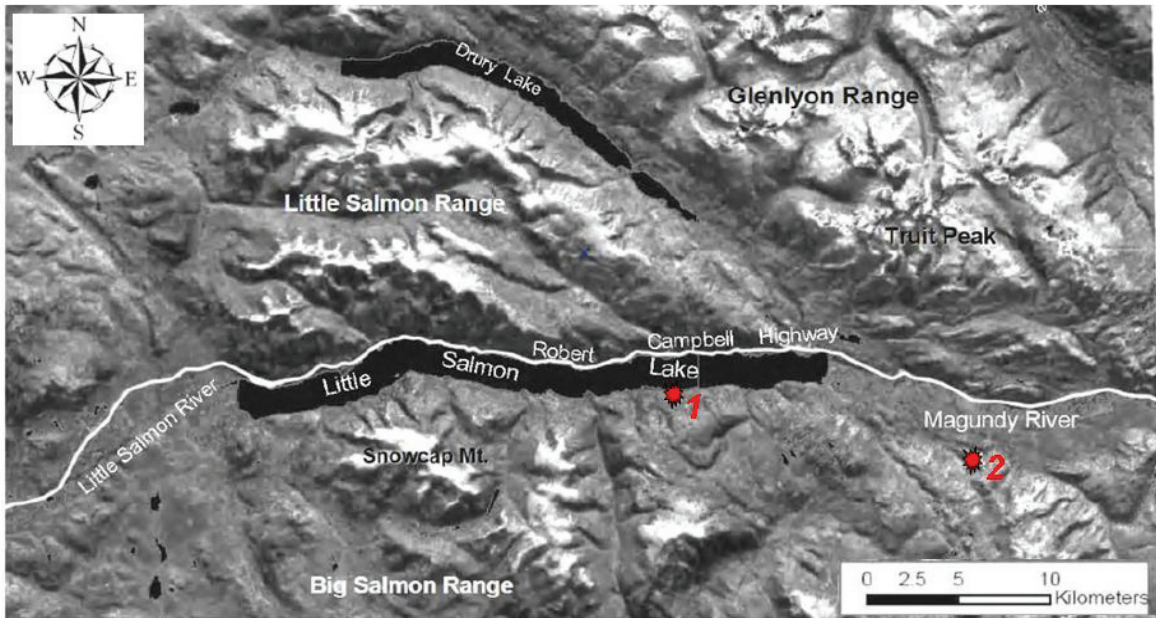
Little Salmon Lake is located in south-central Yukon as shown on Figure 1. The area is located between the villages of Carmacks and Faro, and is bisected by the Robert Campbell Highway. A satellite image shown in Figure 2 shows some of the key physiographic features of the area. The Yukon Plateaus region is 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. Little Salmon Lake lies at 609 m elevation. The Little Salmon Lake valley occupies a glacially scoured and over-deepened U-shaped valley (Campbell, 1967) that is approximately 33 km long and 2 km wide.

The Selwyn lobe of the Cordilleran Ice Sheet covered the Little Salmon Lake area during the last ice age – the McConnell glaciation (Ward and Jackson, 2000). Glacial flow was generally in a northwest direction. Glacial retreat occurred very rapidly through ice sheet down-wasting and stagnation (Ward and Jackson, 2000). 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 common in the valley bottoms.

## 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. The general climatic conditions are illustrated in Table 1, which shows the 1970-2000 climate normals for the meteorological stations in Faro and Carmacks (see Figure 1 for station locations). There is also a meteorological station at Drury Creek Highway Maintenance camp, located near the outlet of Drury Creek into Little Salmon Lake. However, Environment Canada does not calculate climate normals for this station. A temporal plot of average annual temperature for the Carmacks and Drury Creek meteorological stations is shown

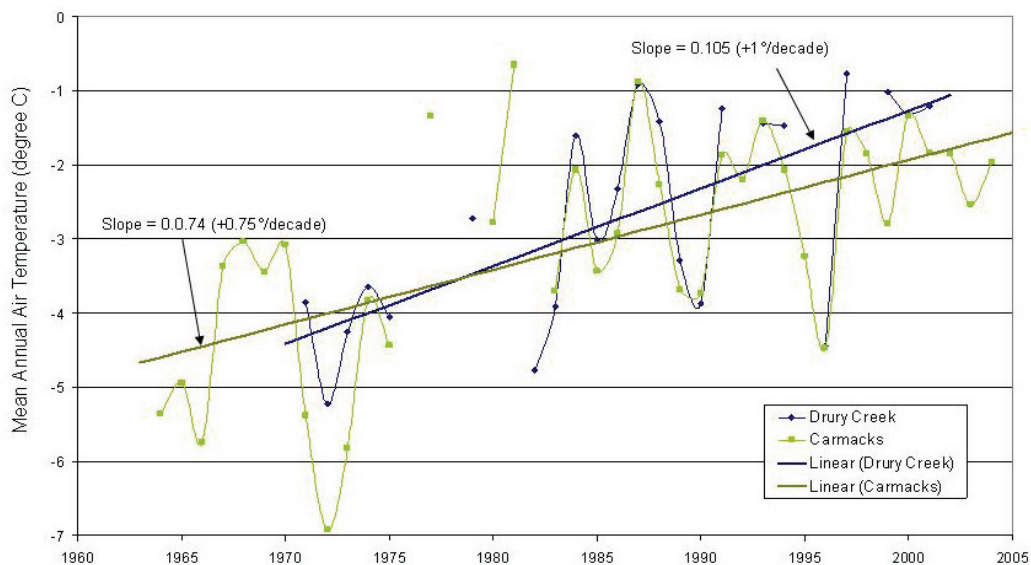
in Figure 3. The apparent warming trend illustrated by the Carmacks station data is even more apparent in the limited data from the Drury Creek station. These data show the climate warming trends noted by Serreze et al. (2000).



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

**Table 1:** Environment Canada (2005) mean climate data for the period 1971-2000.

Station	Daily mean air temperature °C			Mean precipitation (mm)		
	January	July	Annual	January	July	Annual
Faro	-21.5	15.0	-2.2	14.8	58.8	316
Carmacks	-24.9	15.4	-2.9	n/a	n/a	n/a



**Figure 3:** Climate data for Drury Creek, and Carmacks (data from Environment Canada, 2005).

The Little Salmon Lake area is within the zone of sporadic discontinuous permafrost (Heginbottom et al., 1995). 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.

## LANDSLIDE DESCRIPTIONS

### Magundy River Landslide

The Magundy River Landslide is located on a gentle to moderate (10-20°) north-facing slope at 62°08.5'N latitude and 134°11.4'W longitude and 975 m elevation (at the top of the failure). The landslide was previously classified as a bi-modal flow (Lyle et al. 2005, Lyle, 2006, Lyle & Hutchinson, 2006) 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). However, Everdingen (1998) recommends that the term ‘retrogressive thaw slump’ instead of bi-modal flow. The Magundy River Landslide is similar in size and morphology to 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).



**Figure 4:** Magundy River Landslide: a) overview looking south (top scarp is 350 m wide, elevation change from top scarp to depositional is about 350 m) b) active thaw slump area (note 2<sup>nd</sup> author for scale); and c) active debris flow (channel width is approximately 1 m across).

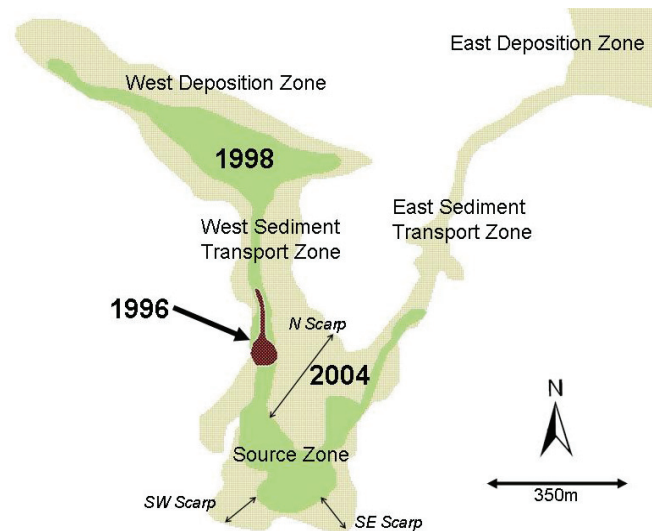
The debris flow has eroded two substantial channels, each having a distinct depositional area (Figure 4a). Two surficial units, exhibiting similar texture, are exposed in the landslide: a colluvial layer of variable thickness overlying denser glacial diamicton (till). The colluvium

consists of reworked till, and is thin or absent in some areas. Multiple organic horizons, one of which was dated at 2200 +/- 40 years BP (BGS 2607), separated by diamicton layers, were found in one active scarp, suggesting previous debris flow activity.

The debris flow materials contain the complete range of grain sizes found in the till and colluvial materials, as well as fragments of organic mat and trees that have fallen to the base of the active scarps. It is believed that the primary controls on the debris flow rheology include moisture availability, and silt and clay content.

The source area is rimmed by active and inactive scarps. The east-facing inactive scarps primarily rest at the angle of repose of till, and vegetation is slowly taking hold. Active areas found in the summers of 2004, 2005 and 2006 were located on south and west-facing slopes. 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 averaging 0.5 cm thickness composed up to 50% of the soil volume in several active scarp exposures.

Figure 5 shows the rapid growth of the Magundy River Landslide. Based on discussions with local residents, it is believed that the slide was initiated in 1996 as a small failure less than 10 m wide. The 1996 location and size is estimated from eyewitness accounts, the 1998 outline was taken from airphoto coverage and the 2004 data are based upon field GPS mapping. The two depositional areas are located at the north end of the plan with the main source zone to the south. Figure 5 also shows the high retreat rates of the active scarp areas.



**Figure 5:** Footprint of the Magundy River Landslide in 1996 (red), 1998 (dark green) and 2004 (light green). Five morphological zones are also defined.

Headscarp retreat rates for retrogressive thaw slumps have been reported by Burn and Lewkowicz (1990) (Table 2). Retreat rates for three different scarps at the Magundy River Landslide were estimated, based on a 1998 airphoto and the 2004 scarp location (Table 2). The southeast and southwest scarps (Figure 5) have retreated an average of 12-16 m per year, which are consistent with the range of rates shown in Table 2. The north scarp has retreated 30-40 m per year. It is believed that this high rate is due to the south-facing aspect of the slope (increased solar radiation), downslope retreat of the scarp, and lateral ablation. In addition, this landslide is further south than any of the slides noted in Table 2.

**Table 2:** Headscarp retreat rates for various retrogressive thaw slumps (data from Burn and Lewkowicz, 1990) compared with the Magundy River Landslide.

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

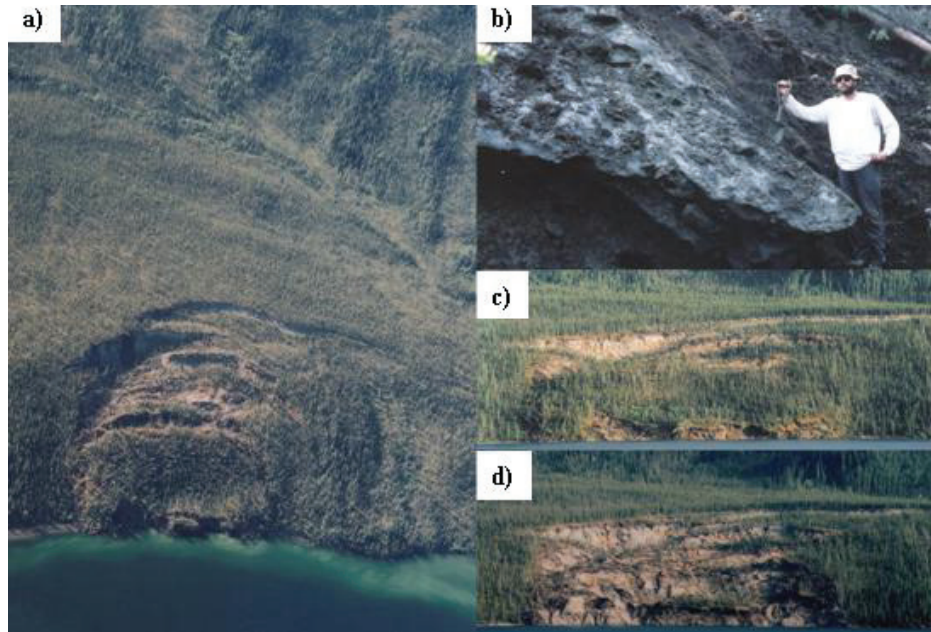
It is difficult to discern the primary causal factor for the Magundy River Landslide. Forest fire activity, active layer detachments, and fluvial and shoreline erosion are considered to be the primary triggers of retrogressive thaw slumps (McRoberts, 1978; Lewkowicz, 1988; Dyke, 2000). No forest fire activity has been noted in the last 50 years at the Magundy River landslide site and there are no lakes/streams 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 in initiating the landslide.

### **YT landslide**

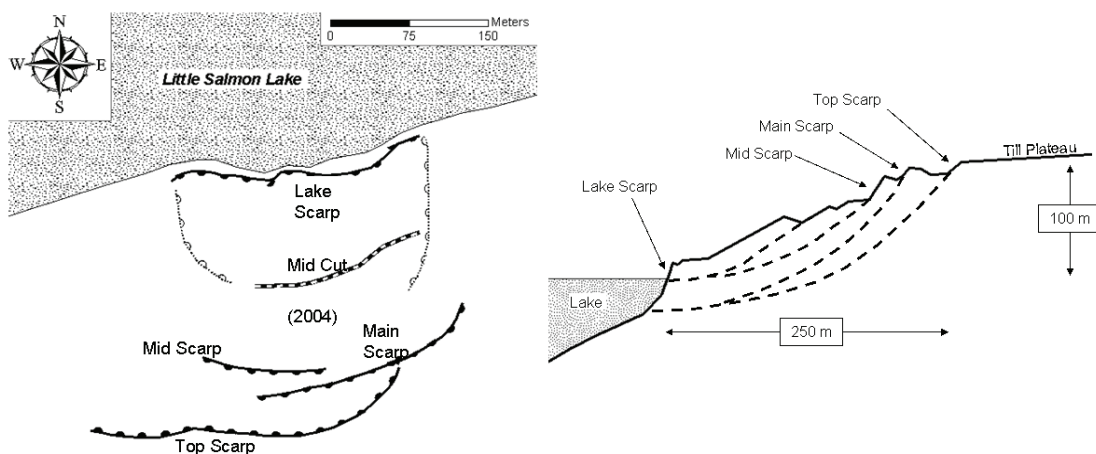
The YT Landslide is located on a north-facing slope, along the south shore of Little Salmon Lake. It is situated at a latitude of 62°10.7'N and a longitude of 134°30.7'W and 700 m elevation (at the top of the failure). At the lateral margins of the landslide, it appears to be bulging out into the lake, while the core of landslide appears to be cut back into the slope (Figure 6). In plan, the landslide is approximately 250 m long, from the lake shore to the top scarp (Figure 7). An elevation change of 90 m over the length of the landslide yields an overall angle of 20°. The slide continues to an unknown depth below the lake surface. It is 350 m across from the west end of the top scarp to the east end of the main scarp. The landslide covers a land area of approximately 80 000 m<sup>2</sup>. The overall depth of the landslide is not known, as no subsurface exploration has been conducted. The maximum vertical height of a scarp was measured to be 20.1 m (main scarp) and it is estimated to involve in excess of 1 million m<sup>3</sup> of sediments and ice.

Figure 7 shows some hypothetical failure planes (dashed lines) along a cross section through the landslide. The curved upper scarps, and pattern of deformation noted on old airphotos, indicate that the landslide is moving in a generally rotational sense. However, the movement noted between the 2004 and 2005 field seasons (Figure 6c,d) indicates a more translational

movement of intact blocks of frozen sediment downward to lake level (i.e., the smallest blocks indicated on Figure 7). The material that has moved rapidly during this time-frame appears to be very ice-rich, while no significant excess ice has been noted in the sediments exposed in the upper scarps. The ice-rich material is quickly thermally eroded by the lake water. Undercutting of the ice-rich material initiates the toppling of large blocks of frozen sediment into the lake. Melting of 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<sup>3</sup>) was witnessed in August 2004. The block remained coherent and rolled out into the lake approximately 40 m before disappearing. Thus the deeper-seated movement is inferred to be rotational and the upper movement is translational.



**Figure 6:** YT Landslide: a) overview, looking south (Aug. 2004); b) massive ice in sediments exposed in landslide scarp (first author for scale); c & d) overview photos, looking south from across Little Salmon Lake. Note the changes between photo (c) taken on Aug. 3, 2004, and photo (d) taken on Aug. 2, 2005. Upper scarp in photos a, c & d is approximately 350 m long.



**Figure 7:** Plan and cross-section views of the YT Landslide based on 2004 survey. Subsurface interpretation is purely schematic.

The stratigraphy is well exposed in the numerous scarps and extensional cracks, though reconstruction of a detailed stratigraphic section is hampered by the disturbance due to slope movement, as well as ice growth. However, the stratigraphy exposed in the scarps is as follows. 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 glaciofluvial (apparently unfrozen) 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 (Beta-197221). Many massive ice lenses were found in this unit (Figure 6). Clasts found in the diamicton are composed of poorly sorted, angular psammitic schist and/or quartzite (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, much of which is in massive ice lenses (described as an ice-rich chaotic melange by Lyle (2006)). Lyle (2006) provides multiple working hypotheses of the depositional history of these sediments.

The origin of the massive ice found in the lower portion of the YT Landslide is debatable. 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, which is common in other parts of the Yukon and central Alaska. Furthermore sand and gravel inclusions and other impurities were found in the massive ice which likely indicates expulsion of impurities during two-sided freezing when water is injected into permafrost.

A temporal analysis of the landslide was completed using aerial photos from 1949, 1967, 1989 and 1998, as well as observations and airphotos from 2004-2006. Some evidence of slope deformation is evident on the 1949 and 1967 photos. Top scarp development is evident in the 1989 airphoto and the main scarp is developed in the 1998 airphoto. A small dark area appears along the shoreline at the centre of the slide in 1989. It is believed that this is the early development of the translational movement and the lake-side scarp, and likely the beginning of the thermal erosion of ice-rich sediments. This feature is much larger in the 1998 airphoto.

Initiation of the YT Landslide is not clearly understood. French (1996) suggests that permafrost creep is most prevalent in ice-rich soils on steep warm permafrost slopes. Deformation is promoted at warmer temperature by the increasingly plastic nature of ice and the high unfrozen water content. The warmer the permafrost, and the greater the amount of ground ice, the greater the deformation. These conditions exist in the lower portion of the slope at the YT Landslide. Thus, permafrost creep likely played an important role in its development. Post Little Ice-Age climate warming, or perhaps warming in the 20<sup>th</sup> century (Figure 3), likely played a role in accelerating permafrost creep. McRoberts (1978) theorized that creep movements may occur in ice-rich permafrost slopes and the potential for creep acceleration due to warming would 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 of this slide.

## **SUMMARY AND DISCUSSION**

The YT and Magundy River Landslides are two examples of large, active landslides involving permafrost degradation, however they exhibit contrasting behaviour. The Magundy River Landslide is a retrogressive thaw slump where viscous flow is the primary movement mechanism for thawing sediments. The YT Landslide is complex with overall rotational movement; much of

the recent movement appears to be translational due to the thermal erosion at the toe. Despite the differing behaviour, several important factors are observed in both landslides. They are located within the same physical setting, on north-facing slopes of gentle to moderate angle with similar climatological, geological and groundwater regimes. These key factors have contributed to the development of ice-rich permafrost at both landslide locations. It is likely that Post-Little Ice Age and recent warming trends are a primary causal factor in their initiation and propagation.

Forest fires commonly trigger landslides in ice-rich permafrost in the Yukon (Mollard and Janes, 1984; Huscroft et al., 2004, Lipovsky et al., 2006,) and the Mackenzie Valley, NWT (Dyke, 2000). However, forest fires do not appear to be a factor in the development of these two landslides. Since conditions already exist for landslide activity without a fire trigger, it is likely that more landslides similar to the Magundy and YT Landslides would develop if forest fires burned on ice-rich slopes in the region and such slopes should be monitored accordingly.

The rapid growth and large size of the Magundy River and YT Landslides illustrate the potential for large slope movements associated with climatic warming in areas of ice-rich permafrost. In anticipation of these warming trends continuing, land-use decisions in the area should take into account the possibility of the increasing occurrence of such landslides. Regardless of projected future climatic trends, the existence of these slides should serve as a further caution to development of any infrastructure in discontinuous permafrost terrain. Any activity that may disturb the thermal regime of potentially ice-rich slopes should be carefully planned and mitigated. All of these considerations highlight the ultimate need for both regional and detailed permafrost mapping and modelling, as well as landslide susceptibility mapping, prior to future development projects proposed in permafrost terrain.

**Acknowledgements:** Financial support for this research was provided by the Yukon Geological Survey (YGS), NSERC, GEOIDE, and NSTP. The YGS and EBA Engineering Consultants Ltd. provided field and laboratory logistical and technical support. J. Bond (YGS) provided the initial project idea and introduced us to the area. W.A. Gorman, R. Harrap, Y. Preston, and G. and W. Eberlein all made significant contributions to the project.

**Corresponding authors:** Panya S. Lipovsky, Yukon Geological Survey, 2099 2<sup>nd</sup> Avenue, Whitehorse, YT, Canada, Y1A 1B5. Tel: +1 867 667 8520. Email: Panya.Lipovsky@gov.yk.ca. or Ryan R. Lyle, BGC Engineering Inc., 503-1315 Summit Drive, Kamloops, British Columbia, Canada, V2C 5R9. Tel: +1 250 374 8600. Email: rlyle@bgcengineering.ca.

## REFERENCES

- BELL, F.G. 1999. Mass Movements. In: F.G. BELL, *Geological Hazards: Their assessment, avoidance and mitigation*. E & FN Spon, London. 114-180.
- BURN & LEWKOWICZ, 1990. Canadian Landform Examples – Retrogressive Thaw Slumps. *The Canadian Geographer*. **34**, No. 3., 273-276.
- CAMPBELL, R.B. 1967. *Reconnaissance Geology of Glenlyon Map-Area, Yukon Territory (105L)*. Geological Survey of Canada Memoir 352. 92p. (2 maps)
- DYKE, L.D. 2000. Slope Stability. In: DYKE, L.D. & BROOKS, G.R. (eds), 2000. *The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change*. Geological Survey of Canada, Bulletin 547, 212 p.
- ENVIRONMENT CANADA. 2005. *Climate Data Online*. <http://www.weatheroffice.ec.gc.ca>.

- EVERDINGEN, R. (ed.) (1998, revised 2005). *Multi-language glossary of permafrost and related ground-ice terms*. Boulder, CO: National Snow and Ice Data Center/World Data Center for Glaciology.
- FRENCH, H.M. 1996. *The Periglacial Environment*. Addison Wesley Longman Company, Essex, 341p.
- HARRIS, C. 1987, Mechanisms of Mass Movement in Periglacial Environments. *Slope Stability*, M.G. Anderson and K.S. Richards (eds.), John Wiley and Sons Ltd. 531-559.
- HEGINBOTTOM, J.A., DUBREUIL, M.A. & HARKER, P.A., 1995. Canada – Permafrost. In *National Atlas of Canada, 5th ed.* National Atlas Information Service, Natural Resources Canada, Ottawa. Plate 2.1: MCR 4177.
- HUSCROFT, C.A., LIPOVSKY, P.S. & BOND, J.D. 2004. *A regional characterization of landslides in the Alaska Highway corridor, Yukon*. Yukon Geological Survey Open File 2004-18, 65 p.
- LEWKOWICZ, A.G. 1988. Slope Processes. In: M.J. CLARK (ed.) *Advances in Periglacial Geomorphology*. John Wiley and Sons, London. 325-368.
- 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: EDMOND, D.S., BRADSHAW, G.D., LEWIS, L.L. & WESTON, L.H. *Yukon Exploration and Geology 2005*. Yukon Geological Survey, 175-194.
- LYLE, R.R. 2006. *Landslide Susceptibility Mapping in Discontinuous Permafrost, Little Salmon Lake, Central Yukon*. M.Sc.E. Thesis. Queen's University. 351 p.
- LYLE, R.R. & HUTCHINSON, D.J. 2006. Influence of degrading permafrost on landsliding processes, Little Salmon Lake, Yukon Territory, Canada. *GeoHazards - Technical, Economical and Social Risk Evaluation*, Lillehammer, Norway, June, 10p.
- LYLE, R.R., HUTCHINSON, D.J. & PRESTON, Y. 2005. Landslide processes in discontinuous permafrost, Little Salmon Lake (NTS 105L/1 and 2), south-central Yukon. In: D.S. EDMOND, L.L. LEWIS AND G.D. BRADSHAW (eds) *Yukon Exploration and Geology 2004*, Yukon Geological Survey, 193-204.
- McROBERTS, E.C. 1978. Slope Stability in Cold Regions. In: ANDERSLAND, O.B. & D.M. ANDERSON (eds) *Geotechnical Engineering for Cold Regions*. McGraw-Hill Inc., New York, 363-404.
- McROBERTS, E.C. & MORGENSTERN N.R., 1974. Stability of Slopes in Frozen Soil, Mackenzie Valley, N.W.T. *Canadian Geotechnical Journal*. **11**, 554-573.
- MOLLARD, J.D. & JANES, J.R. 1984. *Airphoto Interpretation and the Canadian Landscape*. Hull, PQ: Energy, Mines and Resources Canada. 415p.
- SERREZE, M.C., WALSH, J.E., CHAPIN, F.S., OSTERKAMP, T., DYURGEROV, M., ROMANOVSKY, V., OECHEL, W.C., MORISON, J., ZHANG, T. & BARRY, R.G. 2000. Observational evidence of recent change in northern high-latitude environment. *Climatic Change*. **46**, 159-207.
- TART, R.G., 1996. Permafrost. In: A.K. TURNER & R.L. SCHUSTER (eds) *Landslides: Investigation and Mitigation*. Transportation Research Board Special Report 247, 620-645.
- WARD, B.C. & JACKSON L.E. JR. 2000. *Surficial Geology of the Glenlyon Map Area, Yukon Territory*. Geological Survey of Canada Bulletin 559. 60p.
- WARD, B.C., JACKSON, L.E. JR., & SAVIGNY, K.W. 1992. *Evolution of Surprise Rapids Landslide, Yukon Territory*. Geological Survey of Canada Paper 90-18. 24p.