Landslide processes in discontinuous permafrost, Little Salmon Lake (NTS 105L/1 and 2), south-central Yukon

Ryan R. Lyle[1], D. Jean Hutchinson[2] and Yana Preston
Queen's University[3]

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 Exploration and Geology 2004, D.S. Emond, L.L. Lewis and G.D. Bradshaw (eds.), Yukon Geological Survey, p. 193-204.

ABSTRACT

With increasing development in areas of discontinuous permafrost, greater emphasis is being placed on slope hazard assessment. The current research project was initiated in response to the occurrence of a large flow-type slide, the Magundy River landslide, with the aim of identifying and characterizing slope hazards in the Little Salmon Lake area of the central Yukon. Terrain evaluation studies identified over 35 areas of past and present landslide activity in the project area. Field work was completed in the summer of 2004 to obtain ground truth for the terrain evaluation and to further characterize the most prominent and active landslides. This paper provides an overview of the research project and summarizes observations on four distinct landslide processes found in the Little Salmon Lake area: debris flow, rock slumping, bimodal flow and multiple retrogressive slumping.

RÉSUMÉ

Avec la croissance du développement dans les zones de pergélisol discontinu, on met davantage l'accent sur l'évaluation des risques de glissement de terrain. Le projet de recherche actuel a été entrepris en réponse à un grand glissement par liquéfaction, le glissement de la rivière Magundy, afin d'identifier et de caractériser les risques de glissement dans la région du lac Little Salmon dans le centre du Yukon. Des études d'évaluation du terrain ont permis d'identifier plus de 35 zones de glissements passés et contemporains dans la région du présent projet. Des travaux de vérification sur le terrain ont été réalisés au cours de l'été 2004 aux fins de l'évaluation du terrain et d'une meilleure caractérisation des glissements les plus importants et les plus actifs. Le présent article fournit une vue d'ensemble du projet de recherche et résume les observations sur quatre processus distincts de glissement identifiés dans la région du lac Little Salmon, notamment la coulée de débris, l'effondrement de blocs, l'écoulement bi-modal et l'effondrement régressif multiple.

[1]*lyle@students.geol.queensu.ca*

[2]*jhutchin@geol.queensu.ca*

[3]*Department of Geological Sciences and Geological Engineering, Miller Hall, Queen's University, Kingston, Ontario, Canada K7L 3N6*

INTRODUCTION

This project was initiated following the discovery of a large flow-type landslide in the Magundy River valley of central Yukon (J.D. Bond., pers. comm., 2003). A regional landslide inventory and assessment was proposed based on this slide and other landslides in the area documented by Ward and Jackson (2000). The objective of this project was to investigate landslide processes in discontinuous permafrost from an engineering geology perspective, using the Little Salmon Lake area (NTS 105L/1 and 2) as a case study.

Little Salmon Lake is located halfway between Carmacks and Faro, along the Robert Campbell Highway in central Yukon (Fig. 1). The work is confined to an east-west corridor accessible by the Robert Campbell Highway and by boat/canoe on Little Salmon Lake and the Magundy River. Figure 2 shows the general geographical features of the project area.

This paper is based on initial results of the project and highlights the different landslide processes observed in the Little Salmon Lake area. A discussion of the role of permafrost in the various landslides is also given.

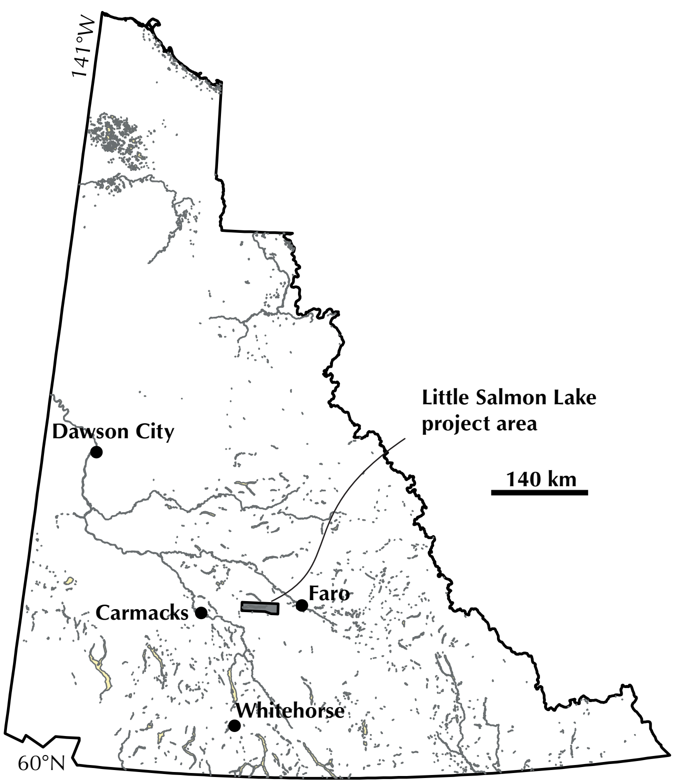

Figure 1. *Map of the Yukon showing the Little Salmon Lake project area.*

BACKGROUND

PHYSIOGRAPHY

The Little Salmon Lake valley primarily lies within the physiographic region of the Lewes Plateau, a part of the Yukon Plateaus. The Lewes Plateau region is a broad uplands area consisting of low, rolling hills and some mountain ranges (Ward and Jackson, 2000). The Little Salmon Lake area contains some of the highest peaks within the Lewes Plateau with elevations in the Big and Little Salmon ranges exceeding 1700 m. The northeast portion of the project area is adjacent to the Glenlyon Range, an extension of the Pelly Mountains.

The east-west corridor being studied consists of the Little Salmon Lake valley and the western portion of the Magundy River valley, where the river flows into Little Salmon Lake. The lake level is approximately 600 m above sea level (a.s.l.) and local relief is greater than 1000 m. The lake sits in a glacially scoured and over-deepened U-shaped valley that is approximately 33 km long and 2 km wide. The Magundy River valley consists of an approximately 2-km-wide floodplain bounded by the Glenlyon Range to the north and the Big Salmon Range to the south (Fig. 2).

CLIMATE AND PERMAFROST

The study 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. Table 1 shows climate data for the nearest meteorological stations in Faro and Carmacks. Climate in the Little Salmon Lake valley may be influenced by cold air drainage into the valley floor in winter as described by Burn (1994) for other Yukon valleys.

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

Table 1. *Environment Canada mean climate data for the period 1971 to 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	--- not available ---		

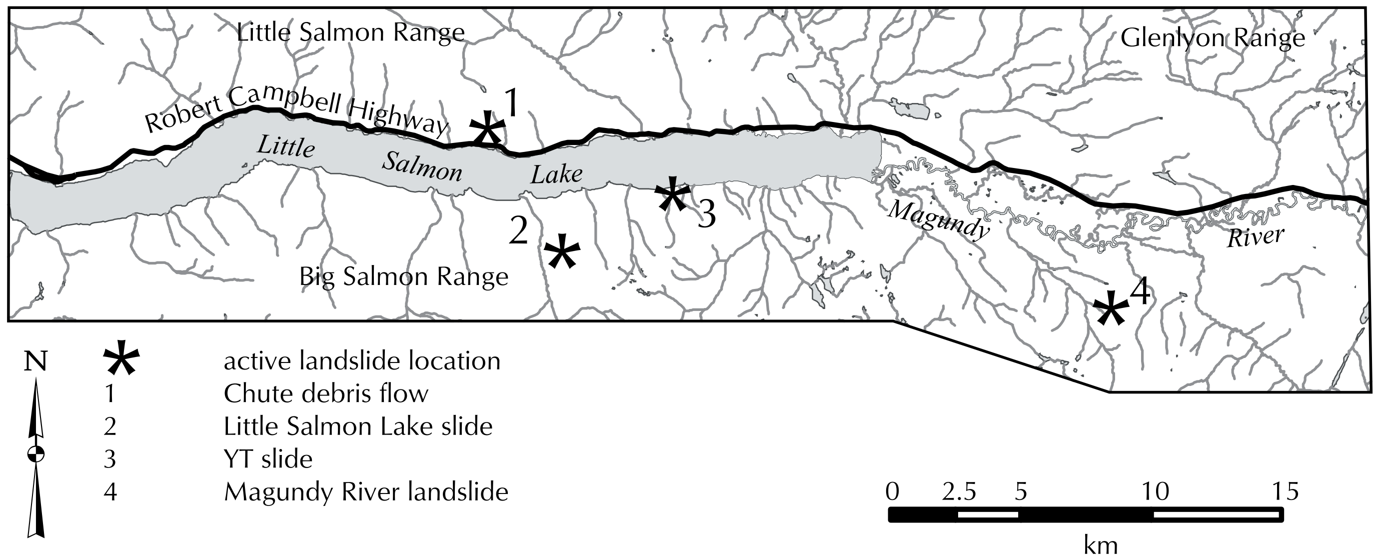

Figure 2. *Map of the project area showing key physiographic features and active landslide locations.*

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.

BEDROCK GEOLOGY

The bedrock geology in the Little Salmon Lake area is complex, and includes displaced North American strata (Cassiar Terrane), pericratonic terrane (Yukon-Tanana Terrane), accreted terrane (Slide Mountain Terrane) and post-accretion strata. Reconnaissance geology was carried out by Campbell (1967). The area has since been re-interpreted and mapped at a larger scale as summarized by Colpron et al. (2003).

The western half of the project area is underlain by the Snowcap assemblage of the Yukon-Tanana Terrane. It is composed of Carboniferous volcanic arc successions, associated subvolcanic plutonic suites and pre-Mississippian metasedimentary basement rocks. This assemblage has been metamorphosed and intensely deformed. The area east of Little Salmon Lake is underlain by the Cambrian to Devonian Cassiar Terrane. The Cassiar Terrane consists of a lower phyllite-dominated unit and an overlying marble unit. The Slide Mountain Terrane, consisting of an obducted volcanic arc sequence, is present at the east end of Little Salmon Lake between the Cassiar and Yukon-Tanana terranes. Post-accretion strata include a Cretaceous pluton near Little Salmon Lake's western margin and the Glenlyon Batholith along the eastern boundary of the project area. Colpron et al. (2003) present details on the bedrock geology.

SURFICIAL GEOLOGY

Regional Quaternary mapping studies in the Glenlyon map area (105L) were undertaken by Ward and Jackson (2000). Their study built upon earlier reconnaissance mapping by Campbell (1967).

In the Glenlyon area, there is evidence for at least three glaciations: pre-Reid (Early Pleistocene), Reid (Middle Pleistocene) and McConnell (Late Wisconsinan). Exposures of pre-Reid and Reid glacial deposits are rare or absent in the project area. Sediments and landforms of the McConnell glaciation, which took place 26 000 to 10 000 years BP (Bond and Plouffe, 2003), are well preserved.

The Selwyn lobe of the Cordilleran Ice Sheet covered the Little Salmon Lake area during the McConnell event. This lobe, which originated in the Selwyn Mountains, flowed in a general northwest direction. Topography had a strong influence on controlling ice flow and many nunataks existed. Local alpine glaciers in the study area did not contribute significantly to the regional glaciation. Interpretation of stratigraphy reveals that during glacial advance, there was significant oscillation at the ice front. Glacial retreat was very rapid, with ice sheet down-wasting and stagnation. Variable thicknesses of glacial 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 common in the valley bottom. Ward and Jackson (2000) present further details on surficial geology.

METHODOLOGY

The methodology being employed for this project is summarized as follows:

- Investigate published background information on permafrost- and non-permafrost-related landslide processes, periglacial processes, regional geology, and landslide assessment techniques;
- Perform a remote analysis of the project area by completing a terrain evaluation;
- Perform field-based ground-truthing in the project area. This includes assessment of the veracity of the results of the terrain evaluation exercise and further characterization of active landslide areas;
- Complete lab tests on soil samples collected during the field season to determine their engineering characteristics; and
- Investigate methods of modeling the natural processes at each landslide.

The terrain analysis was completed in the winter/spring of 2004 and is summarized below. Field work took place throughout the summer of 2004. Traverses by foot, boat and canoe were made to assess the terrain and investigate landslide locations. One day was also spent on a helicopter reconnaissance of the area. Lab testing and the modelling of natural processes are now being undertaken and are briefly described at the end of this paper (see Future Work).

TERRAIN ANALYSIS

In order to identify the landslide processes in the project area, terrain analyses were undertaken. The evaluation was completed following the Terrain Classification System for British Columbia (Howes and Kenk, 1988).

Numerous sources of background data were used in the evaluation, and a brief discussion of the background data follows. All the background geospatial data was compiled in a geographic information system (GIS) database.

The majority of the project area was covered by recent (1998) airphotos at a 1:50 000 scale. Select 1989 airphotos (1:40 000) and airphotos from the 1940s (~1:40 000) as well as LandSat 7 imagery and digital geospatial data were used. Elevation models, slope models and aspect models were all used in the terrain evaluation.

Geological data at various scales were compiled. Regional reconnaissance mapping by Campbell (1967) produced both bedrock and surficial maps at a scale of 1:250 000. The bedrock geology was refined with 1:50 000-scale maps from a geological compilation for the Glenlyon area (NTS 105L) by Colpron et al. (2003). Ward and Jackson (2000) published a report and maps (1:100 000) of the surficial geology of the Glenlyon map area.

Background information on landslide processes in permafrost is summarized by Tart (1996), Lewkowicz (1988) and Harris (1987). However, there are very few case studies presented in these compilations dealing with slopes in the Yukon. Huscroft et al. (2004) summarize many of the landslide case studies in the southern Yukon. Ward et al. (1992) provide an excellent case study of the Surprise Rapids landslide along the South MacMillan River.

Using the data listed above, a 1:50 000-scale map was produced (R. Lyle, unpublished). The map shows the geographic distribution of terrain polygons and geomorphologic features. Identification of polygons is based on interpreted surficial material, texture, surface expression and geological processes. The evaluation revealed more than 35 areas of active or past landslide activity. The majority of the landslides were recognized based on their morphological signature and are mostly relict.

ACTIVE LANDSLIDES

Four areas of prominent and active mass wasting were found in the Little Salmon Lake area. These four distinct landslide processes are summarized in this section. Observations include permafrost conditions, geological materials and slope conditions. Figure 2 shows the locations of the four slide areas.

This is possibly the first published report of any of the landslides described below. The names given for the landslides are as used in the field and have not been formally adopted.

CHUTE DEBRIS FLOW

The Chute is a debris-flow area situated above the Robert Campbell Highway on the north side of Little Salmon Lake. A photo of the overall debris-flow track is presented in Figure 3. There is no evidence for the presence of permafrost in the area of this debris flow. The last major flow event at the Chute likely took place in 1996 (based on discussions with local residents).

Observations from the flow are grouped into initiation, transport and fan zones. The initiation zone headscarp is 1.5 to 2 m high at an angle of 35-45°. The surficial sediment is a polymicton containing angular clasts of local bedrock with sizes ranging from pebble to 25 cm or more. Finer material consists of sand and some silt. The sediments are wet to saturated with a couple of small streams flowing over and through them. One such stream was traced up slope to a spring. The headscarp is located at a slight break in slope with the area above having a gentler slope (15-25°). Morphological evidence from airphoto interpretation shows a relict talus cone in the source area.

The transport zone is an 8- to 15-m-wide track free of vegetation (Fig. 4). A small stream cuts through the middle creating a gully up to 2.5 m deep through the flow mass. The slope is moderately steep (25-35°) in this zone. The transport zone, which extends from the headscarp to the fan, is approximately 450 m long. The sediments, as shown in the stream-cut sections, are nearly identical to those seen in the headscarp. No structure or sediment gradation trends were observed.

The fan zone begins with a slope change to a gentle to moderate slope (10 to 20°). A large pile of woody debris, including logs over 35 cm in diameter, marks this area. Below this, the cleared track disappears and there are few fallen trees. Large amounts of angular clasts of quartzite, marble and schist are found in accumulations on the upslope side of trees. As the flow reached the cleared electrical transmission right-of-way, it downcut a channel up to 2 m deep in the existing sediments. The channel continues until it reaches a highway cut of the Robert Campbell Highway, where the ditch filled with sediment.

Figure 3. *Chute debris-flow track, looking north. The Robert Campbell Highway is the clearing at bottom of the photo.*

Figure 4. *Chute debris-flow track, looking north.*

The soil structure and texture provides evidence that the Chute represents a reoccurring debris-flow track. Trees in the transport and fan zones show multiple phases of damage that support this theory.

LITTLE SALMON LAKE SLIDE

The Little Salmon Lake (LSL) slide (Fig. 5) sits high above the south shore of the lake. It is a deep-seated rotational/ translational slide in psammitic schist and quartzite bedrock. The date of initiation is unknown; however, there has been significant movement in the six years since the last airphoto coverage.

The LSL slide headscarp sits at an elevation of about 1150 m a.s.l. or about 550 m above Little Salmon Lake. The maximum width of rupture surface is approximately 350 m and the total length is estimated to be greater than 800 m. The slide occurs on a moderate slope (15° to 25°). The height of the headscarp varies from 10 to 50 m.

Field time at this slide was limited due to poor accessibility and safety concerns. Numerous small rock falls occurred during inspection of the headscarp.

Figure 5. *Little Salmon Lake slide, looking south*

Dimensions of fallen blocks ranged from a few centimetres to 2 m.

The following key observations were noted. There is an older, relict landslide near the summit of the mountain immediately above the LSL slide. Bedrock in the area consists of the early Mississippian and older (?) Snowcap assemblage (Colpron et al., 2003). Foliated quartzite and psammitic schist were found at the LSL slide. Graphitic layering was found in talus at the base of the headscarp.

YT SLIDE

The YT slide was discovered during the work carried out on this project. The slide appears to be very similar to the multiple retrogressive slumps described by Morgenstern and McRoberts (1974) and Dyke (2004). However, the soil types and their distribution vary greatly from those described for the Mackenzie Valley. Multiple retrogressive slumps are characterized by 'a series of arcuate, concave-toward-the-toe blocks that step upward toward the headscarp' (Lewkowicz, 1988; Fig. 6).

The landslide is described as being primarily rotational, with a slope that bulges out into the lake. Material at the lake margin is very ice-rich (Fig. 7) and is quickly thermally eroded by the lake water. Undercutting of the ice-rich material that has bulged 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 large frozen block (estimated to be 1200 m^3) was seen toppling from the slope in August, 2004. The block remained coherent and rolled out into the lake approximately 40 m before disappearing.

The stratigraphy is well exposed in the numerous scarps and extensional cracks at the YT slide. The entire north-facing slope is underlain by varying thicknesses of permafrost and is covered with up to 0.5 m of organic material, a colluvial veneer, and a thin layer of volcanic ash (White River tephra). The stratigraphy exposed in the scarps is as follows: the top scarp exposes the edge of a very gently sloping till plain (over 12 m thick). This is underlain by a >20-m-thick ice-contact sequence of dense glaciofluvial (apparently unfrozen) (Fig. 8) and frozen glaciolacustrine sediments containing millimetre-scale ice lenses. Underlying the McConnell ice-proximal sequence is a monolithological 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 (Fig. 9). Clasts found in the diamicton are composed of poorly sorted, angular

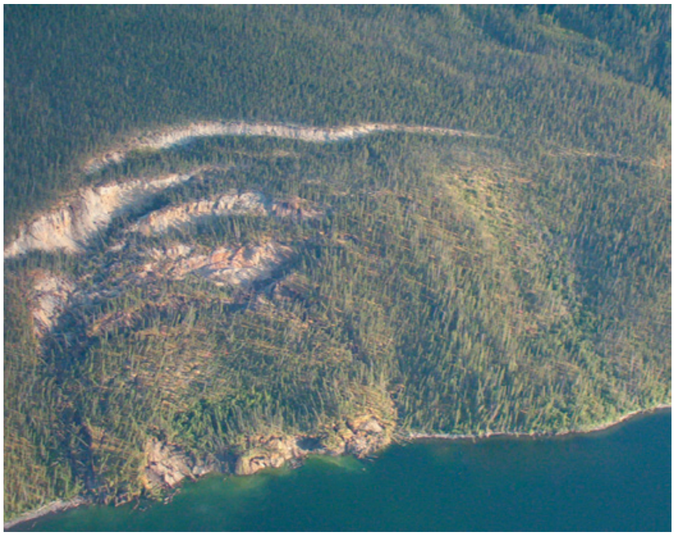

Figure 6. *YT slide, looking south. Little Salmon Lake is at bottom of photo. The top scarp is 350 m wide.*

Figure 7. *Massive ice exposure in the lower levels of the YT slide.*

Figure 8. *Glaciofluvial sediments in the main scarp of the YT slide.*

Figure 9. *Massive ice in the old colluvial unit, YT slide.*

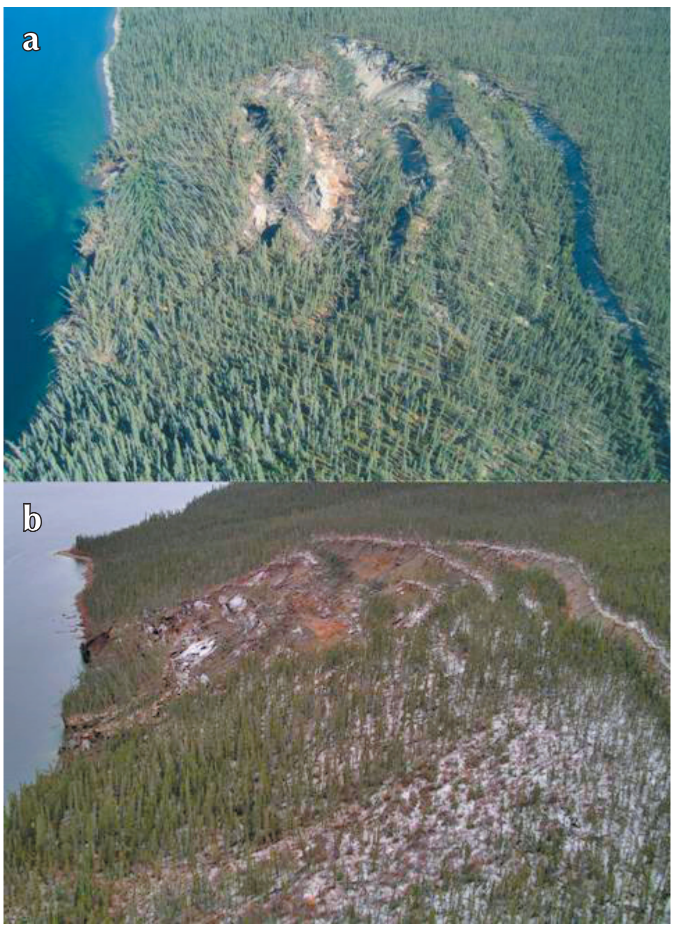

Figure 10. *Photos showing the movement over nearly a two-month period at the YT slide:* ***(a)*** *August 4, 2004 and* ***(b)*** *September 28, 2004 (photo by Panya Lipovsky).*

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% ice by volume, much of which is in massive ice lenses (Fig. 7).

A comparison of photographs taken in late September 2004 (P. Lipovsky, pers. comm., 2004) with others taken in August, 2004 (Fig. 10) shows there has been constant and considerable movement of the lowest sliding block of the YT slide during this time.

MAGUNDY RIVER LANDSLIDE

The Magundy River landslide (Fig. 11) was first noted by Jeff Bond (pers. comm., 2003) of the Yukon Geological Survey in 1998. Based on discussions with local residents, the slide was probably initiated in 1996. It is a large, complex example of a landslide similar to the bimodal flows described by McRoberts and Morgenstern (1974), and Ward et al. (1992). The term bimodal flow is used as the slide can be divided into two distinct morphological sectors: 1) an upper headscarp, where ablation and erosion release sediment, which slides, flows or falls down into 2) a gently inclined mudflow lobe, where it flows away (Harris, 1987).

The Magundy River landslide is set on a gentle to moderate (10-20°) north-facing slope approximately 10 km east of Little Salmon Lake. Material from a source area (approximately 350 by 400 m) has flowed down the slope. The debris flow has eroded two substantial channels, each having a distinct depositional area (Fig. 11).

There are two main surficial geology units found in the slide area. A colluvial layer of variable thickness overlies a denser glacial diamicton (till). Both units have a similar texture and contain large boulders. The colluvium consists of reworked till, and is very thin or absent in some areas. Multiple organic horizons separated by diamicton layers were found in one active scarp, suggesting previous debris-flow activity. In addition, buried upright tree stumps were found in an upper scarp.

The source area is rimmed by active and inactive scarps. The east-facing inactive scarps primarily sit at the angle of repose of till, and vegetation is slowly taking hold. During the summer of 2004, three areas of active thaw slumping were found. The active areas are located on south- and west-facing slopes. Scarps in these areas are very steep – from 40° to near-vertical – commonly with an overhanging organic mat. The active scarps range from approximately 5 to 10 m in height (Fig. 12). Massive ice

Figure 11. *Overview of the Magundy River landslide, looking south. The top scarp is approximately 350 m wide.*

was found in all of the active areas, and presumably provides the necessary moisture to form the debris flows. Close-up study of the ice structure was hampered by problems associated with thaw and accessibility.

The debris has flowed in two general directions. The first is into a small valley to the northwest. Here a small lake was completely infilled with sediment. The second flow path is to the northeast; this channel opened up between 1998 and 2002, and takes the debris to the Magundy River floodplain, nearly 400 m below the top of the slide. A large fan has developed on the floodplain and a small creek has moved limited amounts of sediment to the Magundy River. Currently, the dominant flow is to the northeast, while the northwest valley is mostly inactive.

The debris flows contain the complete range of grain sizes found in the till and colluvial materials, as well as the organic mat and trees that have fallen to the base of the active scarps. Most of the flow witnessed was very viscous. However, very wet, rapid surging flows were noted one day at a single location. Primary controls on the debris-flow rheology likely include moisture availability, clay content and clay mineralogy. Examples of viscous flow paths are shown in Figure 13. Flow and texture patterns on the most viscous flows were very similar to some lava flows with ropey and popcorn textures.

Figure 12. *Active scarp, Magundy River landslide, looking northeast.*

Figure 13. ***(a)*** *Active and* ***(b)*** *inactive flow paths, Magundy River landslide.*

SUMMARY AND DISCUSSION

Four separate landslide processes at work in the Little Salmon Lake area have been described. Three of these processes involve unconsolidated sediments, with two of these involving the degradation of permafrost. The fourth slide is a deep rotational failure in bedrock. A variety of factors thought to be contributing to instability are summarized below.

The Chute, though dormant, appears to be a reoccurring debris-flow track. It is likely activated by extreme moisture conditions such as rapid snowmelt and/or intense rainfall. Seismic activity may also play a role in initiating the flow.

The Little Salmon Lake slide is an active rock slide that illustrates the potential of failure in rock slopes at a moderate angle. Factors such as rock structure and melting ground-ice may be important controls. Graphitic layering in the schist was the weakest rock structure found in the brief investigation of this slide.

The active YT and Magundy River slides involve the degradation of permafrost, though each in their own distinctive manner. It is difficult to compare these slides to slides reported elsewhere. Lewkowicz (1988) concludes that field studies of rapid mass movements in permafrost are problematic due to their episodic and spatially discontinuous nature.

Bimodal flows, such as the Magundy River slide, are most commonly associated with fine-grained (lacustrine) sediments and thermokarst terrain in valley bottom settings (Ward et al., 1992). Furthermore, multiple retrogressive slumps are generally associated with lacustrine sediments (Dyke, 2004). No evidence of widespread lacustrine sediments has been found in any exposures at slides studied in this project. It is possible that there are glaciolacustrine clays at depth in the YT slide. Nevertheless, the Little Salmon Lake area shows that landslide processes in permafrost need not include any widespread lacustrine deposits.

The impact of climate change on permafrost slopes is an issue drawing significant attention today (Dyke and Brooks, 2000; Huscroft et al., 2004). Triggering events for many of the landslides noted are likely in response to changing climatic conditions. Huscroft et al. (2004, p. 118) concluded that determining how global atmospheric conditions will impact site-specific slope stability requires "transcendence of multiple levels of uncertainty and complexity" and will therefore be qualitative. However, the impact of changing climate must be looked at when completing any slope stability assessment in warming discontinuous permafrost.

Dynamic loading is widely regarded as an important triggering factor in landslides throughout the world. However, there is very little published research on the impacts of seismicity on slopes containing permafrost. Dynamic loading may be an important factor in the Little Salmon Lake area as numerous small earthquakes have been recorded in the area. As recently as 2002, an earthquake was recorded approximately 70 km west of the Magundy River slide with a Richter magnitude of 4.6*. Davis (2001) discusses the spectacular effects of earthquakes in discontinuous permafrost in Alaska including one bimodal flow. However, the seismic loading in the discussed region of Alaska is much higher than at Little Salmon Lake.

This project illustrates the difficulty of locating and predicting landslide risk in areas of discontinuous permafrost. At present, all human activity and infrastructure in the project area avoids north-facing slopes that may be susceptible to permafrost degradation. However, hazards not related to permafrost, such as the Chute slide, are equally as important and must be considered prior to any development in the region.

FUTURE WORK

The laboratory testing of samples obtained in the summer of 2004 is on-going. Lab testing for the project includes basic soil index testing: grain-size analysis, Atterberg limits and moisture content, as well as clay mineralogy determination using x-ray diffraction.

An investigation of methods of modeling the natural processes at each landslide is underway. One such natural process is climatic triggering events. Daily climate data from Environment Canada will be used to try to correlate climatic conditions with triggering events. As mentioned previously, seismic loading may play a role in the landslide processes and this will be investigated.

ACKNOWLEDGEMENTS

Results presented in this paper are from field work completed during the summer of 2004. This study is part of an M.Sc.E. thesis of the first author at Queen's University. Funding for the project was provided by the following sources: the Yukon Geological Survey (YGS); Department of Indian Affairs and Northern Development (DIAND) Knowledge and Innovation Fund; a National Science and Engineering Research Council (NSERC) Northern Supplement to R.R. Lyle; a Geomatics for Informed Decisions (GEOIDE) grant to D.J. Hutchinson; and the Northern Scientific Training Program (NSTP).

The field work could not have been completed without the support and assistance of Glenda and Wolfgang Eberlein, the staff at the Drury Creek Highway Maintenance Camp, Peter Lickes at Salmon Lake Adventures, Jason Berkers and Richard Trimble of EBA Engineering, as well as Monique Raitchey and Maurice Colpron at the YGS. Safe and efficient helicopter travel was courtesy of Brian Parsons at TransNorth Helicopters. Dr. Alan Gorman and Robin Harrap at Queen's University have been helpful throughout the project especially in airphoto interpretation and GIS, respectively. Most importantly, the project has been greatly improved by discussions with Crystal Huscroft (Thompson Rivers University), Panya Lipovsky (YGS) and Jeffrey Bond (YGS). Careful review by Jeffrey Bond has enhanced this manuscript, and his time and efforts are very much appreciated.

REFERENCES

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

Burn, C.R., 1994. Permafrost, tectonics, and past and future regional climate change, Yukon and adjacent Northwest Territories. Canadian Journal of Earth Sciences, vol. 31, p. 182-191.

Campbell, R.B., 1967. Reconnaissance Geology of Glenlyon Map-Area, Yukon Territory. Geological Survey of Canada, Memoir 352, 92 p.

Colpron, M., Bond, J.D., Lipovsky, P.S., Gladwin, K., Gordey, S.P., Murphy, D.C., Nelson, J.L., Plouffe, A., Roots, C.F. and Abbott, J.G., 2003. Digital compilation of bedrock geology and till geochemistry, Glenlyon (105 L) and eastern Carmacks (115 I) map areas, Yukon Territory. Geological Survey of Canada, Open File 1561; and Exploration and Geological Services Division, Yukon Region, Indian and Northern Affairs Canada, Open File 2003-7D, CD-ROM.

Davis, N., 2001. Permafrost: A Guide to Frozen Ground in Transition. University of Alaska Press, Anchorage, Alaska, 351 p.

**http://www.pgc.nrcan.gc.ca/seismo/recent/eqmaps.html. Unpublished Geological Survey of Canada data.*

Dyke, L.D., 2004. Stability of Frozen and Thawing Slopes in the Mackenzie Valley, Northwest Territories. *In:* Proceedings of the 57th Canadian Geotechnical Conference, Quebec City, Quebec, Session 1G, p. 31-38.

Dyke, L.D. and 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.

Harris, C., 1987, Mechanisms of mass movement in periglacial environments. *In:* Slope Stability: Geotechnical Engineering and Geomorphology, M.G. Anderson and K.S. Richards (eds.), John Wiley and Sons Ltd., Chichester, UK, p. 531-559.

Heginbottom, J.A., Dubreuil, M.A. and Harker, P.A., 1995. Canada – Permafrost. *In:* National Atlas of Canada, 5th ed., Natural Resources Canada, Ottawa, Plate 2.1: MCR 4177.

Howes, D. and Kenk E., 1988. Terrain Classification System for British Columbia (revised Edition), British Columbia Ministry of Environment, Manual 10, 90 p.

Huscroft, C.A., Lipovsky, P. and Bond, J.D., 2004. Permafrost and landslide activity: Case studies from southwestern Yukon Territory. *In:* Yukon Exploration and Geology 2003, D.S. Emond and L.L. Lewis (eds.), Yukon Geological Survey, p. 107-119.

Lewkowicz, A.G., 1988. Slope Processes. *In:* Advances in Periglacial Geomorphology, M.J. Clark (ed.), John Wiley and Sons Ltd., Chichester, UK, p. 325-360.

McRoberts, E.C. and Morgenstern, N.R., 1974. Stability of Slopes in Frozen Soil, Mackenzie Valley, N.W.T. Canadian Geotechnical Journal, vol. 11, p. 554-573.

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

Ward, B. and Jackson, L.E. Jr., 2000. Surficial Geology of the Glenlyon Map Area, Yukon Territory. Geological Survey of Canada, Bulletin 559, 60 p.

Ward, B., Jackson, L.E. Jr. and Savigny, K.W., 1992. Evolution of Surprise Rapids landslide, Yukon Territory. Geological Survey of Canada, Paper 90-18, 25 p.