A reconnaissance inventory of permafrost-related landslides in the Pelly River watershed, central Yukon

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ABSTRACT

A reconnaissance inventory of permafrost-related landslides in the Pelly River watershed was conducted in 2006, largely in response to local community concerns regarding the potential impacts of climate change on slope stability and possible effects on water quality. Using aerial photograph analysis, satellite imagery, and visual inspection from a fixed-wing aircraft, over 100 permafrost-related slides were located near the Pelly and MacMillan rivers and various tributaries. Basic geomorphic characteristics were determined for many of the failures based on analysis of remote sensing data, and reviews of existing literature and surficial geology maps. Most of the landslides identified were small active-layer detachments and retrogressive thaw failures. Several large failures also illustrate important characteristics associated with permafrost-related landslides, including their source-area setting, triggers, high mobility, the longevity of their activity and their ability to impact very large areas. The nature and distribution of the identified failures highlights a number of implications for land-use in central Yukon and emphasizes the need for enhanced methods of permafrost detection and regional mapping in the Territory.

RÉSUMÉ

Un inventaire de reconnaissance des glissements de terrain associés au pergélisol dans le bassin versant de la rivière Pelly a été entrepris pendant l'été de 2006. Ces travaux ont été effectués en réponse à des inquiétudes de la communauté quant aux incidences possibles du changement climatique sur la stabilité des talus et les effets possibles sur la qualité de l'eau de la rivière Pelly. D'après l'analyse de photographies aériennes et d'images satellites ainsi qu'une inspection visuelle par avion, plus de 100 glissements associés au pergélisol ont été repérés près des rivières Pelly et MacMillan ainsi que de divers tributaires. Les caractéristiques géomorphologiques de base d'un grand nombre de ces glissements ont été déterminées d'après des analyses de données de télédétection et des examens de la documentation et des cartes existantes sur la géologie des dépôts meubles. La plupart des glissements de terrain identifiés étaient de petits décollements de la couche active et effondrements régressifs dus au dégel. Plusieurs grands effondrements illustrent en outre d'importantes caractéristiques associées aux glissements de terrain reliés au pergélisol dont le cadre de l'aire d'origine, les mécanismes de déclenchement, la durée d'activité et l'aptitude à perturber de très grandes étendues. La nature et la distribution des effondrements identifiés mettent en lumière un certain nombre d'incidences pour l'utilisation des terres dans la région du centre du Yukon et soulignent la nécessité de méthodes améliorées de détection et de cartographie à l'échelle régionale du pergélisol dans le territoire.

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INTRODUCTION

Several recent studies have documented the occurrence of permafrost-related landslides in south and central Yukon (Ward *et al*., 1992; Huscroft *et al*., 2004; Lipovsky *et al*., 2006; Lyle, 2006) and northern British Columbia (Geertsema *et al*., 2006; Geertsema and Pojar, 2006). These highlight the fact that such failures are common in discontinuous permafrost regions. Findings from these studies demonstrate that permafrost-related landslides commonly occur in, or proximal to, valley bottoms, suggesting that they are a source of significant sediment into watercourses. Recent increased turbidity in the Pelly River has raised community concerns about possible new sediment sources in the Pelly River watershed. In addition, there are growing concerns about the potential impacts of projected climate change on slope stability in permafrost terrain and the implications this may have for land use in the region.

In light of these facts, a reconnaissance inventory of permafrost-related landslides in the Pelly River watershed was completed during the summer of 2006 to determine the general nature and distribution of these types of failures. This paper describes the results of this work and reviews a number of examples that illustrate some key characteristics of permafrost-related landslides that are important to consider for land-use planning and development in central Yukon.

BACKGROUND

Permafrost contributes to slope stability through its influence on soil drainage, soil moisture and soil strength (McRoberts and Morgenstern, 1974; Dyke, 2004). Ice-rich permafrost, in particular, leads to highly unstable conditions if it thaws. In flat terrain, thermokarst develops when large amounts of ice thaws, allowing the remaining soil particles to consolidate and the ground surface to settle. On slopes, thawing of ice-rich permafrost releases excess water, creating very high pore pressures and highly unstable conditions.

There are two main types of permafrost-related landslides that occur in permafrost terrain. Retrogressive thaw slumps (also known as bimodal flows) are triggered by the initial exposure of massive ground ice, leading to melting and the growth of a steep frozen headscarp. Initial exposure can result from many types of disturbances including river erosion, forest fires, small slope failures, groundwater piping, or even tree blow-downs and animal burrows (McRoberts and Morgenstern, 1974; Lyle, 2006). Ice exposed in the headscarp rapidly and steadily thaws, and the headscarp can retreat up to tens of metres per year (Lyle, 2006). The headscarp eventually stabilizes when either all the ice has thawed, or the headscarp becomes insulated by debris that has fallen from above (Mackay, 1966). The thawing soil is continually transported away in highly mobile debris flows that can travel several kilometres down very gentle slopes to valley bottoms or directly into watercourses. Retrogressive thaw slumps can remain active for decades and can expand in size quite rapidly, as will be shown in the discussion.

Active-layer detachments occur entirely within the active layer, the shallow surface layer of soil (generally < 2 m thick) that thaws and refreezes annually. The permafrost table (the upper surface of permafrost located at the base of the active layer) is impermeable and restricts drainage due to its high ice content. Active-layer detachments are commonly triggered in large numbers by events that lead to rapid increases in active-layer depth, rapid thawing of ice-rich permafrost, and/or sustained soil saturation, such as intense rainstorms or forest fires (Lekowicz and Harris, 2005). They occur on shallow slopes as low as 6° (McRoberts and Morgenstern, 1974) and commonly have a long narrow shape (Lewkowicz and Harris, 2006). While generally relatively small in size (5-20 m wide by up to 200 m long), they commonly occur in large numbers on individual slopes (Lipovsky *et al*., 2006). Where they reach valley bottoms, they can also contribute a large amount of sediment into watercourses.

STUDY AREA SETTING

The areas investigated for this study included slopes immediately adjacent to the Pelly, MacMillan and South MacMillan rivers and selected major tributaries. The study area was generally limited to within 5 km of the aforementioned rivers, within the region bounded by the communities of Pelly Crossing to the west and Ross River to the south, the North Canol Road to the east, and the South MacMillan River to the north (Fig. 1).

PHYSIOGRAPHY

The study area largely lies within the Yukon Plateaus physiographic region (comprised of the Klondike, Stewart and Lewes Plateaus, MacMillan Highland and Willow and Ross Lowlands). The Tintina Trench dissects the plateau areas in a northwesterly trending direction. Upland areas in the eastern part of the study area include the Selwyn Mountains (Hess and Simpson Ranges) north of the

Tintina Trench, and the Kaska Mountains (Pelly Mountains) to the south (Fig. 1).

The Pelly River flows for over 500 km, draining nearly 50 000 km^2 (Water Survey of Canada[1]). Its headwaters lie in the southern Selwyn Mountains. For nearly half of its length, it flows northwesterly along the Tintina Trench, draining the Pelly Mountains to the south and the Anvil Range to the north. It then cuts westward across the Lewes Plateau, just above its confluence with the MacMillan River about 40 km east of Pelly Crossing, and empties into the Yukon River approximately 40 km west of the same community.

The MacMillan River drains approximately 14 000 km^2 (Water Survey of Canada) with the headwaters of the North and South MacMillan rivers located in the central Selwyn Mountains. The South MacMillan and MacMillan rivers flow westward for approximately 200 km through the Yukon Plateaus, draining the Wilkinson Range to the south, and the Russell Range and Clark Hills to the north.

Bedrock geology on the northeast side of the Tintina Trench is generally dominated by Selwyn Basin sedimentary formations of shales, cherts and sandstones that formed off the margin of ancient North America prior to 320 million years ago. Southwest of the trench, a wide variety of younger lithologies from the Yukon-Tanana and Cassiar terranes are found (Gordey and Makepeace, 2003).

Earthquakes have been recorded in the study area, mostly south of the Tintina Trench; the largest (since 1953) occurred 20 km west of Ross River in November, 2002 with a magnitude of 4.6. Only one other earthquake greater than magnitude 4 has been recorded throughout the study area since 1953 (Geological Survey of Canada records).

GLACIAL HISTORY AND SURFICIAL GEOLOGY

Surficial geology throughout most of the study area is primarily a product of the Late Pleistocene McConnell glaciation. This glaciation occurred between 26 000 and 10 000 years ago, covering south and eastern Yukon and reaching its western limit near the confluence of the Pelly and MacMillan rivers (Ward and Jackson, 1993a). During

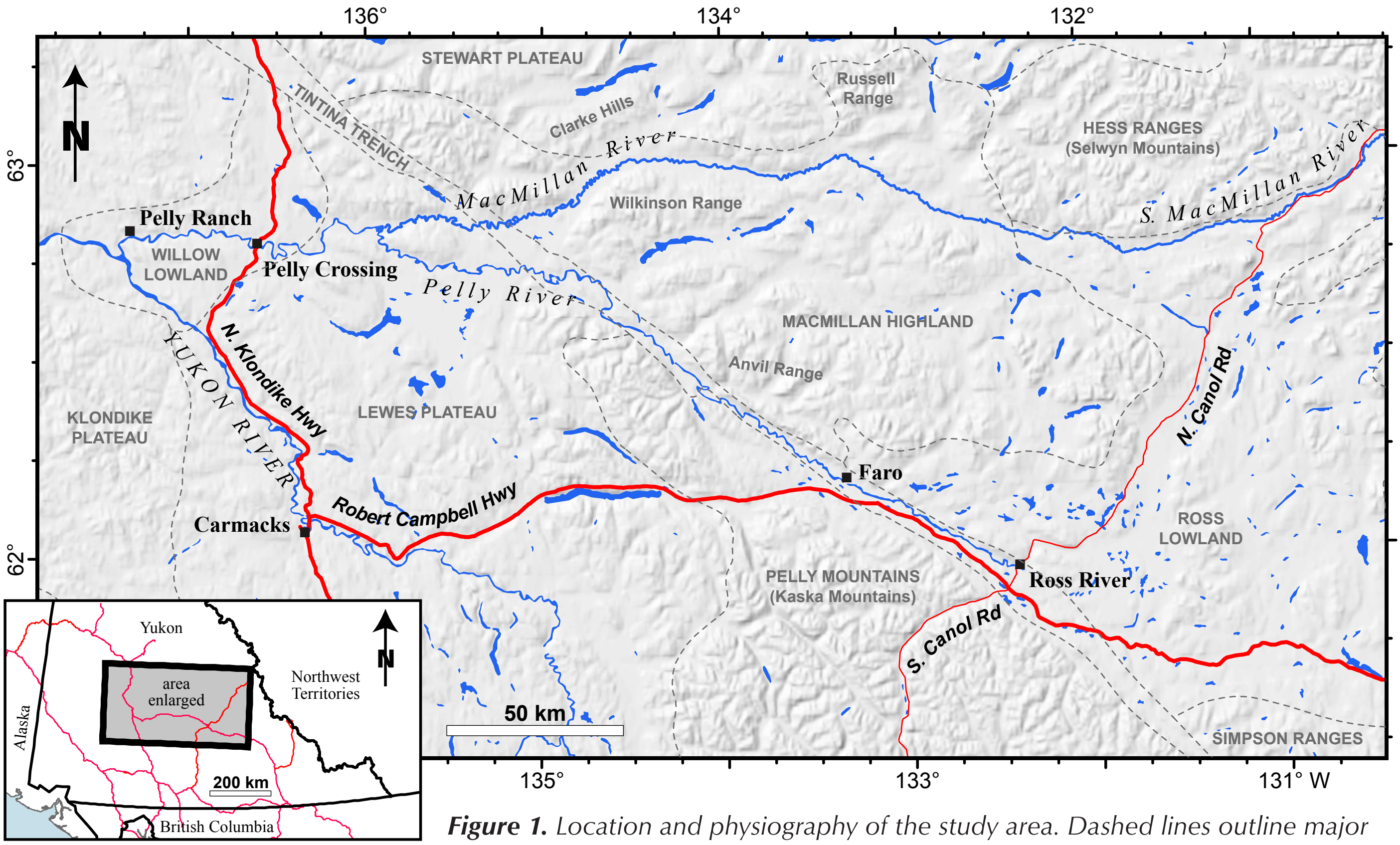

Figure 1. *Location and physiography of the study area. Dashed lines outline major physiographic regions. Inset map shows major roads in southern Yukon and regional location of study area.*

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[1] *http//www.wsc.ec.gc.ca/hydat/H2O/index_e.cfm*

the maximum extent of the McConnell glaciation, the Selwyn lobe of the Cordilleran Ice Sheet flowed out of the Selwyn Mountains in a westerly and northwesterly direction following the main valley of the Tintina Trench (Jackson *et al.*, 1991; Ward and Jackson, 2000). Middle Pleistocene Reid glacial deposits are found west of the McConnell glacial limit near the mouth of the MacMillan River, down to the confluence of the Pelly and Yukon rivers (Jackson, 1997).

As a result of these glaciations, extensive blankets of silt-rich till, derived from the sedimentary Selwyn Basin lithologies, were deposited in low-lying valleys and on most slopes in the study area. Streamlined landforms are common in plateau areas, indicating westerly and northwesterly ice-flow directions, following the general trend of major valleys. As glacial retreat occurred, coarse-grained glaciofluvial meltwater materials were deposited in large meltwater channels and outwash plains that occupied the main valleys. During glacial retreat, large glacial lakes were dammed by ice in many of the main valleys and thick deposits of fine-grained glaciolacustrine material are now found along the lower reaches of the MacMillan River (Ward and Jackson, 1993a,b), and along the Pelly River between Ross River and about 50 km downstream of Faro (Jackson, 1993c).

PERMAFROST

Most of the study region is located in the extensive discontinuous permafrost zone, although the area south of the Pelly River where it flows through the Tintina Trench is located at the northern margin of the sporadic discontinuous permafrost zone (Heginbottom *et al.*, 1995). Local permafrost distribution and ground ice-content is controlled by a number of site-specific factors including aspect, surficial material texture, slope position, elevation, drainage conditions, vegetation cover, microclimate, duration and depth of snow cover, and past and present hydrogeological conditions (Rampton *et al.*, 1983). In general, ice-rich permafrost is most commonly found within silt-rich and organic-rich surficial materials on north-facing slopes and in valley bottoms.

A variety of permafrost features occur throughout the study area, as shown on regional-scale surficial geology maps (Jackson, 1993a,b,c,d,e and 1997; Jackson *et al.*, 1993a,b; Ward and Jackson, 1993a,b,c). Thermokarst commonly occurs in fine-grained glaciolacustrine terraces and in organic-rich alluvial and morainal materials along the MacMillan and Pelly rivers. Pingos also occur in a few locations within till, glaciofluvial and alluvial materials.

CLIMATE

The study area experiences a subarctic continental climate with long cold winters and short warm summers. Environment Canada online climate normals for the period 1971-2000 were used to summarize the following climate characteristics for climate stations at Pelly Ranch (62°49'N, 137°22'W, elevation 454 m, located 35 km west of Pelly Crossing) and Faro (62°12'N, 133°22'W, elevation 717 m) (Fig. 1). Mean annual temperatures are -3.9°C and -2.2°C, respectively. Mean annual precipitation is 310 mm and 316 mm, respectively, and two-thirds of this falls in the summer months.

Monthly temperature and precipitation normals indicate very similar conditions and seasonal variations for the two climate stations (Fig. 2). Mean daily temperatures at Pelly Ranch range between -27.5°C (daily minimum -32.8°C) in January to +15.5°C in July (daily maximum 22.6°C). July is the wettest month, receiving a mean monthly precipitation of up to 59 mm in Faro and 55 mm at Pelly Ranch. Snow depths reported for the two climate stations are up to 33 cm (at the end of each month), and snow cover generally persists between October and April.

HYDROLOGY

Table 1 shows average daily discharges for the Pelly and MacMillan rivers at various times throughout the year (data from Water Survey of Canada online archives). Peak flows are dominated by snowmelt and generally occur in early June, with discharge rates gradually diminishing into the winter. Local spikes in the discharge occur in response to intense rainfall events.

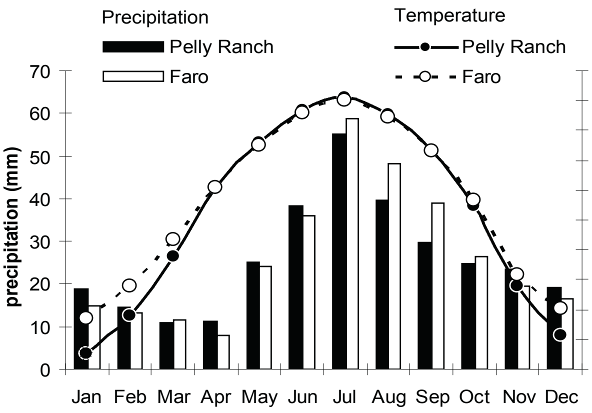

Figure 2. *Monthly temperature and precipitation normals (1971-2000) for Pelly Ranch and Faro (from Environment Canada online climate data).*

Table 1. *Range of average daily flows for the Pelly and MacMillan rivers throughout the year. (Data from Water Survey of Canada online archives).*

	Mean peak discharge (m^3/s) (early June)	Peak discharge range (m^3/s) (early June)	Discharge range (m^3/s) (Nov. 1)	Period of record
Pelly River				
~100 km east of Ross River (below Fortin Creek)	350	275–600	20–75	1986–1994
near Faro (below Vangorda Creek)	850	500–1800	50–150	1972–2005
at Pelly Crossing	1600	700–4300	80–500	1951–2005
South MacMillan River at North Canol Road	85	55–190	5–15	1974–1996
MacMillan River near confluence with Pelly River	600	250–1100	40–95	1984–1996

LANDSLIDE INVENTORY

SURVEY METHODOLOGY

A variety of sources were used to locate over 150 landslides within the corridor surrounding the Pelly, Ross, MacMillan and South MacMillan rivers. Eleven 1:100 000-scale surficial geology maps by Jackson (1993a,b,c,d,e and 1997), Jackson *et al*. (1993a,b) and Ward and Jackson (1993a,b,c) provide nearly complete coverage of the entire study area. Thirty-four large landslides were located on these maps, which were interpreted primarily in the early 1980s. A detailed review of the most recent (1988-2004) 1:40 000-scale aerial photographs available along the corridor was used to classify these landslides, and locate 67 smaller and more recent failures. Finally, a fixed-wing reconnaissance survey was flown on July 11, 2006 up the Pelly River to Ross River, north to the South MacMillan, and back down the MacMillan River to Pelly Crossing. Forty-three additional landslides were identified during this fixed-wing aerial survey. Both previously described and newly identified landslides were documented with digital photographs and GPS locations.

The landslides were described and classified as completely as possible to determine type, relative size, area and setting by analysis of digital photographs, aerial photographs, satellite imagery (GoogleEarth[2]), 1:50 000-scale digital topographic maps and 1:100 000-scale surficial geology maps. The ages of selected large landslides were also constrained from historical aerial photographs.

RESULTS

Permafrost-related landslides were classified as active-layer detachments or retrogressive thaw slumps, and where the type could not be confirmed, they were classified as ‘probable’ based on setting and/or morphology (Table 2). Relative sizes were assigned to each landslide: those wider than 500 m or having travel distances or runouts longer than 500 m were considered large; those less than about 100 m wide or 100 m long were considered small; and all remaining intermediate sizes were considered medium. The distribution of the identified landslides is shown in Figure 3.

Table 2. *Numbers and relative sizes of landslides identified in 2006 survey.*

Landslide type	Total	Large	Medium	Small
Permafrost-related landslides	114	32	48	34
active-layer detachments	47	10	18	19
probable active-layer detachments	5	1	1	3
retrogressive thaw slump	52	12	27	13
probable retrogressive thaw slump	11	8	2	1
Non-permafrost-related landslides	36	7	18	11
slumps along cutbanks	19	2	9	8
probable slumps along cutbanks	3		2	1
debris flows/slides in alpine areas	9		7	2
rock slumps	5	5		

Active-layer detachments

At least 47 active-layer detachments were identified throughout the study area. These occurred primarily on north-facing slopes covered by till veneers and blankets, but also within colluvial

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[2] *earth.google.com/*

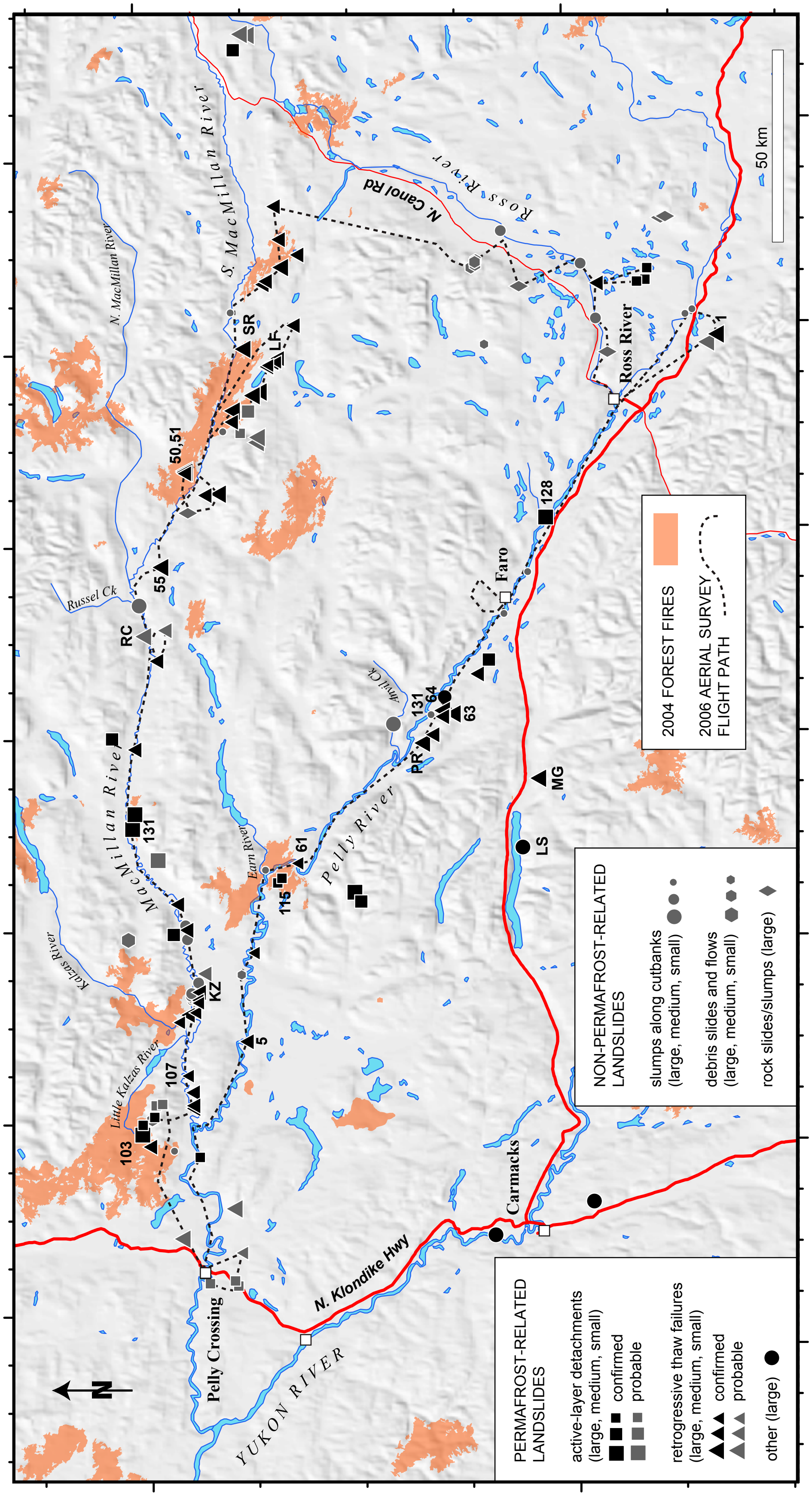

Figure 3. Location and classification of landslides described in the inventory. Numbers and letters refer to specific landslides mentioned in the text.

Figure 4. *A large active-layer detachment was initiated on a gentle north-facing slope near the mouth of Excell Creek following forest fires in 2004. The failure is estimated to be approximately 300 m long. Photo taken in July, 2006.*

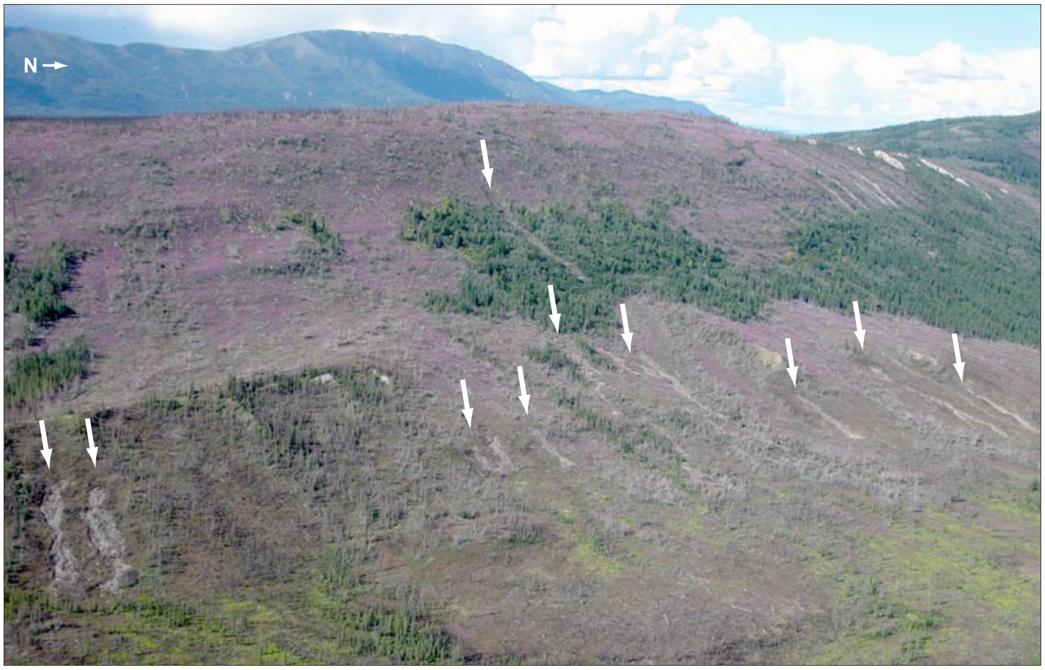

Figure 5. *Multiple small active-layer detachments (highlighted by arrows) were initiated by forest fires in 2004. The slides occur in colluviated till on northeast-facing slopes having angles between 13-16°. Photo taken in July, 2006.*

materials. Only 10 large active-layer detachments were identified. Two of these appeared to have occurred very recently based on the sharply defined headscarps and lack of vegetation regeneration; these were likely initiated by forest fires that burned in 2004 near Faro (Fig. 4 and #128 in Fig. 3), and in the headwaters of the Little Kalzas River near the mouth of the MacMillan River (#103 in Fig. 3). At least 10 small active-layer detachments also appear to have been triggered by the 2004 forest fires on northeast-facing slopes adjacent to the Pelly River, approximately 2 km upstream from the mouth of Earn River (Fig. 5 and #115 in Fig. 3).

Most of the remaining active-layer detachments identified appeared as old overgrown scars. Seven large active-layer detachments occurred prior to 1949 on a north-facing slope south of the MacMillan River, just upstream from the mouth of Moose River (#131 in Fig. 3). The scars from these failures cover nearly 50% of an approximately 2-km-wide stretch of this slope, suggesting that this mode of failure is probably a significant slope-forming process in the area.

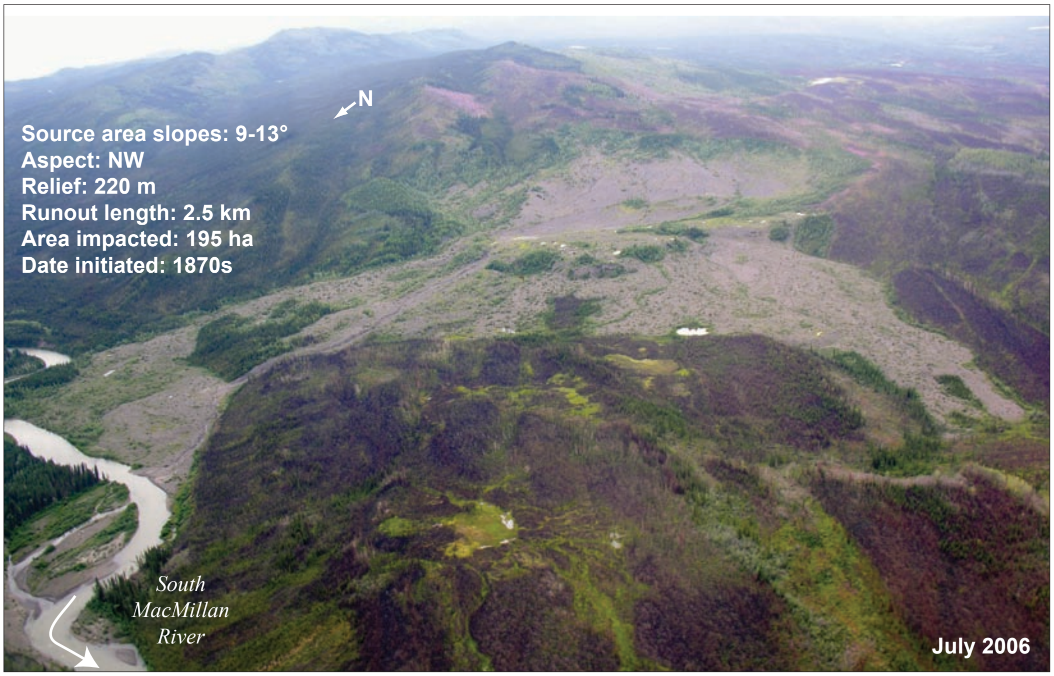

Figure 6. *The Surprise Rapids landslide covers nearly 2 km*^{2}*. Debris has traveled up to 2.5 km from the source area, which is approximately 700 m wide. View is to the southeast.*

Retrogressive thaw slumps

Twelve large retrogressive thaw failures were identified throughout the study area on slopes mantled by till blankets or veneers. Nine of these were located along the South MacMillan River on northwest- to northeast-facing slopes. One large failure suspected to be permafrost-related was located on a south-facing slope further down the MacMillan River, just downstream from the mouth of Russel Creek (RC in Fig. 3). Three large inactive failures occurred along the Pelly River upstream from the mouth of Anvil Creek (#63, 64 and PR in Fig. 3), and one occurred upstream of Ross River and south of Bruce Lake (#1 in Fig. 3). Nearly all of the large failures were initiated decades ago, prior to 1980 and as far back as 1870, with the exception of the two south-facing failures (Clarke Peak and Russel Creek), which occurred after 1988. At least five of the large slumps have been active within the last five years (#50, 51, 55, RC and SR in Fig. 3) and two of these (#50 and 51) appear to have been reactivated by forest fires in 2004.

The Surprise Rapids landslide (Fig. 6 and SR in Fig. 3), located 90 km north of Ross River on the South MacMillan River, is one of the largest retrogressive thaw slumps documented in central Yukon, impacting an area of almost 2 km^2. It was likely triggered by a forest fire in the 1870s, and initiated from gentle source slopes (9-13°) mantled by a blanket of clay-rich till with a high ice content (Ward *et al.*, 1992). The failure has remained active since it was initiated, and the highest levels of activity have coincided with a period in the 1940s when record early summer temperatures occurred in central Yukon (Ward *et al.*, 1992). The aerial survey in the summer of 2006 revealed that the thaw failure had not perceptively retrogressed since 1992 despite a forest fire adjacent to the eastern flank of its headscarp in 2004.

The Russel Creek landslide (Fig. 7) is a large probable retrogressive thaw failure located 150 km east of Pelly Crossing. It is unique due to its southerly aspect, which is uncommon for permafrost-related failures in central Yukon. The classification of the landslide as a probable retrogressive thaw failure is based on the bowl-shaped headscarp geometry and the mobility of the flows. The failure initiated on a gentle (13°) slope and was likely triggered by a 1989 forest fire. Surficial materials on the slope have been mapped as a till veneer.

Twenty-seven medium-sized retrogressive thaw failures were identified. Almost all of these occurred along near the South MacMillan (e.g., Fig. 8) and MacMillan rivers, while only four occurred along the Pelly River (e.g., Fig. 9). Most of the slides occurred in till-blanket or veneer materials, although at least seven occurred in glaciolacustrine deposits and four occurred in glaciofluvial complex deposits. Twenty-one of these medium-sized failures initiated in or prior to the 1980s. Six retrogressive thaw failures initiated since 1990; these are located

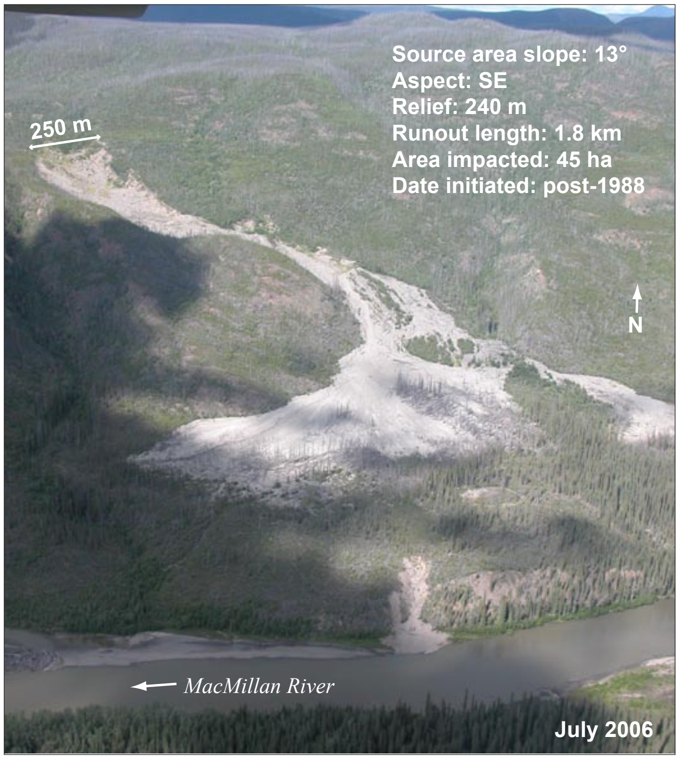

Figure 7. *The Russel Creek landslide covers an area of approximately 0.45 km^2. It has a runout length of approximately 1.8 km and the deposits are over 1 km wide at the toe.*

entirely along the South MacMillan River and have remained active to the present day. One of these appears to have been triggered by forest fires in 2004 (#51 in Fig. 3).

One very active medium-sized failure is located on the MacMillan River, 15 km upstream from the mouth of the Kalzas River (KZ in Fig. 3). Debris flows issuing from this retrogressive thaw slump have formed a tongue that has blocked three quarters of the river's width for at least the past three years. As shown in Figure 10, the headscarp has retreated about 150 m since 1989, averaging nearly 10 m/yr for the last 17 years. Rapid retreat rates are common for this type of failure, and rates as high as 40 m/yr have been documented for a retrogressive thaw failure near Little Salmon Lake (MG in Fig. 3) (Lyle, 2006).

Thirteen small retrogressive thaw slumps were identified within the study area. Seven of these occurred in the lower reaches of the watershed, immediately along the banks of the Pelly and MacMillan rivers and primarily within glaciolacustrine surficial materials. The remaining six occurred in the upper watershed on till-blanketed slopes above the South MacMillan River. Five of the small slumps were active in 2006 and appear to have been

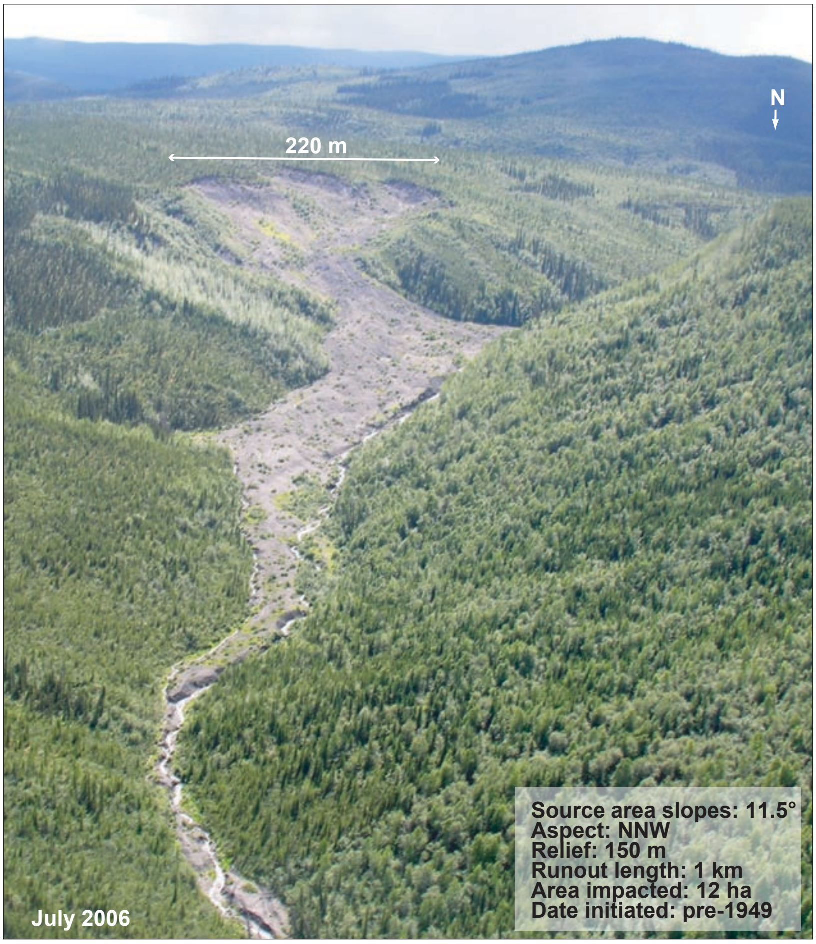

Figure 8. *This large retrogressive thaw slump (#55 in Fig. 3) is located 4 km up a tributary to the South MacMillan River. It was initiated prior to 1949 on a gentle north-facing slope that is mantled by till. Gradual headscarp retreat has caused ongoing deposition of debris along a 700-m-long segment of the creek. View is to the south.*

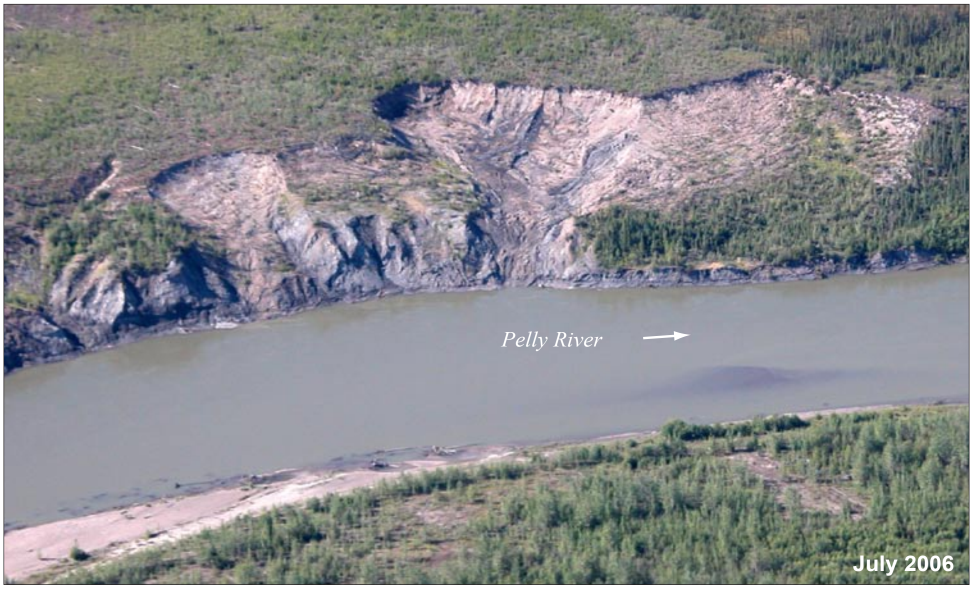

Figure 9. *Oblique aerial photograph of a retrogressive thaw slump (#5 in Fig. 3) that was contributing sediment to the Pelly River in 2006. This landslide has been active and increasing in size since at least 1989. View is to the south. Estimated width of main failure is approximately 200 m.*

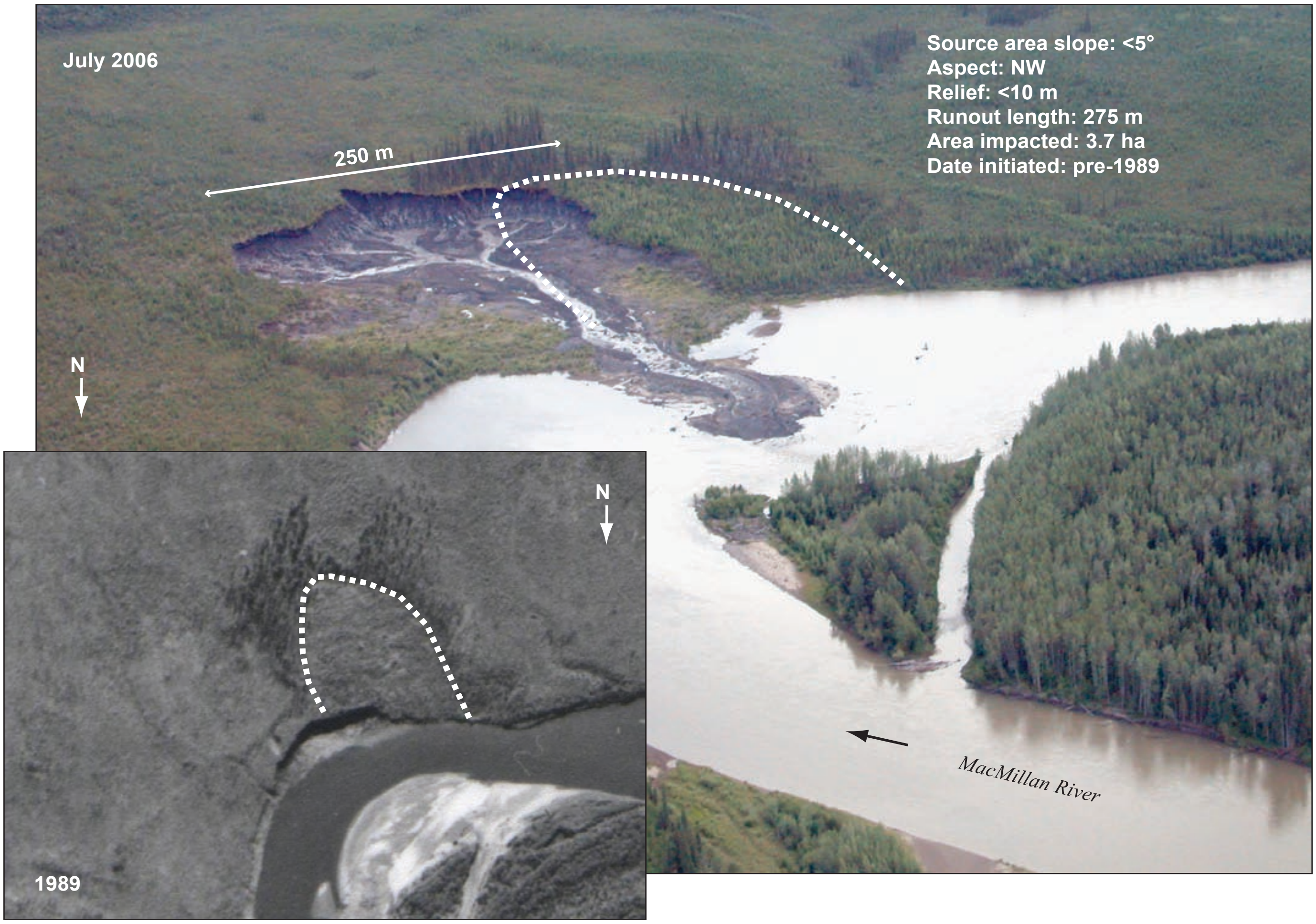

Figure 10. *The Kalzas landslide covered an area of nearly 4 ha and was approximately 250 m wide in 2006. The inset shows the location of the headscarp on a 1989 aerial photograph (National Air Photo Library, A27516-188). The dashed line traces the edge of an older overgrown retrogressive thaw slump.*

initiated in the last ten years. The rest occurred in or before the 1980s.

Surficial materials

The surficial material in which each landslide initiated in was determined from analysis of 1:100 000-scale surficial geology maps (Jackson, 1993a,b,c,d,e and 1997; Jackson *et al.*, 1993a,b; Ward and Jackson, 1993a,b,c). The majority (73%) of the permafrost-related landslides initiated in till blankets and veneers. This is a reflection of the fact that till deposits dominate the surficial geology on most slopes within central Yukon. However, the till in this region is also commonly rich in silt and clay (Lyle, 2006; Ward *et al.*, 1992; Ward and Jackson, 2000), which promotes the growth of ground ice in these materials.

Landslides initiated in glaciolacustrine plain and blanket materials, mapped at the surface, or where glaciolacustrine materials were mapped or interpreted beneath other surface materials, constitute 11% of the permafrost-related failures. These materials were commonly subject to thermokarst processes in the vicinity of the failures.

A total of 9% of the permafrost-related landslides (mostly active-layer detachments and alpine debris flows) occurred in colluvial apron materials; 5% of the landslides initiated in glaciofluvial complexes, plain and delta materials; and less than 2% occurred in organic-rich alluvial materials.

Impacts on water quality

The potential impact of the landslides on water quality in the Pelly and MacMillan River system was subjectively rated based on proximity to a river or stream. Where the debris from the landslide directly reached a river or tributary, it was considered a direct impact. If a landslide occurred on a slope and did not appear to contribute sediment directly to a watercourse, its impact was considered indirect.

Fifty-one landslides were classified as potentially having direct impacts on water quality in the Pelly and MacMillan rivers at some time in the recent past or present. Eight of these are permafrost-related failures that were directly contributing sediment to rivers or their major tributary streams in 2006. All of these failures were retrogressive thaw slumps, of which three are large (#55, Surprise Rapids and Russell Creek), two are medium-sized (#5 and KZ in Fig. 3) and two are small (#61 and 107 in Fig. 3). These medium and large-sized failures are further described in Table 3.

Another large retrogressive thaw slump that is indirectly related to sediment inputs into the Pelly River is shown in Figure 11 (PR in Fig. 3). This failure is known as the Pelly River landslide (Lyle, 2006) and is one of the largest permafrost-related landslides documented in central Yukon. It initiated prior to 1949 on a gentle slope in fine-grained till (Ward and Jackson, 2000), covering an area of approximately 2 km^2. While the landslide itself is not actively contributing sediment to the river, it may have altered local hydrology enough to cause the incision of a new tributary that now empties into the Pelly River.

Table 3. *Characteristics of various large and medium-sized permafrost-related landslides.*

Landslide name	Surficial materials	Date initiated	Source slope (°)	Aspect	Source elevation (m)	Area impacted (ha)	Runout (m)	Deposit width (m)	Relief (m)
Landslides potentially impacting water quality directly in 2006									
#55 (06PR055)	till blanket	pre-1949	11.5	NNW	1050	12	1000	700	150
SR (Surprise Rapids)	till blanket	1870s	9-13	NW	920	170	2100	1700	240
RC (Russel Ck)	till veneer	post-1988	13	SE	880	45.4	1800	1000	240
#5 (06PR005)	glaciofluvial/ glaciolacustrine	pre-1989	10	NE	520	<3	~150	-	10
KZ (Kalzas)	glaciolacustrine	pre-1989	<5	NW	550	3.7	275	-	<10
PR (Pelly River)	till veneer	pre-1949	17	NE	1100	200	4100	1500	450
Other major landslides not directly impacting water quality in 2006									
LF (Laforce)	till blanket	post-1992	10-14	NE	1060	4.7	370	250	70
#50 (06PR050)	till veneer	1949-1976	18-22	NNW	960	7.4	490	250	90

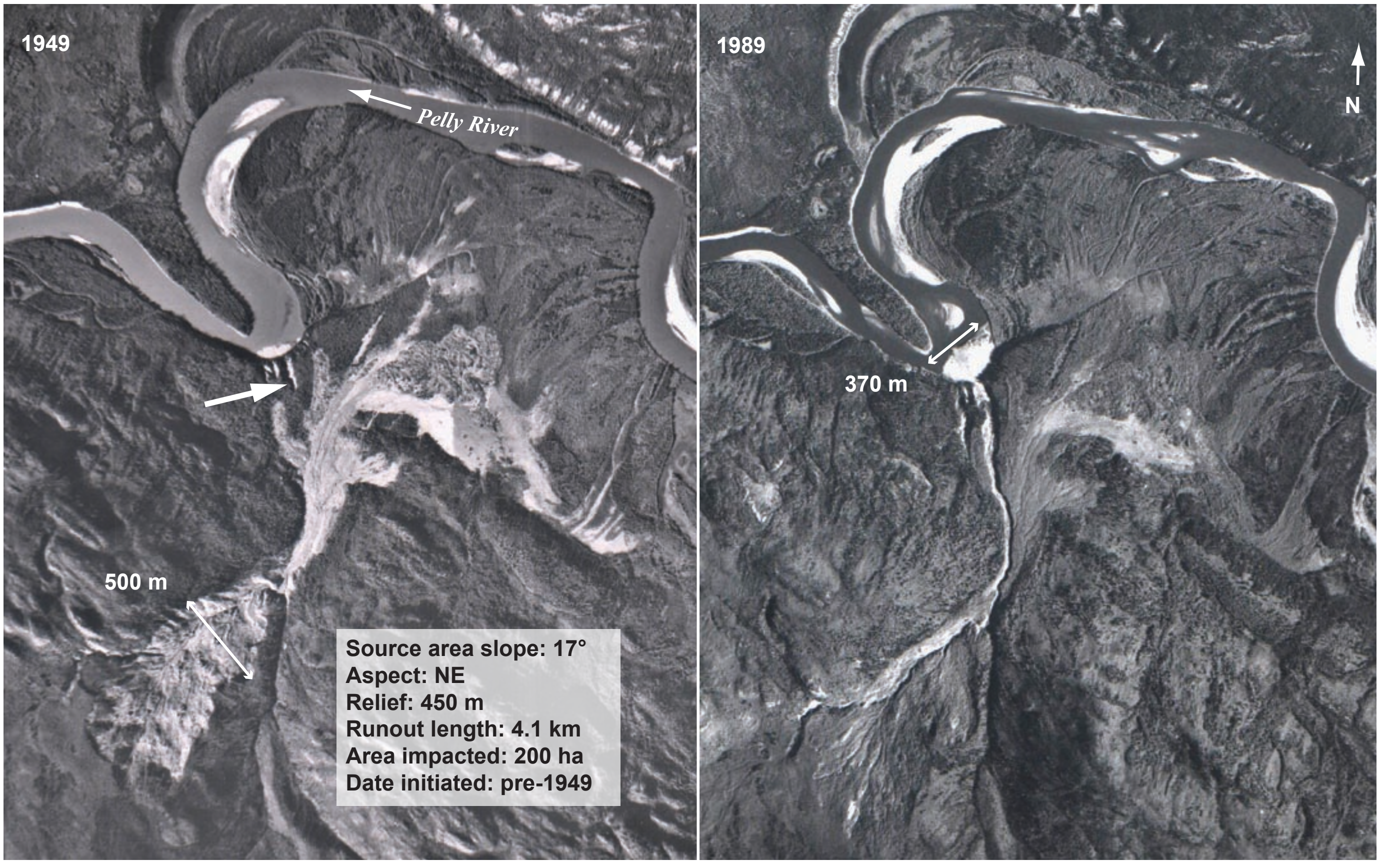

Figure 11. *Comparison of the Pelly River landslide scar in aerial photographs from 1949 (National Air Photo Library, A12182-128) and 1989 (National Air Photo Library, A27516-243). The landslide covered an area of approximately 2 km^2 and its debris traveled over 4 km. The 1989 photo shows a large fan that has grown into the Pelly River due to incision of a new tributary along the western edge of the landslide debris. The large arrow in the left photo shows the extent of the same gully in 1949.*

Ongoing incision of this gully has built a large fan that has constricted the Pelly River on a tight meander bend just upstream from the mouth of Anvil Creek.

DISCUSSION

LANDSLIDE TRIGGERS

Permafrost-related landslides are triggered by disturbances that cause the active layer to become saturated or ground-ice to thaw. Direct exposure of ice to the atmosphere or water will lead to rapid thawing. Alteration of runoff and groundwater flow can also cause thermal erosion or the build up of high pore pressure. The most common disturbances to permafrost and active-layer hydrology in the study area seem to be forest fires and river erosion, combined with the related influences of local synoptic weather conditions and long-term climate trends.

Seismicity is also a potential landslide trigger, although historical records show that all but two earthquakes recorded in the area since 1953 have had magnitudes less than 4. In addition, most epicentres are concentrated south of the Tintina Trench, so it is unlikely that seismicity is a major triggering factor in the study area.

Forest fires dramatically alter surface thermal and hydrological conditions during and immediately following the fire, leading to rapid increases in active-layer depth and changes in soil moisture regimes (Burn, 1998; Yoshikawa *et al.*, 2002; Lipovsky *et al.*, 2006). At least sixteen of the failures identified in the study area were likely triggered or re-activated by forest fires that occurred in 2004. Most of these were small active-layer detachment slides, although the initiation of several older large retrogressive thaw slumps was also coincident with the timing of earlier forest fires. McCoy and Burn (2005) have estimated that the maximum annual burned area may increase by greater than 300% by 2069 in central Yukon. The frequency of failures triggered by forest fires in the region can therefore also be expected to increase during this time.

Ten small to medium-sized retrogressive thaw failures occurred on river banks, primarily on outside meander bends in glaciolacustrine materials. These materials commonly underlie glaciofluvial materials in valley bottoms, and such stratigraphy is not always explicitly shown on surficial geology maps due to poor exposure. This highlights the potential limitations of performing landslide-hazard analyses based on surface-material characteristics alone, and emphasizes the need for a detailed understanding of the glacial history of an area when undertaking such evaluations.

CLIMATE CHANGE

While relatively few landslides identified in this study were triggered in the last 15 years, long-term climate warming in the past few centuries has likely played a role in initiating and promoting the ongoing growth of many of the largest permafrost-related landslides in the region. Lyle (2006) reported long-term climate change as a potential contributing factor in the initiation of two large permafrost-related landslides near Little Salmon Lake (MG and LS in Fig. 3). Ward *et al.* (1992) related warmer summers in the 1940s to a long period of increased activity at the Surprise Rapids landslide due to earlier melting of winter snowpack and faster seasonal thawing of frozen ground.

The potential effects of temperature and precipitation increases on slope stability as projected for southern Yukon in the next 50 years were discussed by Huscroft *et al.* (2004). Climate is intricately linked to a variety of factors that influence the frequency of common landslide triggers, including forest-fire frequency and severity, river-flow levels, bank-erosion rates and extreme synoptic events such as intense rainfall and snowmelt events. It is also strongly linked to many factors that control the distribution of permafrost, including the duration and depth of seasonal snow cover, summer and winter air temperatures, soil moisture, vegetation and microclimate effects.

Where undisturbed, permafrost is very slow to respond to air temperatures due to the fact that it is buffered by the active-layer soil, organic materials and snow cover. However, gradual warming of permafrost has been documented in central Alaska and northern Canada (Osterkamp and Romanovsky, 1999; Smith *et al.*, 2005). Burn (1998) estimated that it would take on the order of a century for permafrost 4-5 m thick in the Takhini River valley to thaw completely under the current climate regime. He also stated that the active layer may increase in thickness more rapidly. Anticipated warming in the next several decades will therefore likely have a more pronounced impact on the frequency and/or magnitude of landslide-triggering events than it will have on the regional distribution and degradation of permafrost (Lewkowicz and Harris, 2005).

WATER QUALITY

It is evident from this survey that permafrost-related landslides have occurred widely throughout the study area for several decades. While a small number of landslides have been initiated in the last 15 years, some of the older ones have remained active for long periods. Following initial failure, most of this ongoing activity is gradual, and very few landslides were directly contributing sediment into the Pelly and MacMillan rivers in 2006. Considering the large size of the study area, and the ongoing amount of sediment inputs from continual bank erosion, it seems unlikely that permafrost-related landslides have contributed enough sediment to cause noticeable impacts to water quality as far downstream as Pelly Crossing.

DEVELOPMENT IMPLICATIONS

As illustrated by the examples presented in this paper, permafrost-related landslides have the potential to impact extremely large areas for decades and they can travel distances up to 5 km down slope. The majority of the permafrost-related landslides identified in this study occurred on gentle north-facing slopes in ice-rich till or along north-facing river banks. However, one large failure, suspected to be permafrost-related, occurred on a southeast-facing slope in the past two decades. Development in the region, and elsewhere throughout south and central Yukon, should therefore avoid or mitigate any disruptions to local thermal and hydrological conditions in these settings. Geotechnical studies that characterize the permafrost distribution, ice-content, and surficial geology stratigraphy and history should also be performed to characterize not only the proposed development site, but also slopes several kilometres upslope and downslope of the site.

FUTURE WORK

Establishing the surficial geology stratigraphy and confirming the presence of permafrost in the initiation zones of the larger landslides documented in this study would be useful for defining the specific settings that permafrost-related failures occur in, and for providing more specific development implications. Monitoring ground temperatures at certain sites would also allow improved modeling of potential permafrost degradation in the future. As better methods of permafrost detection are developed and more detailed permafrost mapping and modeling is performed for central Yukon, refinement of landslide-susceptibility mapping techniques for discontinuous permafrost terrain will become greatly improved.

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