Active-layer detachments following the summer 2004 forest fires near Dawson City, Yukon

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ABSTRACT

Numerous active-layer detachments occurred in watersheds surrounding Dawson City following forest fires that burned the area during the summer of 2004. The distribution of these shallow landslides was mapped in the Mickey Creek, Steele Creek and Fifty Mile Creek watersheds. Selected slope failures were surveyed in detail to describe their geometry and geomorphological settings in order to investigate the mechanisms of failure, and to assess the effects of the forest fires on local permafrost conditions. The failures generally initiated on moderate convex slopes at shallow depths (< 65 cm) in silty colluvium; frost tables were close to 1 m in depth. Most active-layer detachments were on the order of 5-20 m wide and 10-100 m long and occurred on slopes with a variety of aspects; however, the detachments occurred only where permafrost was present. In some cases, they developed on gentle slopes (as low as 10°) and traveled several hundred metres, depositing sediment directly into creeks, or across access trails. Their cumulative effects may significantly impact sediment transport within the watersheds. Potential concerns for fish habitat and implications for placer mining water quality regulations have consequently been raised.

RÉSUMÉ

Des décollements répandus de la couche active se sont produits dans un grand nombre de bassins versants des environs de Dawson City suite aux incendies forestiers qui ont ravagé la région pendant l'été de 2004. Plusieurs décollements dans les bassins versants des ruisseaux Mickey, Steele et Fifty Mile ont été étudiés afin d'en décrire la géométrie et les cadres morphologiques, pour déterminer les mécanismes de glissement et pour évaluer les effets des incendies forestiers sur l'état du pergélisol local. Les glissements s'amorcent généralement à des faibles profondeurs (< 65 cm) sur des talus convexes dans des colluvions limoneuses; la limite du pergélisol se trouvait à une profondeur d'environ 1 m. La plupart des décollements présentaient une largeur de 5 à 20 m sur une longueur de 10 à 100 m et étaient développés sur des pentes d'orientations variables. Cependant, les décollements se retrouvent seulement là où l'on a identifié du pergélisol. Dans certains cas, les décollements se sont produits sur des pentes très douces (d'aussi peu que 10°) et il y a eu glissement sur plusieurs centaines de mètres tel que des sédiments se sont déposés directement dans les ruisseaux et en travers des sentiers d'accès. Leurs effets cumulés pourraient avoir une incidence importante sur le transport de sédiments dans les basins versants. Des préoccupations pour l'habitat du poisson et les incidences possibles en matière de réglementation de la qualité de l'eau destinée à l'exploitation minière des placers ont en conséquence été soulevées.

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INTRODUCTION

BACKGROUND AND PURPOSE

Extensive forest fires burned in the Dawson City area from late-June to mid-September, 2004 (Fig. 1). Numerous active-layer detachment failures subsequently developed in the burnt areas during the summers of 2004 and 2005. Investigations in three watersheds near Dawson City revealed that more than 70 detachments occurred on slopes and tributaries adjacent to a 10-km-reach of Mickey Creek, 40 detachments on slopes adjacent to a 4-km reach of Steele Creek, and a further 28 detachments in the lower 12 km of the Fifty Mile Creek watershed.

Active-layer detachments are defined as slope failures “in which the thawed or thawing portion of the active layer detaches from the underlying frozen material” (van Everdingen, 1998). They are shallow landslides which generally involve an initial sliding movement that may be transformed into, or followed by, flow of the thawed debris. Events which cause rapid thickening of the active layer, such as forest fires and hot and/or wet weather, commonly trigger active-layer detachments (Dyke, 2004; Lewkowicz, 1992; Lewkowicz and Harris, 2005a). Many factors influence the occurrence of detachment failures, including depth of the active layer, meteorological conditions, soil moisture conditions, slope form and steepness, aspect, surficial materials and vegetation cover.

Active-layer detachments have been well documented in the Mackenzie Valley, Northwest Territories (e.g., McRoberts and Morgenstern, 1974; Aylsworth *et al.*, 2000; Dyke, 2004; Lewkowicz and Harris, 2005b), in southwest Yukon (e.g., Hugenholtz, 2000; Huscroft *et al.*, 2004) and in the Canadian Arctic Archipelago (e.g., Stangl *et al.*, 1982; Lewkowicz, 1992; Lewkowicz and Harris, 2005b), but never in unglaciated subarctic regions of Canada. Investigations were therefore conducted in the Mickey Creek, Steele Creek and Fifty Mile Creek watersheds to document the geomorphological controls on the detachments, in order to elucidate active-layer detachment failure mechanisms. The immediate effects of forest fires on local permafrost conditions were assessed, and the role of forest fires in initiating landslides was also examined in this study. In addition, potential environmental and economic implications were identified.

Different methodologies were followed while assessing each of the watersheds. Studies at Mickey and Fifty Mile creeks were reconnaissance in nature, and were undertaken over a nine-day period in July, 2005 by the Yukon Geological Survey (P. Lipovsky and E. Trochim). Studies at Steele Creek were more comprehensive and were undertaken over numerous months by J. Coates and A. Lewkowicz as the basis of a Master of Science thesis (initiated in the fall of 2004); the results from Steele Creek presented in this paper are preliminary.

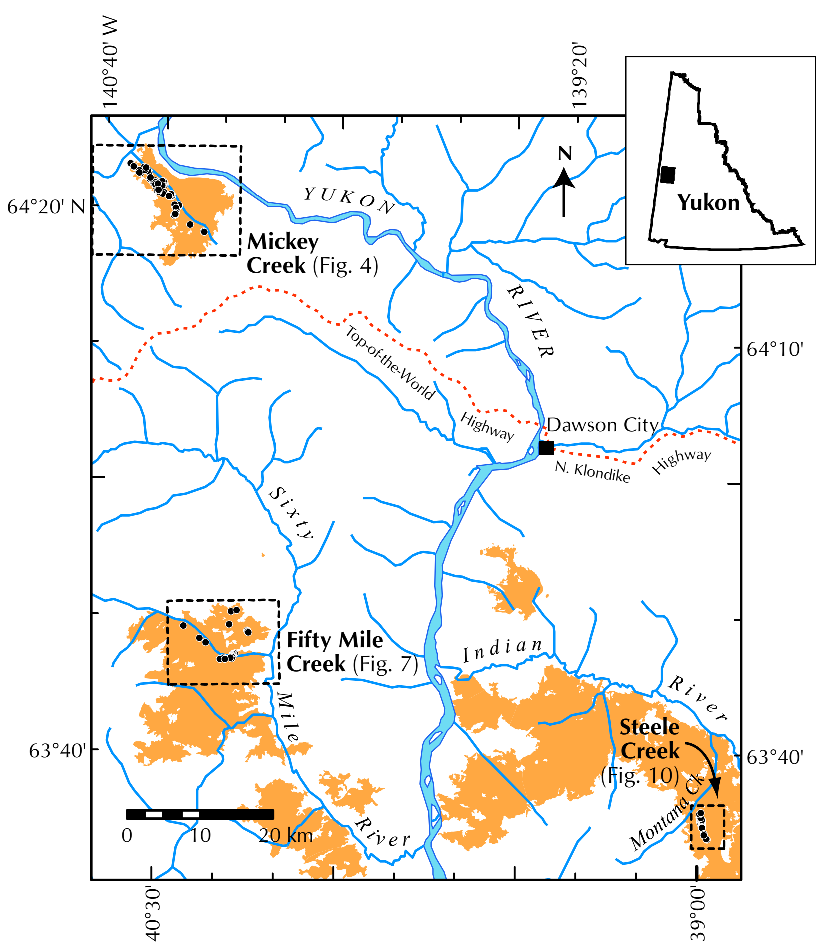

__Figure 1.__ Index map of Dawson area, displaying the locations of Mickey Creek, Fifty Mile Creek and Steele Creek watersheds. Dots represent locations of active-layer detachments. Shaded areas represent those regions burned by forest fires in 2004. Inset map shows location of study area within Yukon.

REGIONAL SETTING

Most of the study area remained unglaciated during the Quaternary period. V-shaped valleys of the rolling Klondike Plateau are dissected by dendritic drainages. Slopes are generally convex in shape and mantled with colluvium derived from local, weathered, Paleozoic quartzite and schist (Duk-Rodkin, 1996; Jackson, 2005). Soils are shallow and are generally capped by deposits of loess.

The Dawson area experiences a subarctic continental climate with long cold winters and short warm summers. Mean annual temperature is -5°C, and mean annual precipitation is 300-500 mm (Smith *et al.*, 2004). Environment Canada (Dawson weather station) daily temperature and precipitation data from May 2004 to November 2005 are shown in Figure 2; climate normals for the summer months are compared with 2004 and 2005 records in Figure 3. Comparison of this data with limited climatic data collected from Steele Creek during the 2004 and 2005 summer months suggests that the Dawson weather station may not necessarily be representative of the surrounding areas. Climatic data

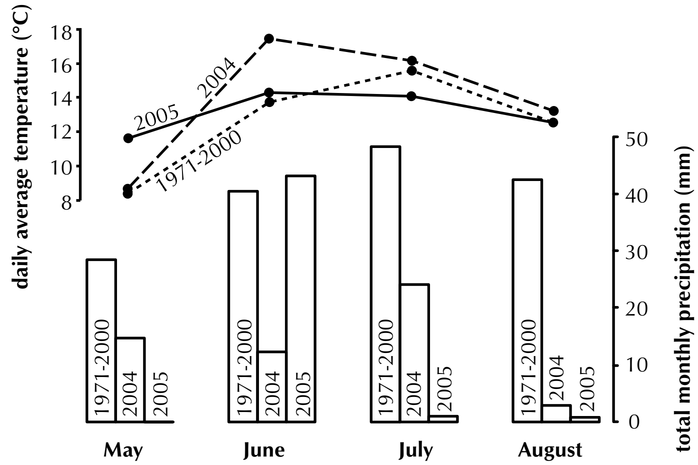

Figure 3. *2004 and 2005 daily average temperature and total monthly precipitation for the months of May to August, compared to 1971-2000 climate normals. (Data from Environment Canada Dawson weather station, 64°3'N, 139°7'W, elevation 370 m.)*

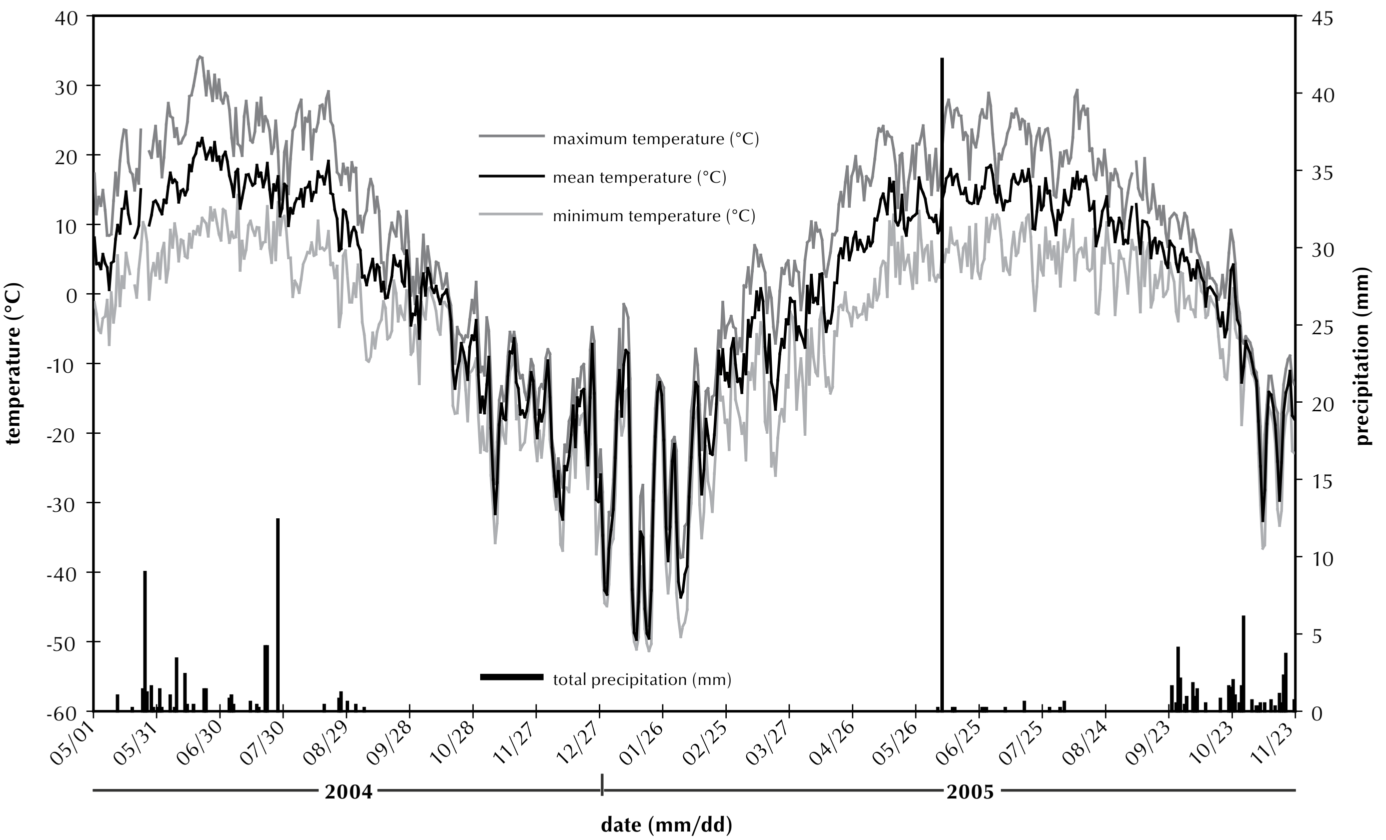

Figure 2. *Daily temperatures (mean, maximum and minimum) and total daily precipitation at Dawson weather station (64°3'N, 139°7'W, elevation 370 m; data from Environment Canada).*

obtained from Steele Creek have shown temperatures to be slightly colder in summer, and precipitation patterns may be entirely different. (Further discussion on Steele Creek climatic data is presented below.)

North-facing slopes in the area are dominated by stands of black spruce, shrubs and thick sphagnum and feather moss. South-facing slopes generally consist of mixed trembling aspen, balsam poplar and paper birch forests (Smith *et al.*, 2004).

The study area is within the extensive discontinuous permafrost zone (Heginbottom *et al.*, 1995). Burn (in Smith *et al.*, 2004) reports permafrost thicknesses of 20-60 m in valley bottoms near Dawson.

North-facing slopes and upland plateaus are perennially frozen, although permafrost can be absent on well drained, south-facing slopes (EBA Engineering Consultants Ltd., 1989a). Massive ice beds and ice wedges are found in valley bottom settings and within loess-rich soil horizons (Smith *et al.*, 2004). Active layers are generally near, or less than, 1 m thick (this study), but can be up to 1.5 m thick in alluvial sediments (EBA Engineering Consultants Ltd., 1983, 1989b).

FIELD OBSERVATIONS

MICKEY CREEK

- **Setting**

The valley of Mickey Creek is located at approximately 64°21'N and 140°30'W (60 km northwest of Dawson City) and spans elevations of 300-1300 m above sea level (asl) (Fig. 4). Mickey Creek is a small, northwesterly flowing tributary that enters the Fortymile River about 6 km upstream from its confluence with the Yukon River. Active placer claims exist along the lower part of the creek, but no commercial mining has been undertaken in the watershed. Steep slopes, averaging between 19° and 27°, flank the southwest side of the valley along the entire 18 km length of the creek. Slopes on the northeast side of the creek are gentler, generally ranging between 11° and 18°. The slopes are blanketed by colluvial deposits, commonly consisting of grey phyllitic bedrock fragments in a matrix of silty loess. On the gentler slopes, surface soil horizons generally contain a higher percentage of loess. In the lower reaches of the creek, Pre-Reid glaciofluvial terraces are found on the upper slopes (Duk-Rodkin, 1996). Probing in mid-July

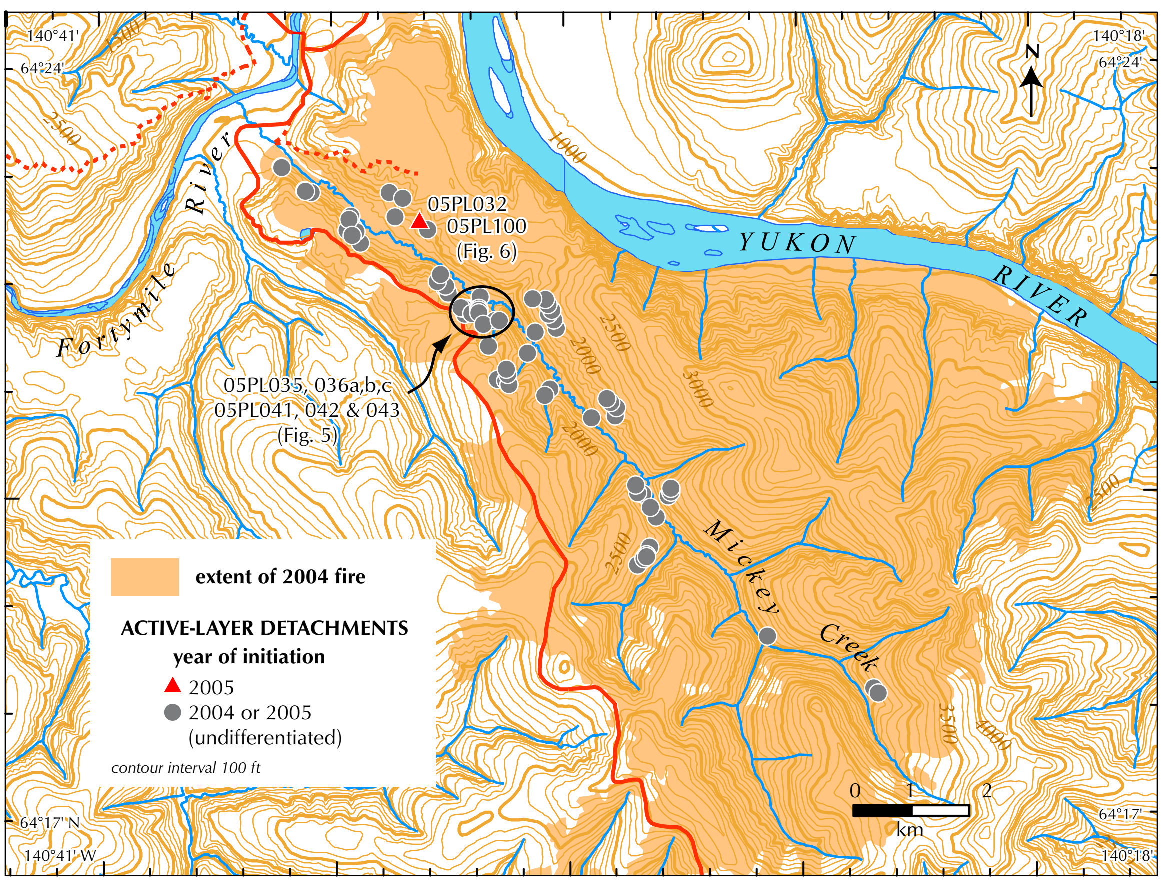

Figure 4. *Location map displaying the extent of burned areas, as well as locations of active-layer detachments surveyed in Mickey Creek watershed.*

revealed frost tables at depths of 57-125 cm at all burned sites visited; on one unburned southwest-facing slope, the frost table was at 75 cm depth.

The forest fire which burned the area was moderately severe. Trees remaining in the area have few branches and little bark left on the trunks, while some trees were charred through. Most of the burned trees are still standing, but some have fallen as blowdown. From 5 to 10% bare mineral soil was exposed at the sites visited, particularly around the base of trees, and in many places at least half of the surface organic mat was removed.

Fires were detected throughout the watershed by MODIS satellite instruments between June 24 and July 17, 2004 (USDA Forest Service, 2005). The fires began burning in the southern portion of the watershed and remained on the upper slopes until June 29. The most extensive amount of burning occurred between June 30 and July 3, during which time the fire spread nearly to the mouth of the creek. After July 4, scattered fires continued to burn until July 17.

Concerns regarding sediment loads in the creek prompted the Department of Fisheries and Oceans to visit the site in 2004; fish surveys were conducted during the summer of 2005. Immediately after the forest fire, they reported that streamflows in Mickey Creek had increased while flows in adjacent unburned watersheds remained very low (A. von Finster, pers. comm., 2005). Periodic water sampling near the mouth of the creek was carried out in an attempt to observe the stream's sediment regime. The results were highly variable and sediment concentrations ranged from clear to very turbid, depending on antecedent weather conditions, time of day and season. Suspended sediment values were only elevated when high streamflows occurred in early summer. Large numbers of juvenile Chinook salmon and slimy sculpin were found near the mouth of the creek, possibly having been displaced from upstream areas by high streamflows and increased sediment loads transported in suspension, or as sand-sized bedload (A. von Finster, pers. comm., 2005). Small numbers of Arctic grayling were also found near the mouth of the creek.

• Field survey methodology

On July 20, 2005, seventy-four slope failures were located in the watershed by hovering above each detachment with a helicopter and recording GPS waypoints. Fifteen of the detachments were visited on the ground on July 13, 20 and 21 (Figure 4).

Reconnaissance-level surveys were conducted at these sites in order to characterize slope steepness, aspect, surficial material type, and basic morphology. At selected failures, a Laser Technology Impulse laser range finder and stadia rod were used to survey slope profiles (accuracy ± 0.1°), detachment shape and failure dimensions (accuracy ± 1 cm). Soil profiles were examined in natural exposures, or pits dug near the headscarps of the detachments, and selected materials were sampled for grain-size analysis. Frost table depths were determined by frost probing. Burn severity was described in the vicinity of the landslide, and digital photographs were taken to document various features of the failures and their surrounding environment.

• Failure settings and morphologies

Approximately two-thirds of all the failures in Mickey Creek occurred on moderately steep, north- to east-facing slopes, in mid- to upper-slope positions. Nearly one-quarter of the detachments reached tributary valley floors, or the main valley floor, thus contributing sediment directly into the watershed's drainage network. In general, the failures occured in three geomorphological settings, as listed below:

1) high-level glaciofluvial terraces, on moderately steep, northeast-facing slopes

Seventeen of the surveyed detachments initiated at, or near the edge of, a narrow (~20-m-wide) Pre-Reid distal glaciofluvial terrace. The terrace is located on the upper, moderately steep, northeast-facing slopes in the lower portion of the watershed. The failures exposed light-coloured gravel which contrasted well with the burned surface and readily defined the existence of the terrace, which was otherwise difficult to detect (Fig. 5).

The surficial materials typically consist of loose, slightly silty, medium to coarse, sandy pebble gravel (50-60% coarse fragments), overlain by a thin (2-3 cm), severely burnt, organic mat. Detachments occurred at depths of 50-65 cm. The top of the terrace had a gentle to moderate slope, ranging between 15° and 26°, while the side of the terrace steepened up to 31°. The frost table within the terrace was found between 57 cm and 125 cm. Grey phyllite bedrock was found at, or close to, the surface near many of the sites visited.

2) shallow bedrock, on moderately steep, northeast-facing slopes

Dark-grey phyllite is found at shallow depths on most of the slopes throughout the lower portion of the watershed.

The phyllite weathers readily and has covered the steep slopes with a colluvial veneer composed of coarse, dark-grey, silty sand (composing 60% of the soil by volume where sampled), as well as granules and flat angular clasts (composing 40% of the soil by volume where sampled). In some cases, the clasts were imbricated parallel to slope, possibly providing a natural sliding plane.

Twenty of the surveyed failures occurred in this setting, as determined by helicopter surveys. At the one detachment visited on the ground, the sliding plane was 26°, the slope directly above the headscarp was 21°, the sliding depth was 40-45 cm , and the frost table was 43-74 cm below the ground surface.

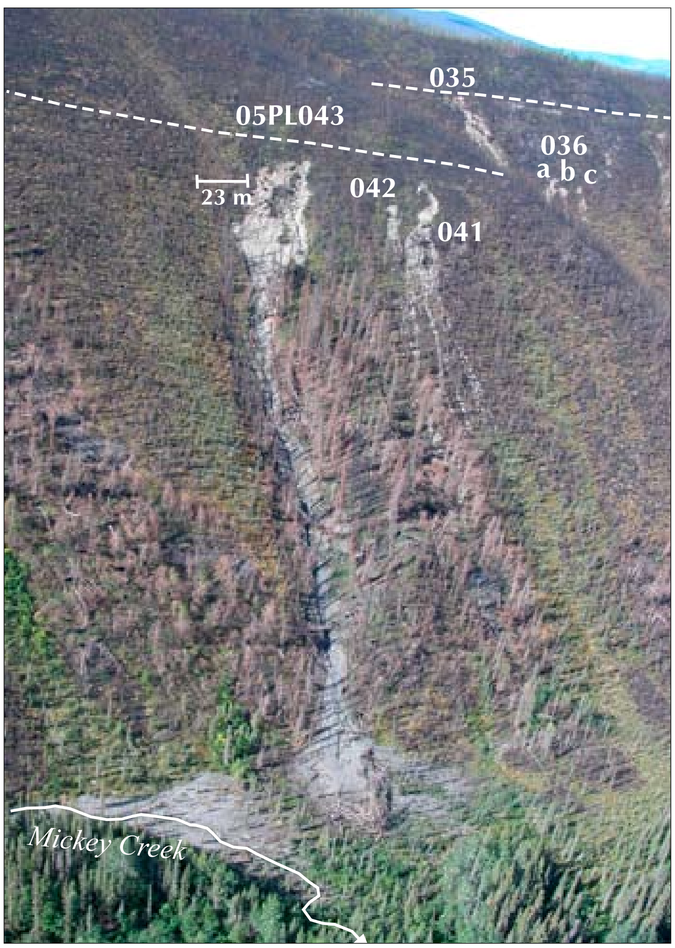

Figure 5. *Oblique aerial photograph of numerous failures originating along the scarp of a Pre-Reid glaciofluvial terrace (see dotted lines) on upper, northeast-facing slopes. View is to the southwest. Numbers represent active-layer detachments surveyed near Mickey Creek.*

3) loess-rich colluvium, on gentle south to west-facing slopes

Southwest-facing slopes in the watershed are veneered by a silty surface layer. At these locations, loess deposits have been mixed into colluviated regolith deposits by the process of colluviation and cryoturbation. The loess-rich horizon is commonly 20-30 cm thick, but can be as thick as 2 m. When saturated, these soils can flow on very gentle slopes, as low as 10°. Nineteen failures were recorded in this setting.

A fresh detachment (05PL032) was observed on July 20, with material still actively flowing (Fig. 6). The detachment was not visible in photographs taken 7 days earlier and it is likely that the detachment occurred within a day or two of the field visit. The failure began with a small slide in a 20-m-wide headscarp bowl, on a southwest-facing, gentle (13°), lower slope. The initial sliding depth was between 10 cm and 50 cm , just below the bulk of the root mat. The organic mat had collapsed along the edge of the headscarp, indicating that it had greater strength than the underlying soil. Probing revealed a frost table at 104 cm beneath a fresh sliding plane, and 88-99 cm behind the headscarp. Above the headscarp, water was ponded around many tree wells. Roots were outstretched in the direction of extension (Fig. 6b) and fresh sliding plane surfaces were exposed between tension cracks above the headscarp, and along the flow path margins where intact blocks of forest floor had been torn away (Fig. 6c).

Following the initial slide, secondary debris flows traveled more than 200 m to the valley floor, down slopes of less than 10°, to form a large shallow debris fan adjacent to the creek. Active debris flows moved at rates of approximately 0.5 m/min, carrying cobbles up to 10 cm in clast diameter (at location S2 in Figure 6a). The flowing material was very viscous, had a moisture content of 10% by weight, and was composed of 70% sticky, sandy loam (54% sand, 37% silt and 9% clay) with 30% clasts (mostly flat fragments of phyllite).

***Figure 6. (a)** Oblique aerial view of two detachments (05PL032 and 05PL100) that occurred on a gentle south- to southwest-facing slope. The larger failure is over 200 m long and initiated only a few days prior to these photos being taken on July 20, 2005. **(b)** Detachment of organic mat exposed in tension cracks above the headscarp (location S1 in Figure 6a). Roots are stretched in the direction of sliding. **(c)** Deformed organic mat (location S3 in Figure 6a), marginal to flow path (heavy arrow). The mat was initially compressed (direction D1) to form folded compression ridges (small dotted lines). It was then torn away from the surrounding mat (direction D2).*

FIFTY MILE CREEK

- **Setting**

The valley of Fifty Mile Creek is located at approximately 63°48'N and 140°20'W (50 km southwest of Dawson City) and spans elevations of 450-1500 m asl (Fig. 7). The Fifty Mile Creek valley is approximately 40 km long from its headwaters to its confluence with Sixtymile River. Field surveys were conducted only in the lower half of the watershed. The unglaciated, subdued slopes are generally mantled by colluvium and veneered by loess up to 1 m thick (Jackson, 2005). Paleozoic Klondike Schist (Mortensen, 1996) outcrops along the creek and comprises the vast majority of clasts in the colluvium. Organic materials, loess and colluvium have commonly been reworked by fluvial and colluvial processes to produce accumulations of muck deposits in lower slope and valley-bottom positions (Fraser, 1995).

Pre-Reid glaciofluvial terraces form valley-bottom benches along the creek (Jackson, 2005) and some placer potential exists within them (Lowey, 2000). Limited exploration has occurred within the benches, and while active placer claims exist along parts of Fifty Mile Creek, no commercial mining has been undertaken. Watershed-scale monitoring of hydrological and biological parameters has been ongoing by various agencies (Department of Fisheries and Oceans; Yukon Environment; Yukon Energy Mines and Resources, Client Services and Inspections) as part of an environmental baseline study to characterize the impacts of placer mining and exploration on watershed systems.

The lower half of the watershed was burned in the 2004 fires (Fig. 7). Fires were detected by MODIS satellite instruments in the watershed between June 25 and July 13, 2004 (USDA Forest Service, 2005). The fires started on the upper slopes, south of Fifty Mile Creek, about a third of the way up the valley. They burned most extensively near the subsequent detachments on June 29 and 30. Between July 1 and 11, only scattered hotspots were detected. On July 12, the entire lower portion of the watershed burnt extensively both north and south of the creek.

- **Field survey methodology**

Twenty-eight slope failures were located in the watershed using GPS waypoints recorded while hovering above each detachment with a helicopter; this data was gathered on July 16 and 19, 2005 (Fig. 7). Twenty of the failures were

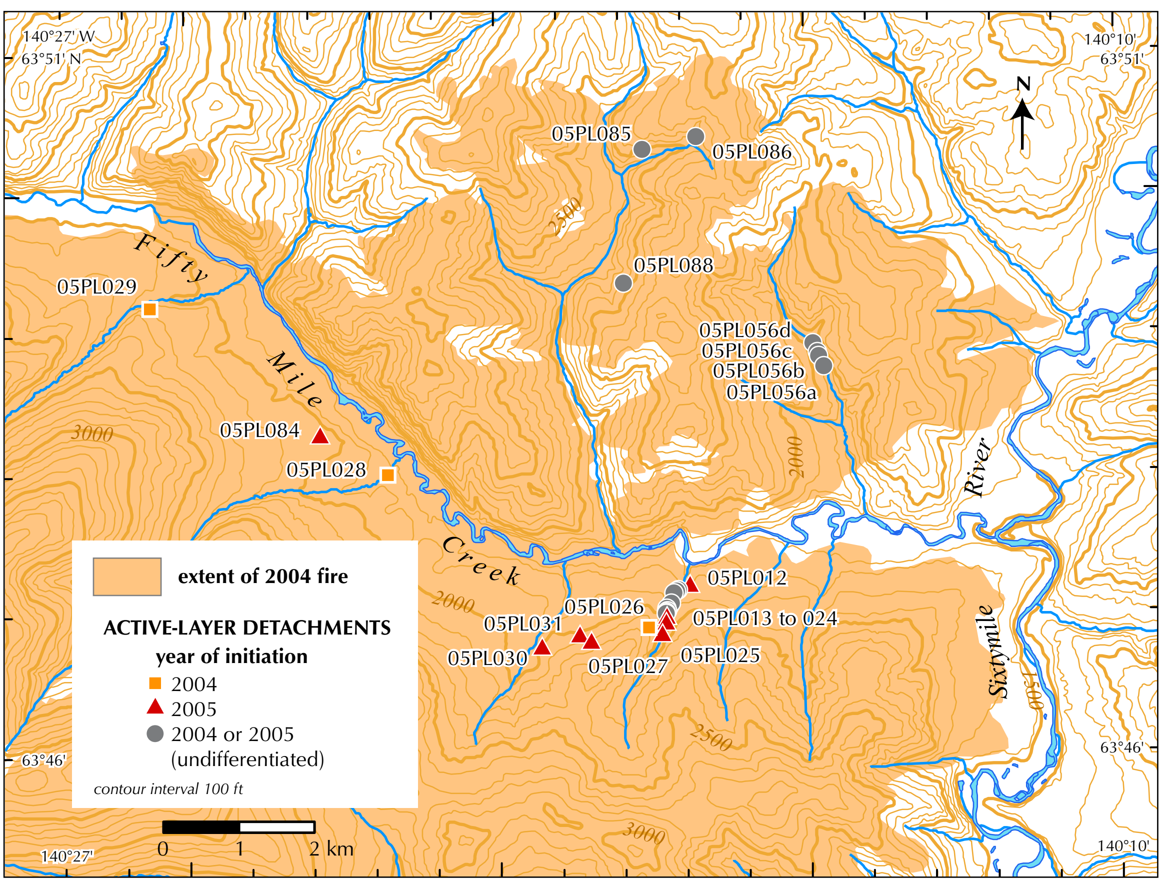

Figure 7. *Location map displaying the extent of burned areas, as well as locations of active-layer detachments surveyed in the lower part of the Fifty Mile Creek watershed.*

visited on the ground between July 16 and 19. The same site survey methods were employed at Fifty Mile Creek as were used in the Mickey Creek watershed.

• Failure settings and morphologies

Active-layer detachments occurred mainly along the upper portions of convex tributary valley slopes in the Fifty Mile Creek watershed. The morphology of a typical elongate-shaped detachment is shown in Figure 8. Slope angles in the initiation zones ranged between 11° and 25°. Failures occurred on all aspects, but were most common on north- and east-facing slopes. The highest density of failures occurred along one tributary valley, where 15 detachments have occurred within 1 km (05PL012 to 05PL027). Failures were very shallow, ranging between 15 cm and 50 cm. They were generally up to 60 m long and up to 25 m wide, although a few failures traveled several hundred metres downslope. Surficial materials in the initiation zones of the failures consisted of brown, silt-rich (up to 37-60% silt) colluvium, with 20-50% angular to sub-angular schistose clasts.

Sediment-laden artesian springs (sediment plumes) were noted in proximity to many initiation zones (Fig. 9), indicating extremely high pore water pressures. Frost probing in mid July located the frost table between 44 cm

Figure 9. *Surface sediment plume created by artesian groundwater flow. These commonly occurred on saturated slopes and near the initiation zones of recent failures.*

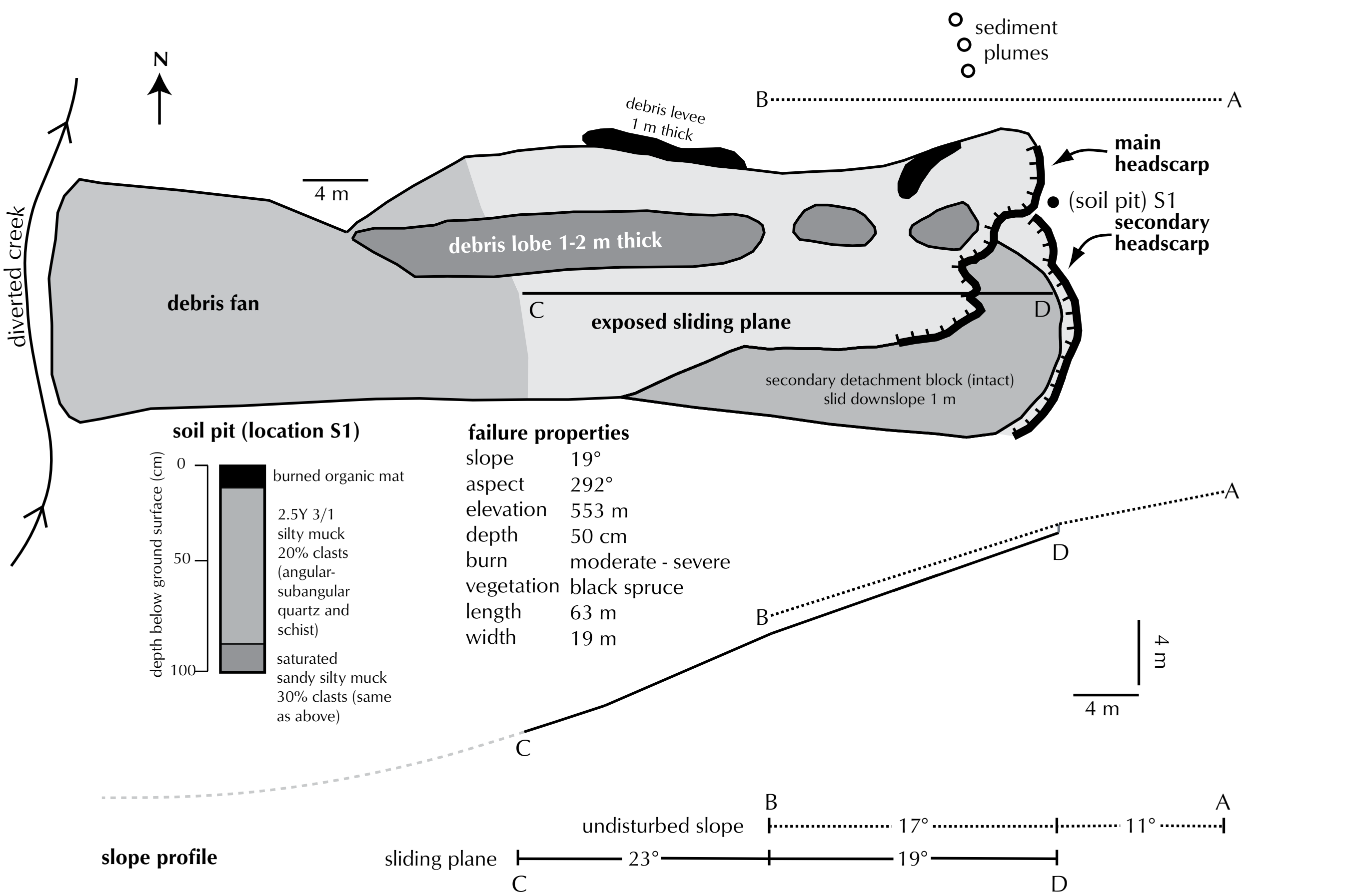

Figure 8. *Morphology and slope profile of typical elongate detachment (05PL012) in Fifty Mile Creek watershed; drawn to scale.*

and 106 cm below the ground surface adjacent to the initiation zones. Three of the failures (05PL024, 05PL027 and 05PL084) appeared to have been triggered within days of the field investigations, as indicated by the highly saturated flow materials, live vegetation in the debris, and the presence of very fine outstretched live roots along the headscarp sliding planes.

STEELE CREEK

- **Setting**

The valley of Steele Creek is located at approximately 63°35'N and 138°59'W (55 km south-southeast of Dawson City) and spans elevations of 580-1000 m asl (Fig. 10). The watercourse is 8 km long and drains north from the Black Hills into Montana Creek, which is a tributary of the Indian River. The terrain in the area is characterized by V-shaped valleys and rolling hills with rounded summits. Hillslopes are blanketed in colluvium derived from the underlying Nasina assemblage graphitic quartzite and muscovite-quartz schist (Gordey and Makepeace, 2003). Field observations confirmed that only well drained, south-facing slopes are permafrost-free. Where permafrost is present, field measurements showed extremely variable active layer depths, ranging from 30-150 cm, depending on vegetation cover and aspect.

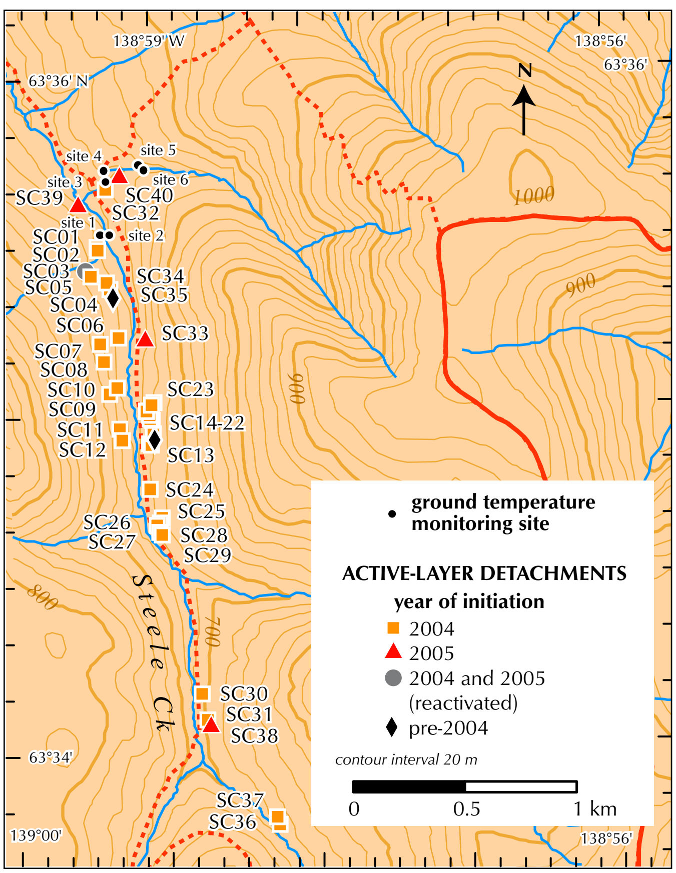

Figure 10. *Map displaying burned area and locations of active-layer detachments surveyed in Steele Creek watershed. The entire area was burned during the summer of 2004.*

MODIS satellite instruments detected fires in the valley of Steele Creek from June 30-July 4, 2004. The fires started in the upper reaches of the watershed on June 30. The majority of the fires were detected between July 1 and July 3 during which time they spread most of the way down the watershed. Scattered hotspots were detected near the mouth of the creek on July 4.

The valley was selected for study based on aerial photographs (taken August 26, 2004 by Jim Leary of Yukon Energy, Mines and Resources, Client Services and Inspections) which revealed the large number of detachment failures that had taken place within weeks of the forest fire. The site is accessible by mining roads, which allowed monitoring of freeze-up processes in the fall of 2004 and observation of additional detachment failures in the summer of 2005.

There are currently no placer mining operations on Steele Creek, but mineral prospecting and active claims exist. Evidence of historical placer works was found, and was likely associated with the old Dawson-to-Whitehorse winter stagecoach trail located along the length of the valley bottom.

- **Field survey methodology**

In the fall of 2004, preliminary observations of active-layer detachments and ground thermal conditions were made. Forty-metre transects were laid out across the boundary between burned and unburned forest at six sites encompassing different aspects and terrain types. Probing to the frost table was conducted at one-metre intervals along each transect, approximately every two weeks, from mid-September to early December. At the end of each transect, as well as at the centre point, boreholes were drilled to depths of 1-2 m below the permafrost table and pipes were inserted into them. On the same dates as the frost-probing transects were performed, thermistors were inserted down the borehole pipes at 20 cm intervals to measure ground temperatures. Observations of vegetation, degree of burn and snow depth were also made.

All existing detachment failures were photographed from the air on May 18, 2005. Since this was immediately after snowmelt, and thaw depths were less than 35 cm, this inventory represented landslides that had occurred in the summer of 2004 immediately following the fires. The inventory revealed that thirty-five detachment failures had occurred in 2004 along a 3.7-km-long section of the main valley and on slopes within its tributaries (Fig. 10). In 2005, an additional five new slides developed by mid-August and several old slides from 2004 were also reactivated.

Representative detachment failures from both years were mapped in detail, and soil pits were excavated in order to examine soil stratigraphy (Fig. 11). Probing was conducted throughout the summer to determine the depth of the frost table.

In May 2005, two-channel Onset Hobo Pro temperature loggers (accuracy ± 0.2°C) were set up on burnt slopes which approximately faced the four cardinal directions (Table 1). These temperature loggers measured screen-height air temperatures (external thermistor) and surface ground temperatures (internal thermistor) at hourly intervals. Two more loggers of the same type were installed on unburnt north- and south-facing slopes in mid-June. Four-channel Onset Hobo 8 temperature loggers were also installed at the same sites and their external

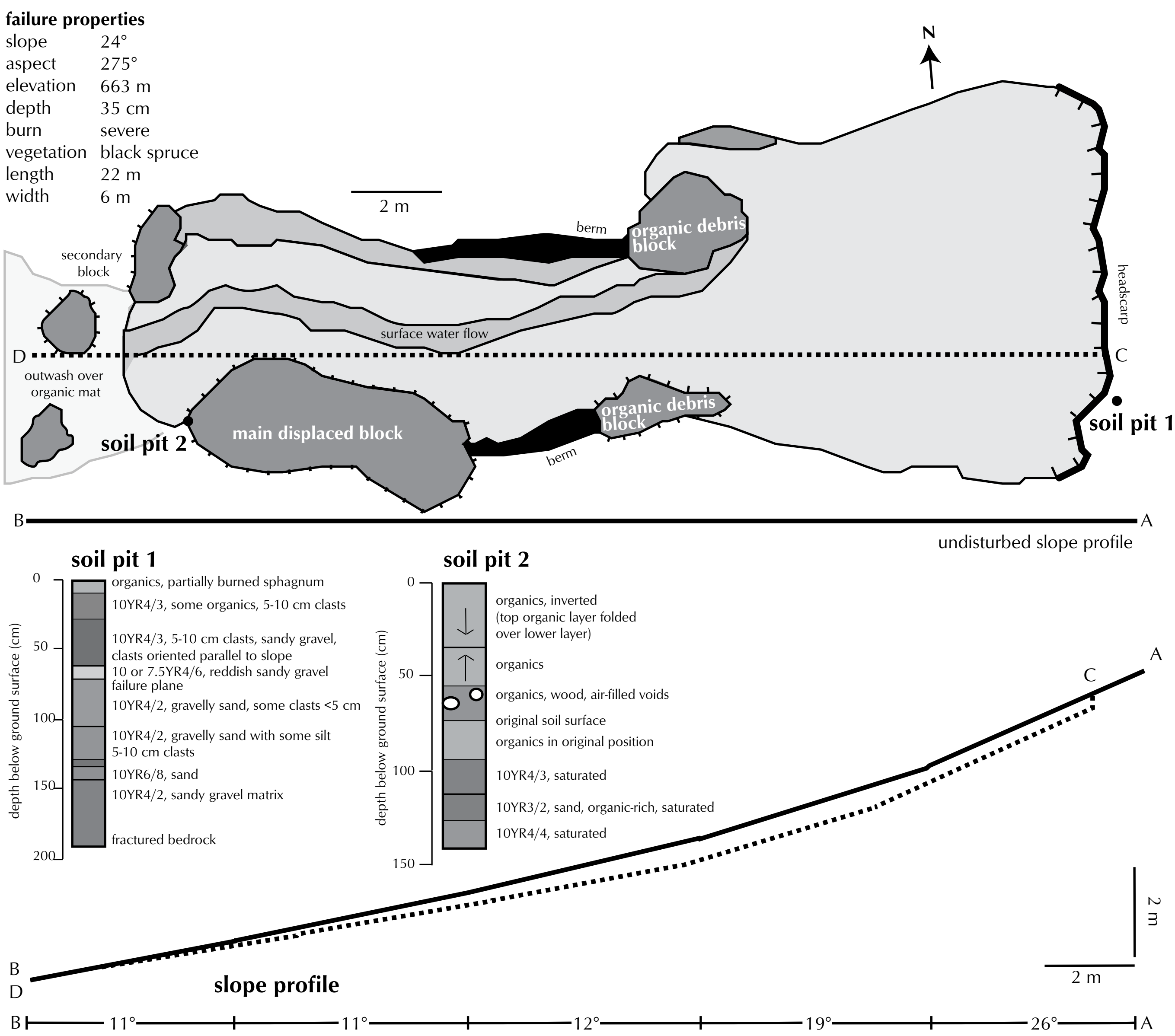

Figure 11. Morphology and slope profile of typical elongate detachment (SC13) in Steele Creek watershed; drawn to scale.

Table 1. *Summary characteristics at temperature monitoring sites, Steele Creek, summer 2005.*

Site	1	2	3	4	5	6
Aspect	east	west	northwest	south-southeast	south	north
Burn condition	burnt	burnt	burnt	burnt	unburnt	unburnt
Permafrost	present	present	present	absent	absent	present
Vegetation type	burnt spruce forest	burnt spruce forest	burnt spruce forest	burnt aspen and birch forest	mixed spruce and aspen forest	open spruce forest with thick moss
Depth of ground sensors and period of data collection[1]	0 cm: May 19, 2005 25 cm: May 19, 2005 50 cm: May 19, 2005 60 cm: May 19, 2005 - July 11, 2005 70 cm: May 19, 2005 100 cm: July 11, 2005			0 cm: May 19, 2005 25 cm: May 19, 2005 50 cm: May 19, 2005 70 cm: May 19, 2005 100 cm: May 19, 2005	0 cm: June 12, 2005 10 cm: June 12, 2005 - June 21, 2005 20 cm: June 12, 2005 - June 21, 2005 25 cm: June 21, 2005 30 cm: June 12, 2005 - June 21, 2005 50 cm: June 21, 2005 60 cm: June 21, 2005 - July 11, 2005 70 cm: July 11, 2005 100 cm: July 11, 2005	
Mean July air temperature (°C)	13.2	13.2	13.7	13.7	12.9	13.1
Mean July ground surface temperature (°C)	11.5	12.7	13.7	14.6	11.7	10.7
Calculated frost table depth on August 12, 2005[2]	158 cm	81 cm	89 cm	unfrozen	unfrozen	80 cm

[1]Data-collection is ongoing where no end-date is indicated; last download was on 13/8/2005.

[2]Frost table depths were calculated using a second-order polynomial fit to measured ground temperatures.

thermistors (accuracy ± 0.5°C) were inserted in the ground at a variety of depths. As the frost table fell during the summer, the thermistors were moved deeper into the ground in order to track the frost table position (see Table 1). A tipping-bucket rain-gauge was also installed in the valley from the end of July to mid-August.

Preliminary analysis of measured summer air temperatures, which are relevant to active layer development, suggest that values are about 1°C colder than those at Dawson, due to the 200-300 m higher elevation difference. The July average temperature at Dawson was 14.2°C, while the average of the two unburnt sites in Steele Creek was 13.0°C (Table 1). Precipitation amounts, however, differed greatly from those at Dawson. Severe thunderstorms were observed frequently at Steele Creek in June and July 2005 and almost 50 mm of rain was recorded between July 27 and August 5. Dawson recorded less than 2 mm of precipitation in these two months.

- **Failure settings and morphologies**

Both bell-shaped and elongated detachment failures (Lewkowicz and Harris, 2005b) were present (Fig. 12). They developed on hillslopes with a variety of aspects. All failures occurred on slopes underlain by permafrost; no detachments were observed on south-facing slopes that were permafrost-free. Most failures initiated on slopes of 19-24°, often proximal to a convex break in slope (Fig. 13).

Active-layer detachments were 50-80 cm in depth, ranged in length from tens to hundreds of metres, and were 1 m to 20 m wide. The morphology and slope profile of a typical elongate detachment failure (SC013) is shown in Figure 11. Several of the failures deposited sediment and debris directly into Steele Creek (Fig. 14). One detachment failure partially blocked the creek, creating a small pond upstream.

Based on observations of failure morphology and stratigraphy, most failure histories appear to have involved a combination of slide and flow. As in the other two watersheds, the failure surface for almost all the detachment failures that occured in 2005 was between the ground surface and the frost table. By mid-August, the frost table varied between 81 cm and 169 cm below the ground surface at the burnt sites underlain by permafrost

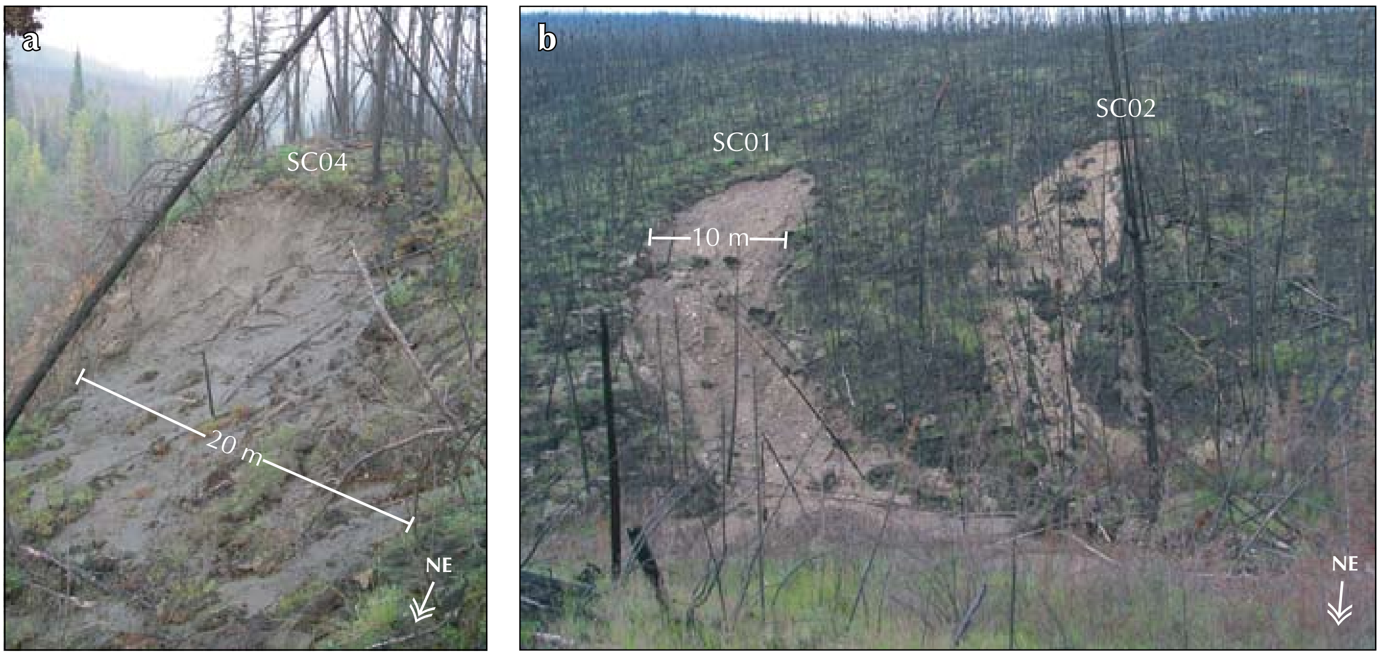

Figure 12. *Typical bell-shaped* ***(a)*** *and elongate* ***(b)*** *detachment failures on northeast-facing slopes in the Steele Creek watershed.*

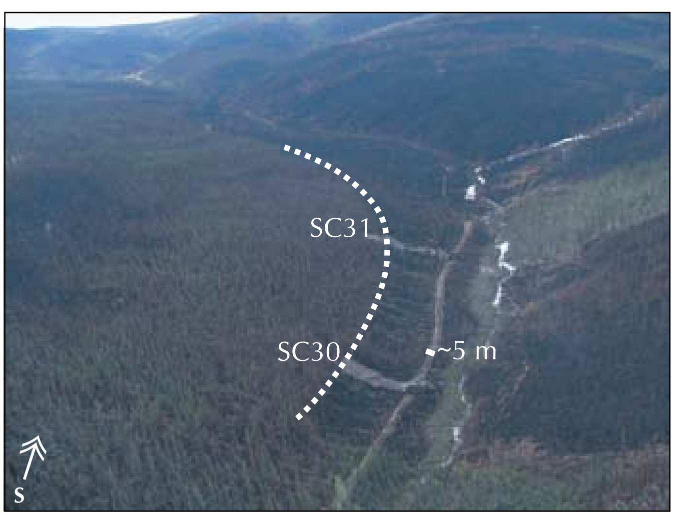

Figure 13. *Oblique aerial photograph of active-layer detachments in Steele Creek, which initiated from a prominent convex break in slope (shown by dotted line).*

Figure 14. *Oblique aerial photograph of multiple active-layer detachments on a west-facing slope. The failures crossed local access trails and deposited material directly into Steele Creek.*

(see Table 1). Although the failure depths observed for the 2004 detachments did not appear to be different from those in 2005, it is not known whether movements took place along the frost table (which would likely have been higher than in 2005), or within unfrozen soil layers. The location of the 2005 failure surfaces above the frost table distinguishes these active-layer detachments from those observed elsewhere following fire or other disturbance on permafrost slopes (e.g., Lewkowicz and Harris, 2005a, 2005b).

Most of the reactivations involved relatively small movements at the headscarp and shallow minor mudflows in the floors, but in some cases, major blocks of material moved downslope. As in the other watersheds, there was evidence of high pore water pressures within the slopes in 2005, with sediment plumes emerging onto the burnt organic mat, particularly near failure headscarps. Water under artesian pressure was also observed bubbling to the surface in the floor of one of the detachment failures.

DISCUSSION

IMPACTS OF FOREST FIRE ON SLOPE STABILITY

Forest fires impact numerous aspects of the thermal, hydrological and geotechnical conditions of slopes underlain by permafrost. A conceptual framework for these direct and indirect factors is shown in Figure 15. The relative significance of each of these controls on overall slope stability is difficult to assess, and merits future study.

Fire alters slope thermal conditions by burning the vegetation canopy and ground cover, thereby reducing shading. Simultaneously, charring of the surface organic mat decreases the albedo. The result of these two changes is an increase in the solar radiation absorbed at the ground surface. As a consequence, the mean July ground surface temperatures on burnt north-facing and south-facing slopes in Steele Creek were about 3°C warmer than comparable unburned slopes (see Table 1). The destruction of live vegetation may also reduce evapotranspiration so that less of the heat available at the ground surface is lost by latent heat transfer to the atmosphere. Finally, a reduction in the thickness of the insulating surface organic mat allows heat to be transmitted downwards more easily. All of these impacts cumulatively lead to enhanced summer ground heat flux

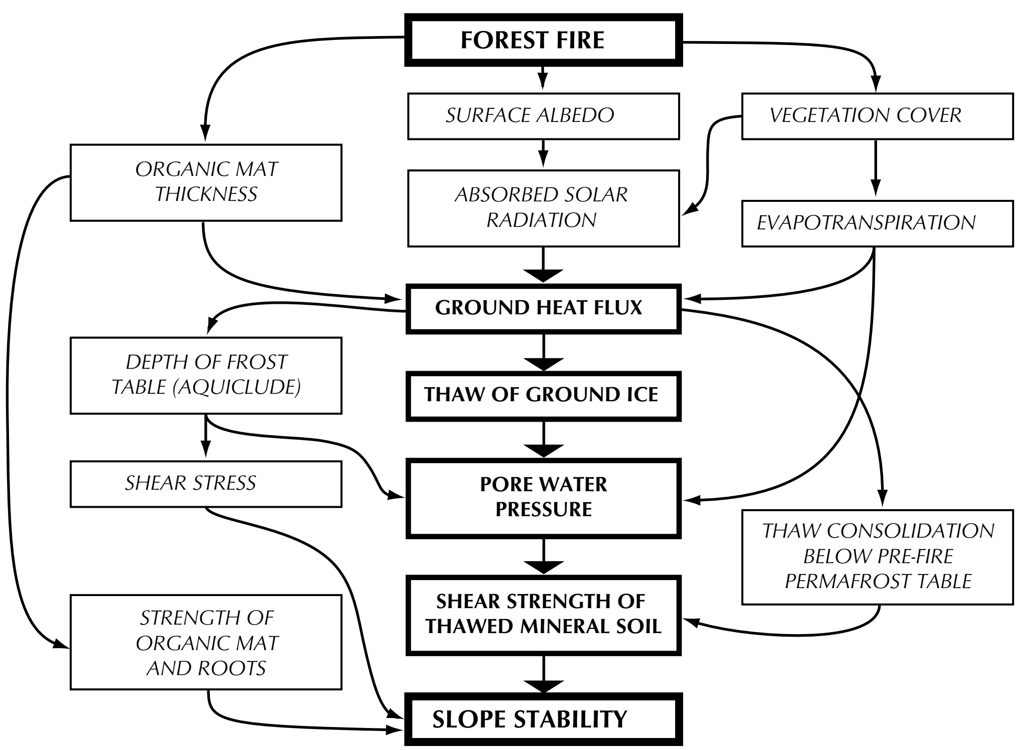

Figure 15. *Conceptual framework for the impacts of forest fire on the stability of slopes underlain by permafrost. Note: for clarity, factors that are unaffected by fire (e.g., topography, precipitation) are not shown.*

downwards towards the frost/permafrost table (Yoshikawa *et al.*, 2002; Ping *et al.* 2005).

The increased downward ground heat flux can be expected to cause deeper thaw than in the pre-fire period, both in the year of the fire and in subsequent years. Data from both pairs of comparable burned and unburned temperature monitoring sites (north-facing sites 2 and 6 and south-facing sites 4 and 5 in Table 1 and Fig. 16) suggest this effect, but the observations are too limited spatially to be regarded as conclusive. Where the upper layers of permafrost contain excess ice, their thaw may result in increased porewater pressure (McRoberts and Morgenstern, 1974; Dyke, 2000; Harris and Lewkowicz, 2000). Porewater pressures may also be affected by the reduction in surface evapotranspiration and subsequent increase in overland flow. Maximum porewater values may additionally be influenced by the increased depth of the thaw plane.

Other geotechnical changes relate to burning of the organic mat and tree roots, as their contribution to slope shear strength can be significantly reduced following forest fires. Organic mats were shown to have greater strength than the underlying soil, even in burned areas, as they were commonly observed draped over the edges of detachment failures. Thaw settlement of the thawing permafrost material may contribute to breaking the bond between the organic mat and the underlying soil, as suggested by the presence of gaps between dried rigid organic mats and the underlying mineral soil at the edge of some failures. At the advancing thaw plane, the faster the release of water and the slower the consolidation, the lower the shear strength will be (McRoberts and Morgenstern, 1974).

Although not shown in Figure 15, which focuses only on changes following forest fire, topography and precipitation are also very important factors for slope

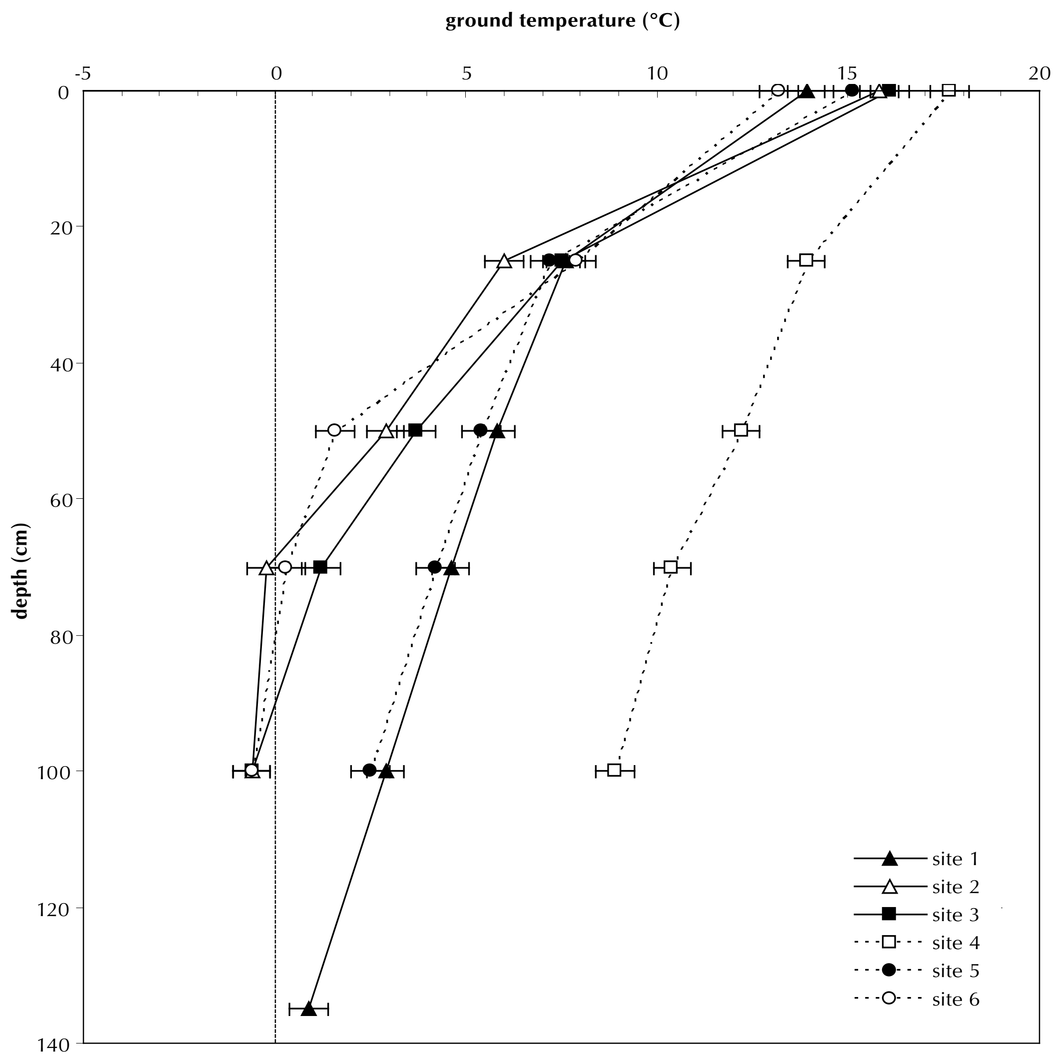

Figure 16. *Average ground temperature profiles on August 12, 2005 at the Steele Creek monitoring sites. Values shown are 24-hour averages. A sensor accuracy of ± 0.5°C is shown by error bars at respective measurement depths.*

stability. Topography (slope steepness) directly affects shear stress, while precipitation acts to alter slope stability through its effect on shear stress, cohesion and porewater pressure. The numerous heavy precipitation events observed over the summer of 2005 in Steele Creek likely contributed to slope instability in the watershed.

The relative severity of the 2004 fires within the three watersheds was examined using 30-m resolution Landsat 7 Thematic Mapper (TM) satellite imagery taken at approximately the same time of year before and after the forest fires. TM Band 4 (near infrared) is sensitive to live vegetation, while Band 7 (middle infrared) is sensitive to ash, char and mineral soil. A Normalized Burn Ratio (NBR) was calculated (NBR = (Band 4 – Band 7) / (Band 4 + Band 7)) for all pixels in the pre-fire scene (September 2001) and the post-fire scene (September 2004). The difference in the pre-fire NBR and the post-fire NBR is referred to as the Differenced Normalized Burn Ratio (DNBR), which has been shown by field testing to be a reliable indicator of burn severity (Cocke *et al.*, 2005). Preliminary analyses of the data (Fig. 17) suggest that detachment failures in all three watersheds occurred in areas where the relative burn severity (with respect to each watershed) was moderate to severe. This indicates that significant burning promotes detachment failures in the watersheds. Not all significantly burned slopes fail, however, since numerous other factors (as described above) affect their stability.

DETACHMENT FAILURE FREQUENCY AND CLIMATE CHANGE IMPLICATIONS

The long-term frequency of fire-related active-layer detachments depends on the frequency of fires and on the recovery time for degraded icy permafrost (Lewkowicz and Harris, 2005a). Minimum return intervals for fire frequency are limited by the recovery of vegetation and the redevelopment of sufficient fuel. Estimates of current fire frequency in the northern boreal forest range between 30 to 500 years, but are typically about 100-200 years (Johnson, 1992; Yoshikawa *et al.*, 2002; Hinzman *et al.*, 2003).

The time needed for permafrost to become stable following a fire depends on the ground thermal regime. In the southern Yukon, where ground temperatures at the top of undisturbed permafrost are ≥-1°C, the permafrost table was still falling slowly, 40 years after a forest fire (Burn, 1998). However, in interior Alaska where conditions are similar to those at Dawson, it was estimated that it would take 25-50 years for the permafrost table to return to its original depth, following re-establishment of spruce and feathermoss as part of post-fire succession (Viereck, 1982; Van Cleve and Viereck, 1983). Consequently, it appears that at present, detachment failure recurrence around Dawson is limited by vegetation recovery and the frequency of forest fire, and not by geocryological conditions.

There appear to be broad links between climate change and fire frequency in the northern boreal forest. While the climate has warmed, the annual burn area in Canadian boreal forests has doubled in the past 20 years (Kasischke and Stocks, 2000; Stocks *et al.*, 2002) because of increased aridity, drier fuel and more frequent convective storm activity. Attempts at modeling future changes in Canadian forest fire activity project increases of 40% in size and 46% in severity, for a doubling of carbon-dioxide levels (Van Wagner, 1988; Flannigan and Van Wagner, 1991). In central Yukon (including Dawson), the number of fires are projected to increase by up to two-thirds, while the area burned is projected to increase by up to 300% by 2069, based on general circulation models and regional climate scenarios (McCoy and Burn, 2005). If this occurs, there should be a concomitant increase in the frequency of detachment failure activity for the same period, given the current state of permafrost thermal conditions in the area.

ENVIRONMENTAL AND ECONOMIC IMPLICATIONS

The impacts of active-layer detachments on watershed-scale sedimentation processes in the Dawson area may be significant, particularly if their frequency increases in the future. Aside from the obvious risks to infrastructure and local access roads, fisheries stocks, as well as placer mining could be affected. The active-layer detachments could also provide new prospecting opportunities by exposing fresh colluvial materials at the surface.

Following the forest fires in Mickey Creek, increased stream sedimentation into summer-rearing habitat was reported as having the potential to displace juvenile Chinook salmon (A. von Finster, pers. comm., 2005). This was of concern as Yukon River Chinook salmon support commercial, subsistence and aboriginal fisheries in Canada and Alaska. Settleable solids, and in particular, sand-sized particles, can clog spawning gravel and abrade algae beds. Suspended solids reduce visibility for capturing prey, and limit the productivity of algae and invertebrates, thereby reducing fish food sources. In some places along Mickey Creek, the landslides blocked the

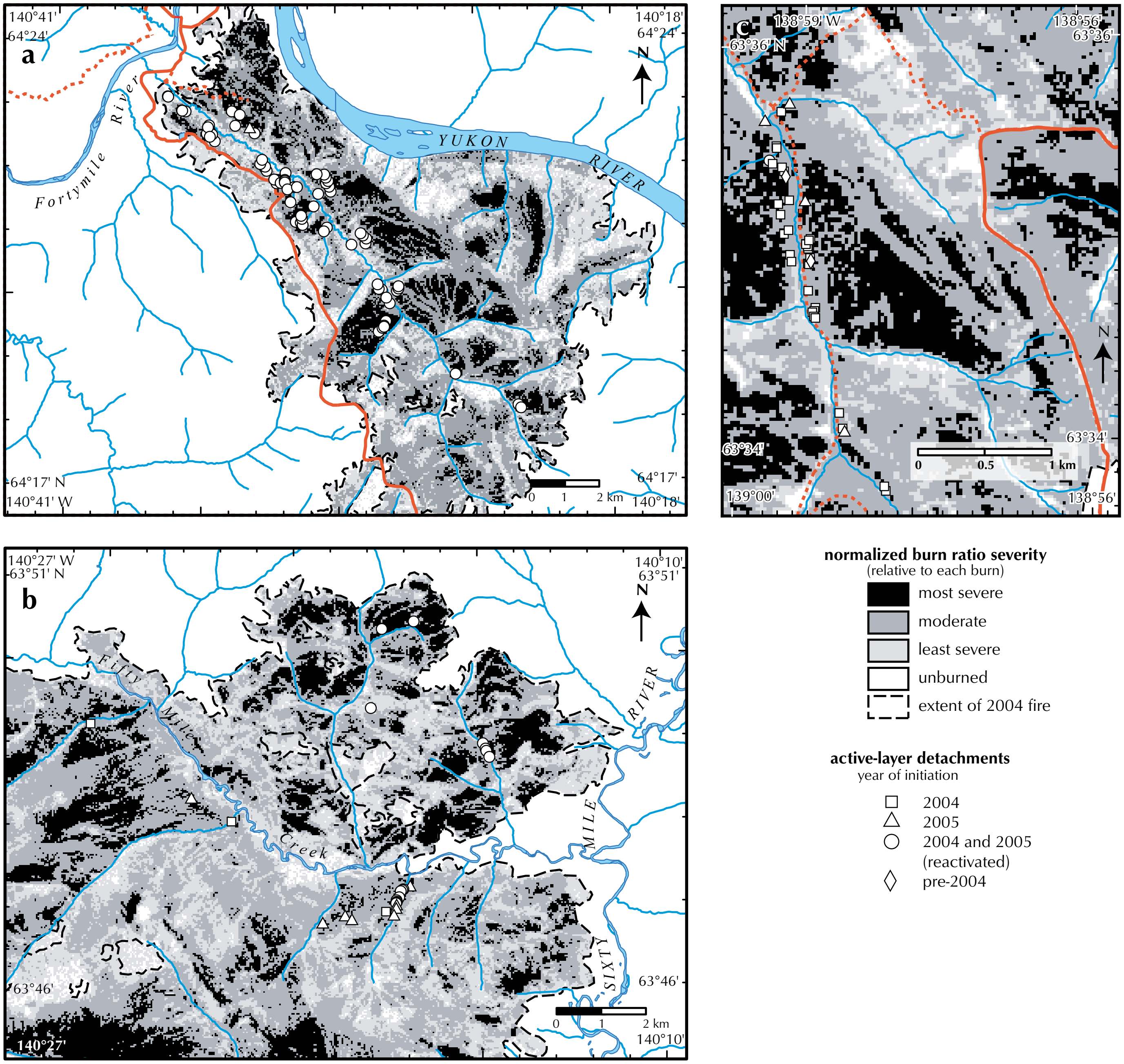

Figure 17. *Example of relative burn severity evaluation performed in the* ***(a)*** *Mickey Creek,* ***(b)*** *Fifty Mile Creek and* ***(c)*** *Steele Creek watersheds. Differenced Normalized Burn Ratio (DNBR) analysis is based on differences in ground cover reflected in Landsat 7 TM Bands 4 and 7 (30 m resolution) before (September, 2001) and after (September, 2004) the forest fire. White outlined shapes represent active-layer detachments as shown on Figures 4, 7 and 10.*

stream channel, and destroyed natural cover and shading. However, detachment failures may also introduce nutrients into the stream system and create new habitat.

Understanding the degree to which active-layer detachments contribute to sedimentation in the drainage network is critical at the present time, as the Department of Fisheries and Oceans (DFO) transitions into a new placer mining regulatory framework for the Yukon by 2007. The new regulatory regime proposes to consider natural sediment contributions and incorporate local watershed health monitoring strategies in determining the water quality objectives that are appropriate to individual watersheds. The limited amount of data collected by DFO in the summers of 2004 and 2005 demonstrate that natural turbidity levels in burned watersheds can be highly variable throughout the day and season. It will be important that the proposed adaptive management strategy reflects potential sediment contributions that will occur from active-layer detachments after forest fires. More detailed water quality monitoring will be needed in the future to quantify the amount of these sediment contributions.

CONCLUSIONS

Nearly one hundred and fifty active-layer detachments developed in three catchments in the Dawson region following the 2004 forest fires. While field measurements and data analyses are continuing in 2006, the following preliminary conclusions could be reached:

1. The majority of detachment failures initiated in the summer months immediately following the fires; a minority of the landslides developed in 2005.
2. Active-layer detachments developed on moderate to steep slopes of all aspects, provided permafrost was present. Aspect may influence the distribution of these landslides where surficial materials vary widely with orientation. No failures were observed on south-facing permafrost-free slopes. Relative burn severity at most failure sites, established from satellite imagery, was moderate or high.
3. The location of the failure plane in the majority of the landslides in the Dawson area appears to have been within the thawed surficial materials of the active layer and not at the frost table. This differs from those reported in the literature from the Mackenzie Valley and Canadian Arctic Archipelago.
4. The number and size of the active-layer detachments appears to have been sufficient to affect stream sediment loadings.

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