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Cover photo. *Southward view of 1988 Horseshoe Bay debris-flow scar. Alaska Highway runs along the southwestern shore of Kluane Lake in foreground. Slims River delta is in the background.*

Executive summary

The following report describes the settings, causes and geological controls of landslides in the Alaska Highway corridor. Although diverse geologic, geomorphic and climatic environments exist in the region, most landslides are related to the presence of shallow bedrock or permafrost, unconsolidated sediment on steep slopes, weak bedrock, groundwater hydrology, river erosion or the degradation of ice-rich permafrost.

Where geologic controls provide appropriate settings, intense rainfall, rapid snow melt and seismic events play important roles in triggering failures. Rainstorms that reach thresholds of combined intensity and duration have triggered abundant shallow landslides within the corridor. Debris flows have historically posed the highest risk to low-lying regions and are capable of damaging settlements and transportation routes.

The Shakwak Valley has the highest concentration of landslides within the corridor due to the abundance of steep slopes, high relief and widespread discontinuous permafrost. In Wellesley Depression, shallow permafrost and its subsidence has an important influence on slope instabilities. Landslides in the Yukon Plateau primarily relate to the presence of silt- and ice-rich tills on steep valley sides as well as the incision of fine-grained lacustrine terraces in valley bottoms. Debris flows after intense rainfall events are the most common form of landslide in the Kaska Mountains. Finally, in Liard Lowland, failures associated with glacial meltwater and modern stream incision are the most common landslide events.

Permafrost plays an important role in landslide processes in the corridor due to its influence on soil moisture, drainage and strength. Slopes composed of icy sediment that have been burned by forest fires are particularly vulnerable to rapid mass movements due to permafrost degradation. The consequences of the dramatic increase in landslide potential after fire should be considered in local fire management plans.

The climate's local and regional influence on hydrology, fire frequency and permafrost distribution greatly affects landslide processes. Current climate change projections call for warmer temperatures and increased precipitation for the Yukon in the next half century. Among the anticipated effects of global warming in southern Yukon, increased incidents of intense snowmelt and/or precipitation events, river migration, permafrost degradation or forest fires may lead to an increase in landslide frequency and/or magnitude within the settings described in this report. The most significant impact of increased landslide activity may not be a direct impact. Rather, increased sediment input from landslides will likely increase stream channel instability and flooding. This would be particularly acute in the vicinity of alluvial and colluvial fan complexes along Kluane Lake where highway maintenance is already a challenge.

ACKNOWLEDGEMENTS

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INTRODUCTION

The Yukon section of the Alaska Highway corridor is a nearly 1000-km route extending from the British Columbia-Yukon border near Watson Lake in southeastern Yukon, to the Alaska-Yukon border near Beaver Creek in west-central Yukon (Fig. 1). It encompasses the valleys and mountain ranges adjacent to the Alaska Highway and the proposed Alaska Highway pipeline route.

The Alaska Highway corridor is critical for transportation, settlement, tourism and resource development in Yukon. The Alaska Highway is the main land-based transportation corridor connecting Yukon, Alaska and western North America. More than 80% of the 315 000 tonnes of goods shipped into the Yukon each year are transported on the Alaska Highway. In addition, 85% of Yukon's population resides within the corridor and 70% of tourists visiting the Yukon travel the highway. The Alaska Highway corridor also includes a proposed route for a railway and a pipeline linking Alaskan natural gas reserves near Prudhoe Bay to the Midwestern United States. Settlement and infrastructure in the corridor may increase significantly with the construction and operation of these potential megaprojects.

LANDSLIDES AND THEIR IMPACTS

Landslides refer to the gravitational, downslope movement of rock, debris or earth. Throughout the Alaska Highway corridor, landslide activity is a major landscape-altering process that can damage property and habitat, and potentially cause injury or death. Landslides pose a significant direct hazard to linear developments such as highways and pipelines where they are not appropriately positioned or designed. Landslides are capable of suddenly severing, burying and blocking roads, as well as burying buildings and undermining their foundations or fill. Mass movements may also lead to buckling or rupture of pipelines. Environmental impacts of landslides include loss of nutrient-rich soil, enhanced surface erosion, stream scouring and stream sedimentation, all of which can impact fish and wildlife habitat. Each of these potential incidents could have severe socioeconomic repercussions on communities relying on regional infrastructure and ecosystem integrity for their livelihood.

GOALS, SCOPE AND OBJECTIVES

The objective of this report is to present a first-order regional characterization of the setting and behavior of landslides within the Alaska Highway corridor. Another goals is to provide an estimate of how landslide activity within the corridor may be affected by predicted climate change. Although many landslide occurrences are documented in this report and the accompanying database, a complete inventory of landslides is not presented. Instead, case studies drawn from fieldwork and literature are provided to illustrate various dominant landslide processes. Landslide types discussed within this report are limited to subaerial rapid mass movements of primarily soil and rock. Solifluction, creep, nivation, snow avalanches and subaqueous earth sliding or flows are not included in the discussion. The intent of this report is to serve as a guide to regional landslide processes to help focus more detailed work.

SETTING

Physiography

Climate, glacial history and bedrock geology divide the Alaska Highway corridor into various regions with distinct physiography (Fig. 1). From east to northwest these physiographic regions are: Liard Lowland, Kaska Mountains, Yukon Plateaus, Shakwak Trench, Kluane Ranges and Wellesley Depression (Mathews, 1986). The Liard Lowland is a large area of subdued relief dominated by broad, gently rolling hills, till and outwash plains incised by Pleistocene meltwater channels and modern streams. The Kaska Mountains comprise an incised plateau (Nisutlin Plateau) above which the rounded mountains of the Cassiar Range project. Similarly, the Yukon Plateaus zone displays broad upland areas with rounded summits 1500 to 2000 m above sea level (a.s.l.). The Yukon Plateaus are bounded to the west by the Shakwak Trench, a deep, wide and flat-bottomed valley which divides the Yukon Plateaus from the St. Elias Mountains, and from the Selwyn Mountains to the east (Mathews, 1986). The Kluane Ranges, which are apart of the St. Elias Mountains, abruptly rise above Shakwak Trench as a narrow band of steep glaciated peaks. To the north, the Wellesley Depression occurs as a broad lowland with isolated rounded hills. Further descriptions of each physiographic region are given within the landslide zone summaries presented in the Landslide Proccesses section (p.10).

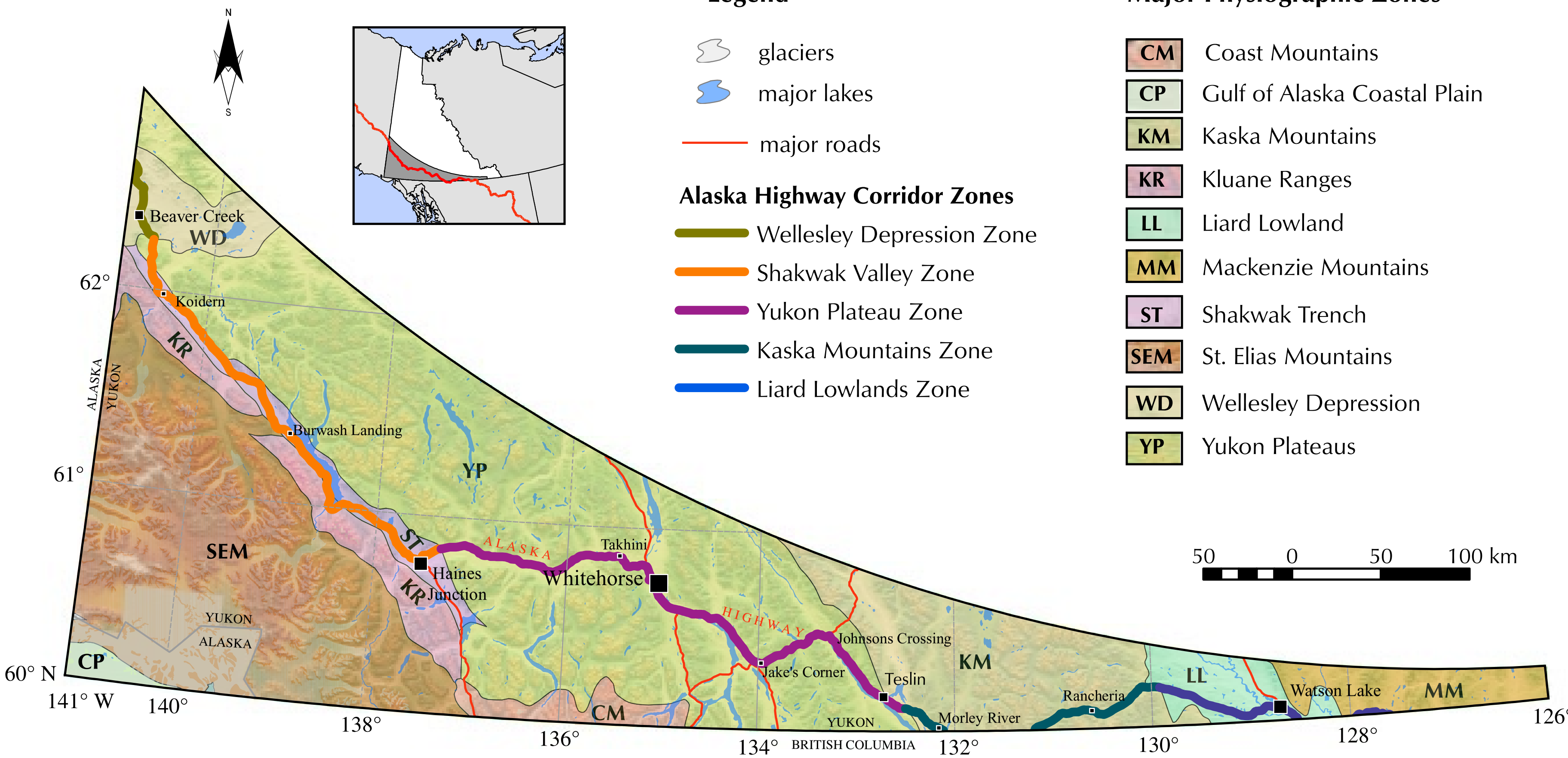


Figure 1. *Alaska Highway corridor and the five landslide zones used in this report. Each zone is characterized by the predominant landslide characteristics seen in this and prior studies. Physiographic zones modified from Matthews (1986).*

Tectonic setting

The bedrock geology of the Alaska Highway corridor is largely the result of 190 million years of accretion of exotic terranes and intervening sediment onto the western edge of the ancient North American continental platform. Consequently, bedrock geology varies considerably throughout the study area (Fig. 2 on pages 4 to 5). The Kaska Mountains are composed of folded and faulted continental platform sedimentary rocks that have been displaced by movement along the Tintina Fault. These rocks are primarily limestone and sandstone, but also include shale and chert from basinal deposition within the platform. Although bedrock exposures are rare along the Alaska Highway, where it traverses the Liard Lowland, outcrops of Paleozoic sedimentary rocks suggest that west of the Tintina Fault, rocks have the same tectonic affinity as the Kaska Mountains (Gabrielse, 1967). East of the Tintina Fault, splices of accreted island arc assemblages that have been variably folded, faulted and metamorphosed underlie the Alaska Highway corridor.

Overlapping older tectonic assemblages are sedimentary packages, felsic plutons, Upper Cretaceous volcanic rocks and isolated Quaternary basalt flows. For example, young (<150 million years old) sedimentary rocks are found within the Kluane Ranges, and felsic plutons dominate most of the mountains adjacent to the Alaska Highway within the Yukon Plateaus. Upper Cretaceous volcanic rocks are found north of the study area near Whitehorse, and valley-filling Quaternary basalt flows occur at Whitehorse, and between Rancheria and the Liard River.

Surficial geology and glacial history

Surficial geology along the Alaska Highway corridor is heavily influenced by the glacial history of southern Yukon. Several periods of glaciation occurred in the region in the Quaternary, the latest being the Late Wisconsinan McConnell Glaciation (Fig. 3). Ice flow during the McConnell Glaciation was generally out of ice centres in higher mountainous areas, such as the St. Elias, Coast and Cassiar mountains, and along major structural trenches and valleys.

In general, hillslopes throughout the corridor are blanketed and veneered by till. These hillslopes are commonly flanked by coarser ice-marginal meltwater deposits. Moraines and kame terraces are particularly common within the Yukon Plateaus where numerous pauses in the retreat of glaciers allowed the accumulation of debris along valley sides. In steep mountainous areas with high relief, weathered bedrock and reworked till form colluvial blankets, veneers, aprons and fans on valley sides. These unconsolidated sediments are a major source material for mass movements within the Alaska Highway corridor.

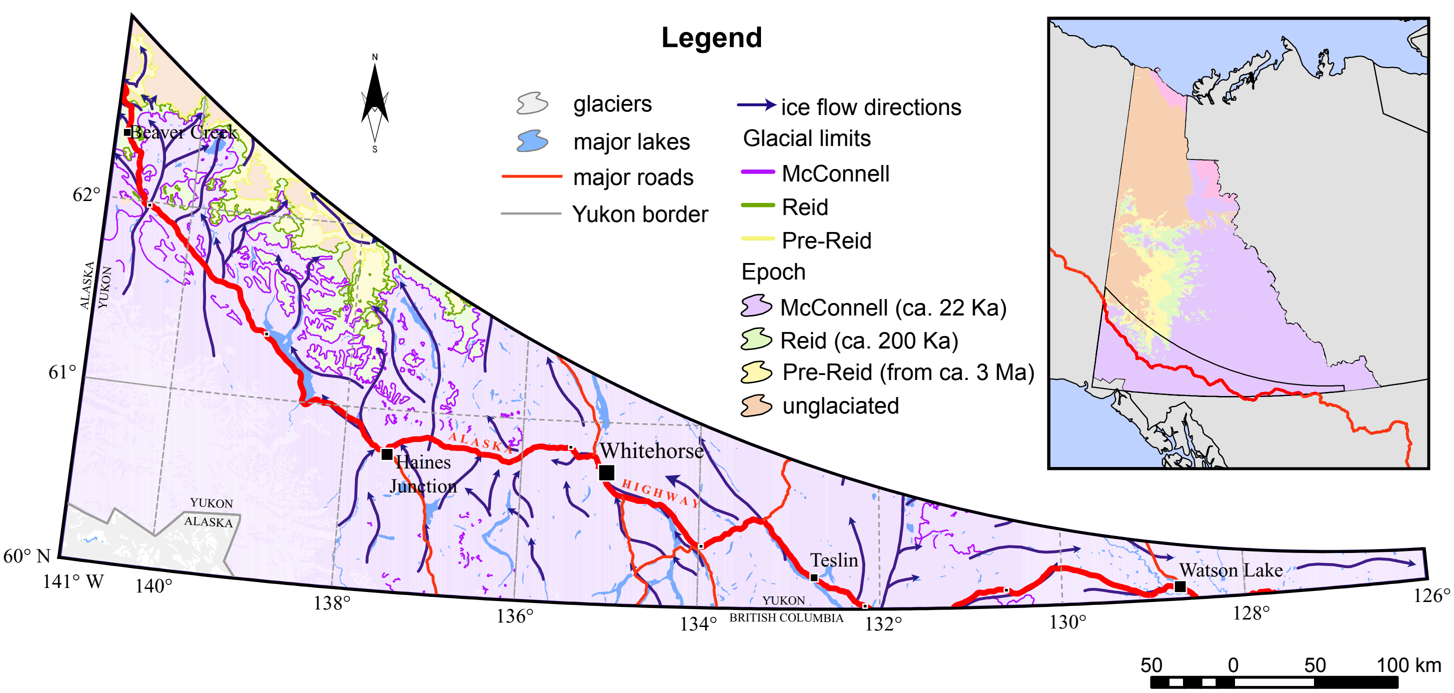


Figure 3. Glacial limits of Yukon (after Duk-Rodkin, 1999).

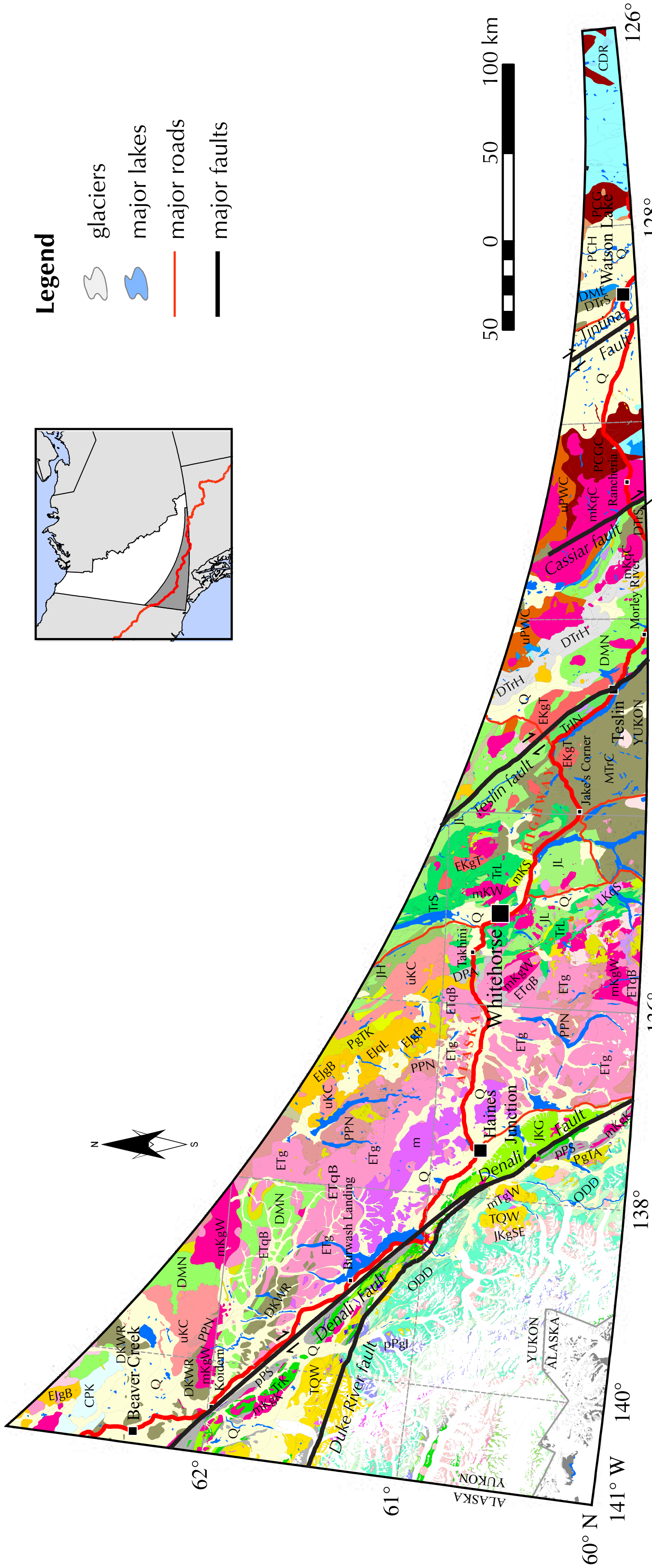


Figure 2. *Bedrock geology of southern Yukon (after Gordey and Makepeace, 2003). Bedrock geology legend on next page.*

QUATERNARY
Q - UNDIVIDED: undivided sediments (sand, silt, gravel, till)

MIOCENE
MTgW - WRANGELL: Mt. Steele phase of Wrangell plutonic suite (biotite granodiorite)

MIOCENE - OLIGOCENE
MOTqT - TKOPE: heterogeneous epizonal plutonic suite (hornblende-biotite granite, quartz syenite, quartzite)

EARLY TERTIARY
ETg - UNDIVIDED: undivided plutons (granodiorite, leucogranodiorite, quartz monzonite, quartz-diorite, tonalite)
ETgS - SEWARD: plutonic suite (biotite-hornblende-tonalite, quartz diorite, biotite-muscovite granodiorite, quartz monzonite)
ETqB - BENNETT: epizonal plutonic suite (alaskite)

PALEOGENE
PgTA - AMPHITHEATRE: easterly derived non-marine fault-trough clastic wedge (sandstone, siltstone, conglomerate, lignite)
PgTK - KAMLOOPS: calc-alkaline non-marine transitional arc volcanic rocks (andesite, basalt, dacite, rhyolite, pyroclastic rocks)

TERTIARY and QUATERTARY
TQE - EDZIZA: transitional rift volcanic rocks (basalt, trachyte)
TQW - WRANGELL: arc and transform volcanic rocks (andesite, dacite, basalt, rhyolite)

LATE CRETACEOUS
LKqS - SURPRISE LAKE: epizonal plutonic suite (alaskite, hornblende granite, quartz monzonite)

UPPER CRETACEOUS - OLIGOCENE
uKC - CARMACKS: transtensional arc volcanic rocks (andesite, pyroclastic rocks, rhyolite, trachyte, dacite, basalt)

UPPER UPPER CRETACEOUS
uKY - YAKUTAT: accretionary prism (greywacke, conglomerate, shale, siltstone, turbidite, mélange)

EARLY CRETACEOUS
EKgT - TESLIN: plutonic suite (granite, granodiorite, quartz monzonite, quartz monzodiorite)

MID-CRETACEOUS
mKgK - KLUANE: plutonic suite (hornblende-biotite granodiorite)
mKgW - WHITEHORSE: plutonic suite (hornblende-biotite granodiorite, quartz diorite, biotite-quartz monzonite, leucogranite)
mKqC - CASSIAR: locally sheared plutonic suite (biotite quartz monzonite, granodiorite)

mKS - SOUTH FORK: transtenstional cauldron-subsidence and arc volcanic rocks (basalt, andesite, latite, rhyodacite, pyroclastic rocks)

CRETACEOUS
KS - SKEENA: easterly derived back-arc clastic rocks (greywacke, sandstone, siltstone, shale, conglomerate, coal)

KV - VALDEZ: accretionary prism (argillite, greywacke, greenstone, breccia, tuff)

LATE JURASSIC - EARLY CRETACEOUS
JKgSE - ST. ELIAS: plutonic suite (hornblende-biotite granodiorite, quartz diorite, quartz monzonite, diorite)

UPPER JURASSIC - LOWER CRETACEOUS
JKG - GAMBIER: arc/rift volcanic rocks and associated sediments (conglomerate, greywacke, siltstone, argillite, rhyolite)

MIDDLE JURASSIC
MJg - UNDIVIDED: foliated plutons (hornblende-biotite diorite, granodiorite)

LOWER and MIDDLE JURASSIC
JH - HAZELTON: volcanic arc complexes in Stikinia (basalt, andesite, rhyolite, dacite, pyroclastic rocks)

JL - LADNER : arc clastic and volcanic rocks (argillite, siltstone, greywacke, conglomerate, andesite, pyroclastic rocks)

EARLY JURASSIC
EJgB - BLACK LAKE: suite of discordant plutons with marginal phases of monzonite (hornblende-biotite granodiorite, quartz monzonite, biotite-hornblende quartz diorite, hornblende monzonite)
EJqL - LONG LAKE: porphyritic plutonic suite/clasts occur in L. Jurassic conglomerate (biotite-hornblende quartz-monzonite, biotite quartz monzonite)

LATE TRIASSIC
LTrgS - STIKINE: sub-alkaline/calc-alkaline plutonic suite (biotite-hornblende diorite, hornblende quartz monzodiorite, granodiorite, quartz monzonite)

UPPER TRIASSIC - LOWER TRIASSIC
TrJN - NICOLA: arc volcanic and related clastic rocks (andesite,dacite, rhyolite, limestone, volcaniclastic rocks , shale, siltstone)
TrK - KARMUTSEN: rift volcanic and marine carbonate rocks (tholeiite, limestone)
TrL - LEWES RIVER: arc clastic rocks (tuff, sandstone, siltstone, limestone, chert)
TrS - STUHINI: arc volcanic and related clastic rocks (andesite, basaltic andesite, ignimbrite, volcaniclastic rocks , sandstone, siltstone)

TRIASSIC - JURASSIC
Trdum - UNDIVIDED: undifferentiated plutons (diorite, gabbro, ultramafic rocks)

MESOZOIC
Mg - UNDIVIDED: individual plutons (diorite, quartz monzonite, monzonite)

PERMIAN
EPqSC - SULPHER CREEK: foliated pluton (biotite- muscovite quartz monzonite gneiss)

PENNSYLVANIAN - PERMIAN
pPS - SKOLAI: arc volcanic and sedimentary rocks (sandstone, argillite, chert, limestone, basalt, andesite, dacite)

pPgI - ICEFIELD RANGES: plutonic suite (diorite, quartz diorite, syenite, granodiorite, hornblende-biotite quartz monzonite)

CARBONIFEROUS - PERMIAN
CPK - KLONDIKE SCHIST: metamorphosed felsic volcanic rocks? (phyllite, quartzite, schist, gneiss, amphibolite)

MISSISSIPPIAN - UPPER TRIASSIC
MTrC - CACHE CREEK: oceanic volcanic and sedimentary rocks and local accretionary prism melange (basalt, peridotite, gabbro, blueschist, chert, argillite, sandstone, limestone)

DEVONIAN - CRETACEOUS
DKWR - WHITE RIVER: mixed oceanic assemblage and overlying clastic rocks (chert, argillite, phyllite, gabbro, peridotite, sandstone, conglomerate)

DEVONIAN - MISSISSIPPIAN
DMB - BESA RIVER: distal marine clastic wedge (shale, mudstone, siltstone)

DME - EARN: fault-trough clastic wedge and related volcanic rocks (conglomerate, sandstone, mudstone, shale, trachyte, rhyolite, basalt)
DMEC - EARN: fault-trough clastic wedge and related volcanic rocks (conglomerate, sandstone, mudstone, shale, trachyte, rhyolite, basalt)

DMgM - MINK CREEK: S-type plutons and metamorphosed equivalents (muscovite-biotite granite, leucogranite, augen gneiss, biotite quartz monzonite gneiss)

DMN - NASINA: metamorphosed continental margin sedimentary rocks (schist, gneiss, marble, metachert, metatuff)

DEVONIAN - PERMIAN
DPA - ASITKA: arc volcanics and platform carbonate rocks/ basement of Stikinia (basalt, rhyolite, pyroclastic rocks, limestone, shale, sandstone, chert)

DEVONIAN - TRIASSIC
DTrH - HARPER RANCH: arc clastic rocks/ basement of Quesnellia (volcanic rocks, sandstone, basalt, andesite, dacite, pyroclastic rocks)

DTrS - SLIDE MOUNTAIN: oceanic marginal basin volcanic and sedimentary rocks (basalt, peridotite, gabbro, chert, argillite, volcaniclastic rocks)

ORDIVICIAN - DEVONIAN
ODD - DONJEK: marine back-arc volcaniclastic rocks (siltstone, sandstone, slate, phyllite, schist, greywacke, limestone, marble)

ODKP - KASKAWULSH: metamorphosed back-arc sedimentary rocks (phyllite)
ODKC - KASKAWULSH: undivided marine back-arc sedimentary rocks (shale, conglomerate)

CAMBRIAN - DEVONIAN
CDR - ROCKY MOUNTAINS: passive continental margin marine sedimentary rocks (dolomite, limestone, sandstone, shale)
CDRC - ROCKY MOUNTAINS: displaced passive continental margin marine sedimentary rocks (dolomite, limestone, sandstone, shale, alkalic tuff, basalt)

PROTEROZOIC - PALEOZOIC
PPa - AMPHIBOLITE: metamorphosed mafic volcanic and ultramafic rocks of uncertain affinity (amphibolite, gneiss, schist, ultramafic)

PPN - NISLING: metamorphosed continental margin sedimentary rocks (schist, marble, orthogneiss)

UPPER PROTEROZOIC - PALEOZOIC
PCG - GOG: rifted and passive continental margin sedimentary rocks (quartzite, conglomerate, mafic flows, siltstone, shale, limestone, slate, schist)
PCGC - GOG: rifted and passive continental margin sedimentary rocks (quartzite, conglomerate, mafic flows, siltstone, shale, limestone, slate, schist)

UPPER PROTEROZOIC - LOWER CAMBRIAN
PCH - HYLAND: mainly clastic off-shelf passive continental margin sedimentary rocks (slate, siltstone, sandstone, conglomerate, shale, limestone)

UPPER PROTEROZOIC
uPWC - WINDERMERE: mainly continental margin sedimentary rocks (quartz-feldspar grit, sandstone, siltstone, shale, limestone, greenstone, marble)

UNCERTAIN
m - UNDIVIDED: undifferentiated metamorphic rocks of uncertain protolith (schist, gneiss)

Figure 2. *Legend.*

Towards the end of the McConnell, deglaciation occurred in a series of intervals of retreat and stagnation, with ice lobes occupying valley bottoms and damming numerous drainage routes. Extensive glacial lake deposits were left behind blanketing valley bottoms with thick sequences of silt, fine sand and lesser amounts of clay. These glaciolacustrine materials are widespread in the southern Yukon, and their fine-grained textures are particularly susceptible to the growth of ground ice, gullying and landslides. During and immediately following deglaciation, expanses of freshly exposed sediments were reworked by the wind so that loess veneers and dunes commonly cap glacial sequences in the valley bottoms especially near glacial limits.

Climate

The study area generally has a sub-arctic continental climate with long, cold winters, short mild summers, low relative humidity and low to moderate precipitation (Table 1). The area between Kluane Lake and Haines Junction has a more moderate climate than to the north or east due to its relative proximity to the Pacific Ocean. The Yukon Plateaus zone experiences the most extreme temperatures as well as the driest climate. In contrast, farther east, the Cassiar Mountains form an orographic barrier causing precipitation totals to be relatively high. The Liard Lowland is the wettest basin in Yukon and experiences cold winters with few mild spells. Local relief and aspect modify regional climate throughout the entire region; for example, cold air trapped in the valleys of the Yukon Plateaus frequently causes temperature inversions (Wahl et al, 1987).

Vegetation

The Alaska Highway corridor lies entirely within the Boreal Cordillera Ecozone. Dominant tree species include white and black spruce. Most south-facing slopes are occupied by meadows and open forests of trembling aspen. Lodgepole pine is commonly found on well drained sites or within recent burns. Less common tree species include balsam poplar, alpine fir, and white birch. Treeline varies between 1400 m in the east and 1200 m in the northwest of the corridor. Shrub birch and willow are characteristic in subalpine areas and extend into alpine tundra. Forest fires are frequent throughout the corridor (Fig. 4), and the majority of forested areas may be regarded as being in various stages of post-fire succession.

Table 1. Environment Canada climatic norms for period 1971-2000.

Station	Daily mean temperature (°C)			Mean precipitation (mm)		
	January	July	Annual	January	July	Annual
Beaver Creek	-26.9	14.0	-5.5	13.5	97.2	416.3
Burwash Landing	-22.0	12.8	-3.8	9.6	66.2	279.7
Whitehorse	-17.7	14.1	-0.7	16.7	41.4	267.4
Teslin	-19.2	11.4	-1.2	27.3	45.9	343.3
Watson Lake	-24.2	15.1	-2.9	26.1	59.9	404.4

Permafrost

The Alaska Highway corridor is underlain by discontinuous permafrost. For much of its length it lies within the transition zone from sporadic discontinuous permafrost to extensive discontinuous permafrost (Fig. 5; Heginbottom, 1995). Local climate, vegetation cover, and terrain (aspect, surficial materials and hydrologic conditions) are the primary controls on the distribution of permafrost. However, snow depth also plays an important role. Rampton et al. (1983) characterized the distribution and character of ground ice along the proposed Alaska Highway gas pipeline route based on geotechnical drillhole data. They found the percentage of ground underlain by permafrost varied considerably: 80% of valleys and lowlands north of Kluane Lake; <50% of the ground between Kluane Lake and Takhini River; <20% from the Takhini River valley to just west of Teslin; and <5% east of Teslin Lake. The distribution and character of permafrost is far less known on the hillslopes, plateaus and summits adjacent to the corridor. The structure and extent of permafrost in these locations may be exceedingly irregular due to variations in the land surface, materials, snow and vegetative cover. Temperature inversions further complicate altitudinal trends in permafrost distribution. Nonetheless, permafrost is generally thicker and more widespread on north-facing slopes where thick vegetative mats, tree canopy and poor soil drainage conditions exist.

Loss of soil strength due to the thaw of ground ice is an important factor in landslide processes in the corridor. Where permafrost conditions exist, the presence of shallow ground ice is strongly related to the occurrence of fine-grained material and ample groundwater supply. Rampton et al. (1983) describe several settings where these conditions exist. They include locations where fine-grained material overlies, truncates or is interstratified with more permeable coarse-textured material, poorly drained areas adjacent to wetlands and streams, and sites adjacent to bedrock valley walls.

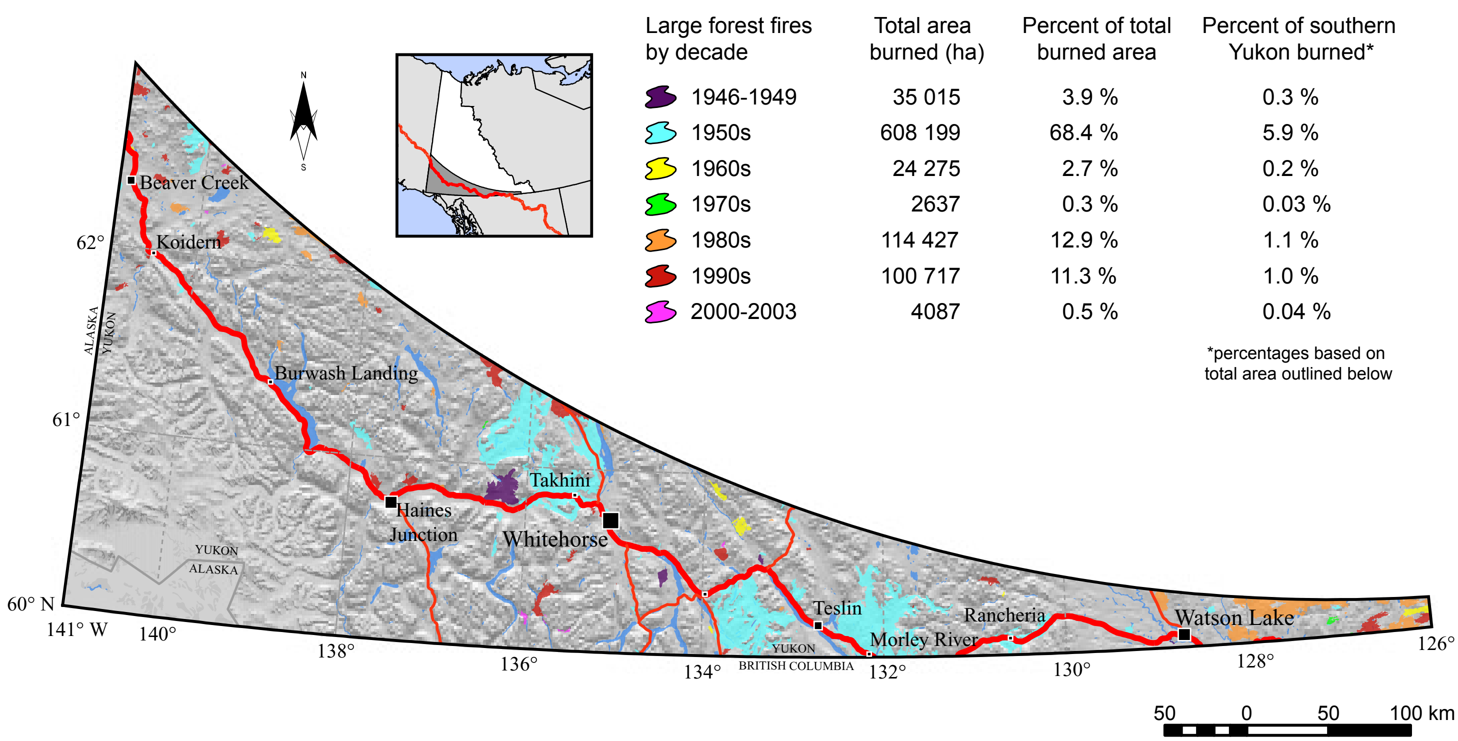


Figure 4. *Distribution of large forest fires documented within the Alaska Highway corridor since 1946. Data courtesy of Fire Management, Protective Services Branch, Yukon Government, 2004. Before 1997, only fires larger than 200 hectares were included in this compilation.*

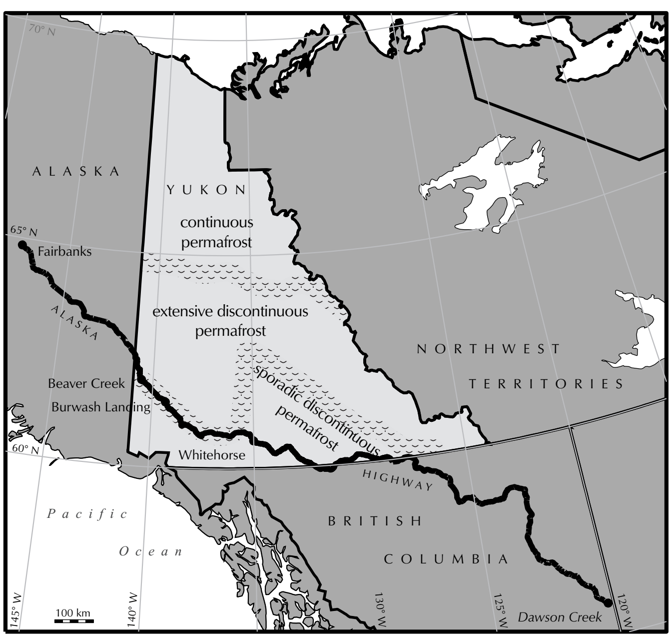


Figure 5. *General distribution of permafrost in Yukon Territory (after Heginbottom, 1995).*

Seismicity

The Alaska Highway corridor comprises areas of high seismicity (Fig. 6). Transform boundary movement between the Pacific and North American crustal plates, to the west of the study area, and dextral transcurrent movement along the Denali Fault system are the two primary causes of seismicity in the corridor. Although older surface disturbance has been noted, Clague (1979b) estimates that there has not been any major surface rupturing on the Denali Fault in Yukon Territory during the last few hundred to several thousand years. Along segments in Alaska, however, the Denali Fault is currently active, and has recently caused numerous large landslides (Harp et al., 2003).

PREVIOUS STUDIES

Numerous terrain studies have been undertaken within the Alaska Highway corridor in association with highway construction, pipeline proposals, as well as national and territorial mapping strategies and academic research. In general, the material and stability of the terrain immediately surrounding the highway and proposed pipeline route are well constrained. The possible downstream effects of processes operating on adjacent hillsides and drainage basins,

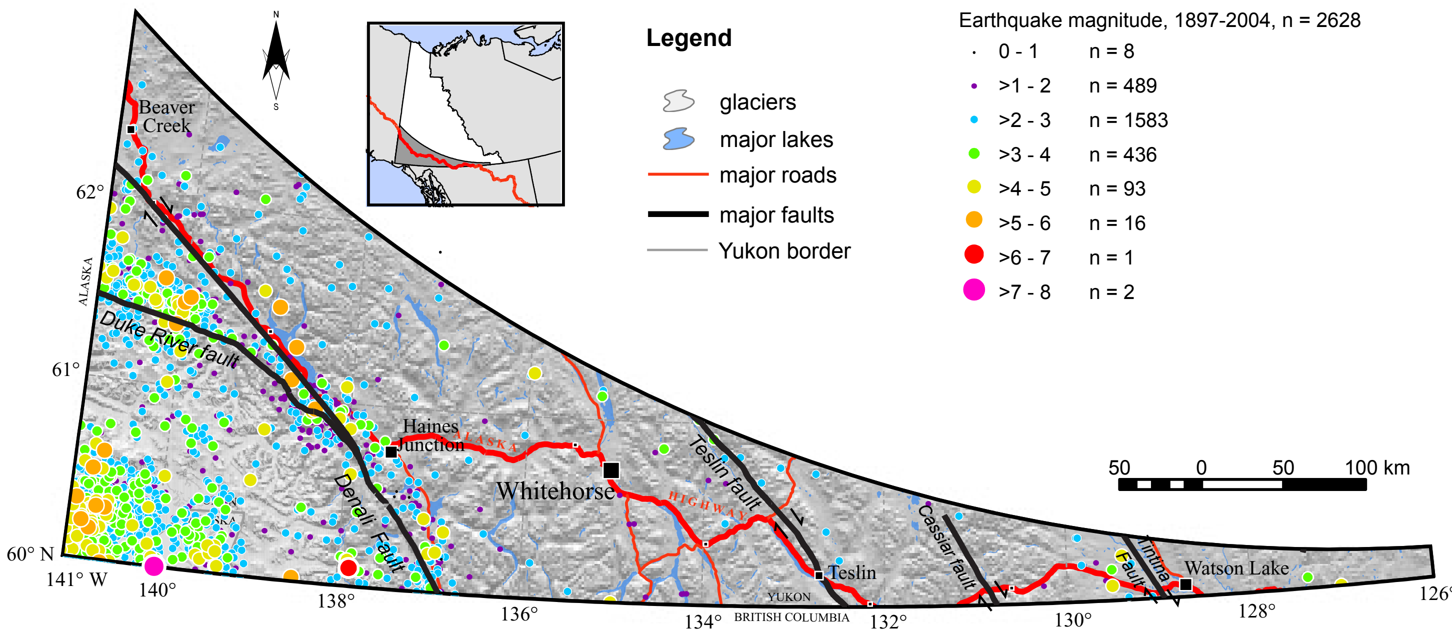


Figure 6. Seismic activity map of southern Yukon, 1899 to 2003. Data courtesy of Geological Survey of Canada.

however, have mostly not been considered. In addition, the influence of climate change on the distribution, frequency and magnitude of landslides within the corridor remains unexplored.

Surficial geology

Surficial geology mapping by the Geological Survey of Canada has been carried out throughout the entire study area at scales between 1:100 000 and 1:250 000. In addition, GEOPROCESS File maps exist for the study area at a scale of 1:250 000 (Doherty et al., 1994a,b,c; Mougeot et al. 1994, 1996 a,b,c,d; Exploration and Geological Services Division, 2002). These maps highlight geological processes and terrain hazards in a regional context, by identifying mass movements, permafrost distribution, flood risks, faults, seismic activity and recent volcanism. This mapping, however, is largely at a scale unsuitable for distinguishing individual landslides and potential instabilities. Soils mapping at 1:20 000 scale is available for limited locations within the study area also (Smith, 1988).

Landslide case studies

A number of case studies of mass movements found within the Alaska Highway corridor have been completed. These studies include investigations of glacier-related hazards (Bayrock, 1967; Driscoll, 1976; Clague, 1979a), rock glaciers (Blumstengel, 1988), fire-induced permafrost degradation (Burn, 1998) and landslides (Broscoe and Thomson, 1969; Price, 1973; Clague, 1981; Gustafson, 1986; Evans and Clague, 1989; Harris and Gustafson, 1993; Everard, 1994; Hugenholtz, 2000). These studies generally concentrate on activity in the St. Elias Mountains where the greatest current landslide hazard exists. Although the effect of episodic climatic events on slope stability has been investigated (Clague, 1981; Evans and Clague, 1989, 1994), the anticipated effect of climate warming in the study area is poorly understood.

Proposed pipeline assessments

Extensive work has been performed by Foothills Pipelines Ltd. in order to secure a viable pipeline route along the Alaska Highway corridor. These studies include terrain mapping, as well as geotechnical and permafrost investigations. As a collection, these studies are very thorough and reflect a considerable body of knowledge. However, these studies focus on a 3-km wide strip of the corridor and do not take into account the effects of processes operating on adjacent mountain sides and within adjacent drainage basins. In addition, the studies do not evaluate potential slope instabilities within the context of global warming and they only consider the effect of potential permafrost degradation where it would be pipe-induced.

Alaska Highway investigations

In conjunction with construction, maintenance and upgrades of the Alaska Highway, a collection of studies related to slope stability along the Alaska Highway have been made by the Government of Yukon Department of Highways and Public Works. The department possesses numerous maintenance reports of repairs related to landslide activity. As well, environmental assessments and geotechnical drill hole logs for every half-kilometre have been completed for the entire length of the highway. Along sections of the highway that have been realigned in the past ten years, geotechnical boreholes have been drilled every 100 m.

Permafrost studies

Permafrost distribution in the Alaska Highway corridor has been described in a very generalized sense at a scale of 1:250 000 on GEOPROCESS File and surficial geology maps as well as on 1:1 000 000-scale national permafrost maps (Heginbottom and Radburn, 1992). Post-fire permafrost degradation is described by Burn (1998). Permafrost conditions directly beneath the Alaska Highway and the proposed pipeline route are well constrained by extensive geotechnical drilling programs. A characterization of ground ice distribution in the corridor was given by Rampton et al. (1983) based on boreholes drilled in association with pipeline planning. The highway and proposed pipeline routes characteristically lie in valley bottoms and on flat terrain. As a result, the distribution of permafrost on adjacent hillsides is largely unstudied.

LANDSLIDE PROCESSES

In recognition that the modes of failure in any region are strongly controlled by local geology, physiography, seismicity and climate, this report divides the Alaska Highway corridor into five zones according to dominant types of mass movement (Fig. 1). These zones approximate the broad physiographic regions of Mathews (1986). However, the transitions from one zone to another do not always coincide precisely with physiographic boundaries. In the following sections, landslide setting and behaviour are described using case studies, and referring to previous work, where available.

The landslide terms applied in this report are illustrated in Figure 7. Varnes' (1978) terminology is used to describe the processes as well as the type of material involved in non-periglacial displacements. Where two separate modes of failure contribute to movement, the apparent dominant mode is used to name the landslide type.

Where the presence of permafrost influences the failure process, terminology from the *Glossary of permafrost and related ground-ice terms* (Everdingen, 1998) is utilized. "Active-layer failures" describe flows or slides of material in which failure occurs at the interface of a frozen substrate (Fig. 7). 'Retrogressive thaw slumps' describe mass movements which involve the thaw of a steep headscarp face from which thawed veneers or blocks of soil flow or fall. Material from the headscarp area is subsequently transported away entirely by flow processes along a low angle tongue (McRoberts and Morgenstern, 1974).

WELLESLEY DEPRESSION ZONE

Physiography and drainage

The Wellesley Depression zone comprises the northernmost 64 km of the Alaska Highway corridor (Fig. 8). It is a lowland area of subdued relief north of the Denali Fault. For the most part, it lies within the Wellesley Depression physiographic region of Mathews (1986). It also includes, for the purpose of this report, a small section of the Klondike Plateau physiographic region (Mathews, 1986).

A number of streams drain this zone (Fig. 8). Beaver, Dry and Snag creeks drain north and eventually eastwards into the White River. Scottie Creek drains the northernmost few kilometres of the corridor west into Alaska and the Tanana River. In general, due to the presence of widespread permafrost and fine-grained soils, this portion of the Alaska Highway corridor is characteristically imperfectly drained. Exceptions to this characterization include isolated upland areas, which may be well drained (Rampton, 1978d,e).

Surficial geology and glacial history

The Wellesley Depression zone contains the limits of the McConnell (late Wisconsinan), Reid (middle Pleistocene), and preReid (<2.6 Ma) ice sheets (Rampton, 1978d,e; Duk-Rodkin, 1999a and b). Ice and outwash from these various glaciations flowed northwest from the Shakwak Trench and

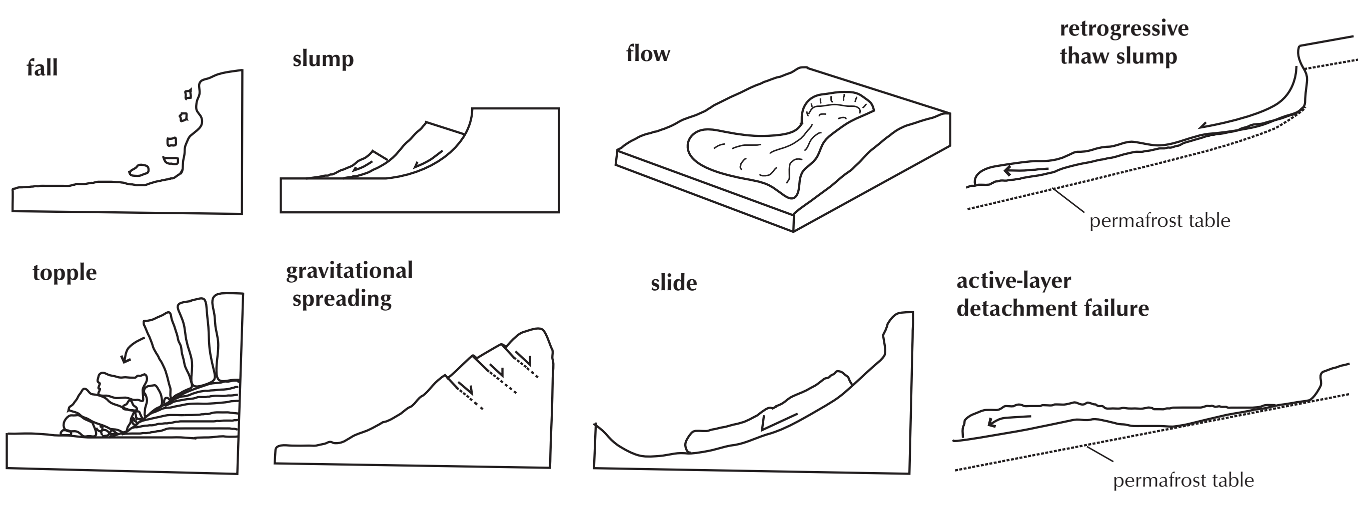


***Figure 7.** Landslide terminology used in this report. Numerous landslide types exist that are transitional between the types illustrated above, but for the purpose of classification, a simplified nomenclature is used.*

spread out over the Wellesley Depression, leaving behind a landscape with wide flat river valleys and broad, rounded hills.

Most lowland surfaces are underlain by fine-grained or gravelly alluvium. Glaciofluvial plains and terraces are found along Beaver, Enger and Dry creek valleys. An extensive gravelly outwash plain occupies the lowland between Beaver and Snag creeks. Thick (0.5 to 14 m) peat deposits blanket alluvial silts, sands and gravel (Rampton, 1978d,e), and thermokarst lakes commonly dot the lowlands. Pleistocene glaciers dammed several drainages and ponded lakes in Scottie Creek and the headwaters of Dry Creek. These areas are underlain by lacustrine sand and silt material which is subject to intense thermokarst activity.

Till plains commonly flank alluvial deposits found in valley bottoms and may be locally pitted and hummocky. Uplands are generally blanketed by till colluvium and weathered bedrock. A thin veneer of wind-blown silt and tephra covers most deposits.

Bedrock geology

Bedrock exposures are confined to natural and man-made outcrops along the isolated hills in the Wellesley Depression zone. In general, bedrock in the area consists of a 400- to 150-million-year-old oceanic assemblage of sheared and massive mafic and ultramafic rocks, as well as deep-sea sedimentary rocks of the Windy-McKinley Terrane (Fig. 2; Tempelman-Kluit, 1974).

Permafrost

Permafrost is discontinuous but widespread in the Wellesley Depression zone (Heginbottom and Radburn, 1992; Heginbottom, 1995). It is absent from well drained south-facing slopes, but extensive along valley bottoms and uplands. Boreholes drilled in association with the proposed Alaska Highway corridor pipeline suggest that permafrost is up to 30 m thick, but is typically 15 to 18 m thick (Foothills Ltd., 1976).

Ice lenses and ice wedges are common features in fine-grained alluvial plains, fans and aprons as well as within colluvium and till deposits. Segregated ice is less common in gravelly alluvial and glaciofluvial sediments, which may be thaw stable (Horel, 1988).

Landslide processes

Landslides are rare in the Wellesley Depression due to the area's subdued relief and the limited extent of stream incision (Fig 8). Slope failures are primarily related to thermokarst subsidence and streambank erosion of icy organic or fine-grained sediments. Shallow debris slides and rock slumps are less common.

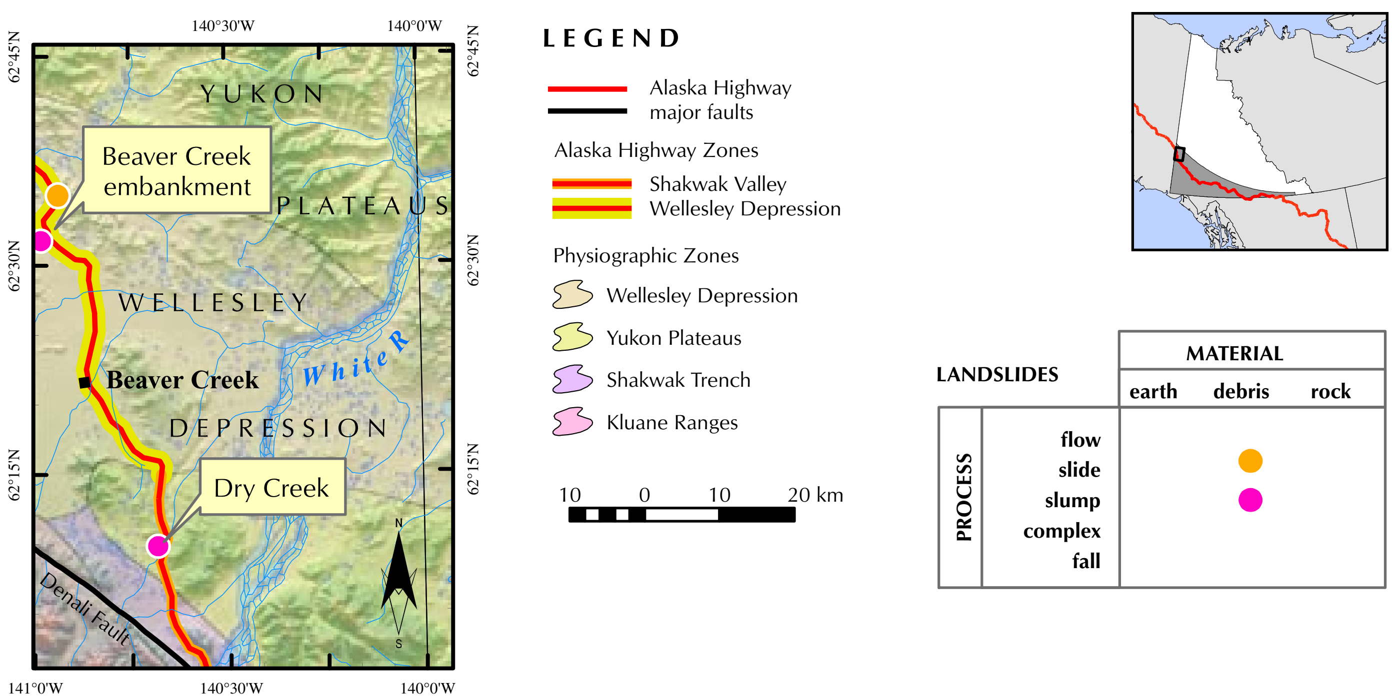


Figure 8. *Overview of noted landslide locations within the Wellesley Depression landslide zone. Physiographic zones modified from Matthews (1986).*

Figure 9. *Debris slide related to growth of a thermokarst depression adjacent to the Alaska Highway near Dry Creek (see Figure 8). Thermokarst activity was initiated after overlying vegetation and gravel was removed by aggregate mining for highway construction.*

Debris slides and topples

Terrain susceptible to thermokarst activity is widespread within the valley bottoms of the Wellesley Depression zone. Two dominant landslide settings were identified: firstly, along the periphery of growing thermokarst depressions on flat terrain, and secondly at the base of slopes underlain by thaw-unstable ground.

Where thaw-related subsidence causes the formation of depressions that are several metres deep, the periphery of the depression is susceptible to slow landslide processes (see Fig. 9). Although translational sliding is the most prevalent mode of failure in these settings, localized flexural toppling of narrow blocks of debris was inferred due to the presence of tension cracks dipping away from the direction of movement near the base of many slopes surrounding thermokarst lakes in the region.

Where permafrost-related subsidence occurs at the base of a slope, debris slides may be initiated due to debutressing of the slope (see *Case study 1: Beaver Creek embankment*, p. 38). These slides characteristically display multiple headscarps that are arcuate and concave towards the direction of movement. Slight back-tilting of individual blocks may also be evident. Runout distances are small because a portion of the displaced material fills the volume created by thaw consolidation of the underlying ice-rich sediment. At the Beaver Creek embankment site, the failure rate of these landslides is generally slow, on the order of centimetres to several metres a year (unpublished data, Department of Highways and Public Works). Although both the Dry Creek and Beaver Creek embankment failures were triggered by such development, it is suspected that naturally occurring permafrost subsidence leads to similar mechanisms of failure.

One large debris slide was identified within the Wellesley Depression zone near the Canada-U.S. border, where the Alaska Highway circumnavigates a large (1 km^2) lobe of debris (Rampton, 1978e; Fig. 8). The deposit, which is located at the base of a small drainage basin, is subdued in form and supports mature vegetation. Aerial photograph interpretation of the suspected source area indicated that it lacks a definable headscarp and any signs of modern instability. Due to the highly modified form of the landslide and its position beyond late Wisconsinan glacial limits, it is suspected to be of Pleistocene age.

Active-layer failures

Rare active-layer failures are also observed on moderately steep (35 to 15°) slopes blanketed by medium- to fine-textured till or colluvium in the Wellesley Depression zone (Fig. 10). However, the presence of extensive areas underlain by icy sediment suggests that disturbance of vegetation or groundwater may also initiate active layer detachment slides on gentler slopes.

Debris slumps

Small rotational slides are frequently found along the banks of rivers such as Beaver Creek and Dry Creek as a result of fluvial erosion. Slumps may also occur along man-made highway cuts in ice-rich fine-grained deposits if precautions are not taken to adequately insulate the exposures and minimize disturbance to drainage.

Figure 10. *Active-layer failure scar (arrow) on an isolated upland within the Wellesley Depression landslide zone. This type of landslide is related to the extensive permafrost located in the area.*

SHAKWAK VALLEY ZONE

Physiography, and drainage

The Shakwak Valley is a structurally controlled trench dividing the rugged and glaciated peaks of the St. Elias Mountains from the expansive uplands, rounded summits and adjoining ridges of the Yukon Plateaus. It is a broad 7- to 20-km-wide valley at around 800 m a.s.l. Except for the bottoms of meltwater channels, and areas of thaw-unstable ground, the trench floor is well to moderately drained. The southernmost 20 km of the Shakwak Valley zone drains south to the Alsek River and Pacific Ocean. North of this area, Kluane Lake, and the Kluane, Donjek and White rivers drain north into the Yukon River.

The Kluane Ranges (Fig. 11) abruptly rise 1600 m above the southwest side of the Shakwak Valley as a narrow band of steep glaciated peaks that reach elevations of up to 2500 m a.s.l. In several locations, the main divide of the Kluane Ranges are broken by high gradient rivers draining the large valley glaciers of the Icefield Ranges. The Icefield Ranges are an area of extremely high relief (Fig. 11) that support the largest non-polar icefield in the world and include the highest mountain in Canada (Mt. Logan, 5959 m). The isolated glaciers in the Kluane Ranges comprise cirque and small valley glaciers that are generally situated above 3000 m, and are commonly debris covered. Periglacial features, such as solifluction lobes, patterned ground and rock glaciers are common.

On the opposing valley side, the topography and relief of the western Yukon Plateaus is much more subdued than that of the Kluane Ranges (Fig. 11). Local relief rarely exceeds 1750 m a.s.l. and rock faces are rare except along Kluane Lake. Generally, the rounded or dome-like summits of the Ruby Range, which flank the northeastern side of the Shakwak Valley, are separated by smooth broad ridges. Drainage within the Ruby Range is well incised and of moderate to low gradient.

Surficial geology and glacial history

The Shakwak Valley comprises a gently undulating and glacially fluted floor underlain by thick deposits of till, lacustrine silts and outwash from a number of glaciations, as well as Holocene alluvium and loess (Denton and Stuiver, 1967; Rampton, 1969; Rampton and Paradis, 1981a,b; Rampton, 1979, 1978a,b,c). Along the base of the mountain fronts of the Kluane Ranges and the Ruby Ranges, colluvial aprons and fans grade into broad alluvial fans and aprons.

During the McConnell Glaciation, ice flowed out of the valleys of the St. Elias Mountains and extended northwest along the Shakwak Trench and into the Ruby Range (Fig. 3; Rampton 1978a,b,c,d; Rampton and Paradis, 1981a). Most of the uplands in the Ruby Range remained ice-free during the McConnell, although glacial features in the southern portion of the range suggest it did support cirque glaciers and local ice caps. Earlier glaciations submerged all the uplands east of the Shakwak Trench beneath ice (Fig. 3, 11). During the waning stages of the McConnell glaciation, several glacial lakes were created within the Shakwak Trench including Glacial Lake Kloo and Champagne (Rampton, 1978a,b,c,d,e). During the subsequent neoglacial (3000 years ago to present), glaciers in the Kluane and Icefields ranges advanced and led to the creation of many ice-cored moraine complexes which now occupy upper catchments in the Kluane Ranges. Glacial Lake Alsek inundated the area near Haines Junction several times during this period due to repeated advances of the Lowell Glacier (Clague and Rampton, 1982; area just south of Fig. 11).

Bedrock geology

A central feature of the bedrock geology of the Shakwak Valley zone is the striking contrast in the distribution of bedrock types across the Shakwak Trench (Fig. 2). The contrast is the result of approximately 340 km of dextral transcurrent movement across the Denali fault system that is thought to occupy the length of the Shakwak Trench. Movement along the Denali Fault, which underlies the trench, is responsible for this contrast.

Bedrock in the Kluane Ranges consists mainly of rocks of the Alexander and Wrangellia terranes. In southwest Yukon, the Alexander Terrane is made up of Paleozoic to early Mesozoic oceanic volcanic and sedimentary rocks intruded by Paleozoic and Late Jurassic to Early Cretaceous plutons (Campbell and Dodds, 1988; Dodds and Campbell, 1992). The Wrangellia Terrane lies between the Denali Fault and the Alexander Terrane, separated from the Alexander Terrane by the Duke River fault. In the Kluane Ranges, the Wrangellia Terrane is characterized by highly deformed Permo-Triassic clastic sedimentary, carbonate and volcanic rocks, intruded by Triassic ultramafic sills and Cretaceous to Tertiary plutons and dykes (Campbell and Dodds, 1978, 1982; Dodds and Campbell, 1992). The Duke River fault, another major structural discontinuity in the study area, separates Wrangellian rocks from the Paleozoic carbonates, slates, greywackes and volcanic rocks of the Alexander Terrane to the west. Overlapping these volcanic arc sequences are sandstones and mudstones of the Jura-Cretaceous Dezadeash Formation, and Tertiary non-marine clastic and volcanic rocks (Read and Monger 1976; Dodds and Campbell, 1992).

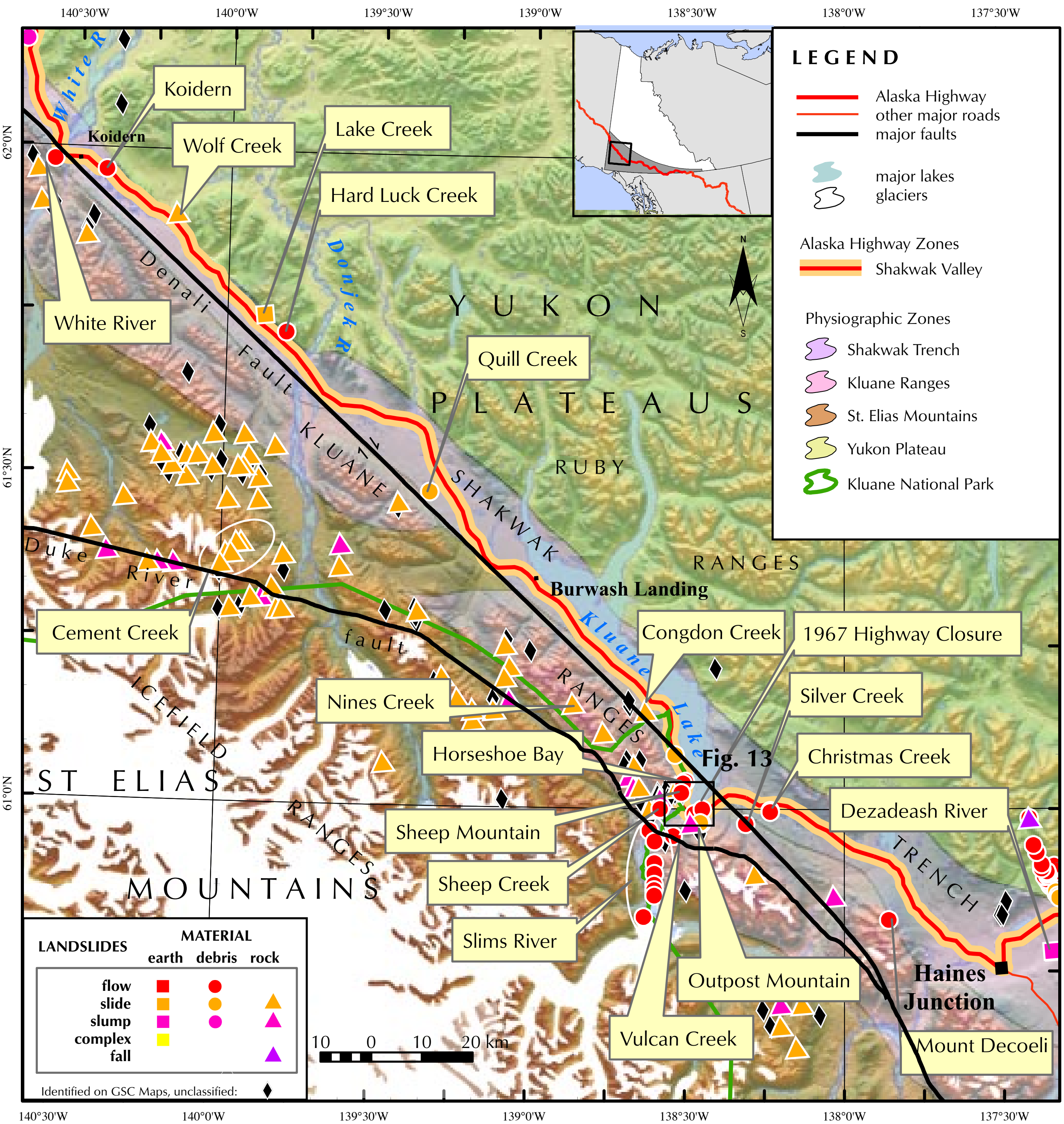


Figure 11. *Overview map of noted landslide locations within the Shakway Valley landslide zone. Physiographic zones modified from Matthews (1986).*

In contrast, the area north of the Denali Fault, the Ruby Ranges, comprises undifferentiated Paleozoic and late Precambrian high-grade metamorphic rocks intruded by, or structurally interleaved with, Mesozoic and early Tertiary plutons and late Proterozoic and Paleozoic ultramafic bodies (Muller, 1967; Tempelman-Kluit, 1974). The metamorphic rocks have an uncertain history and have been grouped together as the Kluane Metamorphic assemblage (Mezger, 1997).

Permafrost

Within the Shakwak Valley zone, the Alaska Highway corridor lies within the transition from sporadic discontinuous permafrost to extensive discontinuous permafrost (Fig. 5; Heginbottom, 1995). Rampton et al. (1983) described the distribution and character of ground ice along the proposed Alaska Highway gas pipeline route based on geotechnical drillhole data. They determined that 80% of the terrain within valleys and lowlands north of Kluane Lake are underlain by permafrost, whereas less than 50% of the area between Kluane Lake and Takhini River supports perennially frozen ground. Permafrost is generally thicker and more widespread where thick vegetative mats, dense tree cover and poor drainage conditions exist.

The distribution of permafrost and ground ice on hillsides within the Shakwak Valley zone has received little study. Widespread evidence of slow deformation on colluvial slopes and active rock-glacier development within the Kluane Ranges indicates that ground ice is abundant (Fig. 12). Harris (1987) determined that permafrost depth correlated more closely with the thickness of vegetative cover than to altitude near the south end of Kluane Lake. In addition, limited soil probing suggests that below 1800 m altitude, permafrost is absent within 2 m of the surface on south-facing slopes underlain by till (Hugenholtz, 2000; this study).

Figure 12. *Slow deformation of steep colluvial slope within Kluane Ranges indicating the presence of abundant ground ice. Many slopes within the Kluane Range exhibit similar behaviour.*

Landslide processes

Landslides are widespread in the Shakwak Valley zone and are more abundant than in any other zone described in this report. The Kluane Ranges, in particular, are subject to the most intense landslide activity in the zone due to their rugged slopes, high relief, and intensely faulted and folded rock formations. Slope failures within the Ruby Range and the main Shakwak Valley are less common. The dominant landslide processes in the entire region include rock slides, rock slumps, rock fall, gravitational spreading, rock flows, debris slides and debris flows, many of which are related to active-layer failures.

Rock slides

Numerous large rock slides have been documented in the Shakwak Valley zone and adjacent mountains (Clague, 1981; Gerath and Smith, 1989; Rampton, 1968; Everard, 1994). Where a sliding rock mass loses cohesion, a rock slide may develop into a mobile rock avalanche. Due to their high velocities, volumes and run-out distances, rock slides, particularly those that develop into rock avalanches, are potentially amongst the most destructive, yet least frequent form of slope failure in the corridor.

Rock slides are most abundant in the tributary valleys of the Kluane Ranges where regional uplift and incision by streams and glaciers have left steep valley walls. Everard (1994) found that the regional distribution of large rock slides is related to the distribution of Neogene volcanic rocks of the Wrangellia Terrane. The frequency of failures in these sequences was attributed to their intensely fractured and faulted nature and their high topographic position relative to valley bottoms. For similar reasons, rock slides are especially common in the Amphitheatre Group. The location of rock slides was also found to correlate well with zones of weathered rock along regional faults, particularly near fault segments that are seismically active, as is the case along Cement Creek (Everard, 1994). Within the main Shakwak Valley, large rock slides have been documented in the Sheep Mountain, Congdon Creek and Wolf Creek areas.

The failure history of a large rock avalanche deposit on the southern slopes of Sheep Mountain is documented by

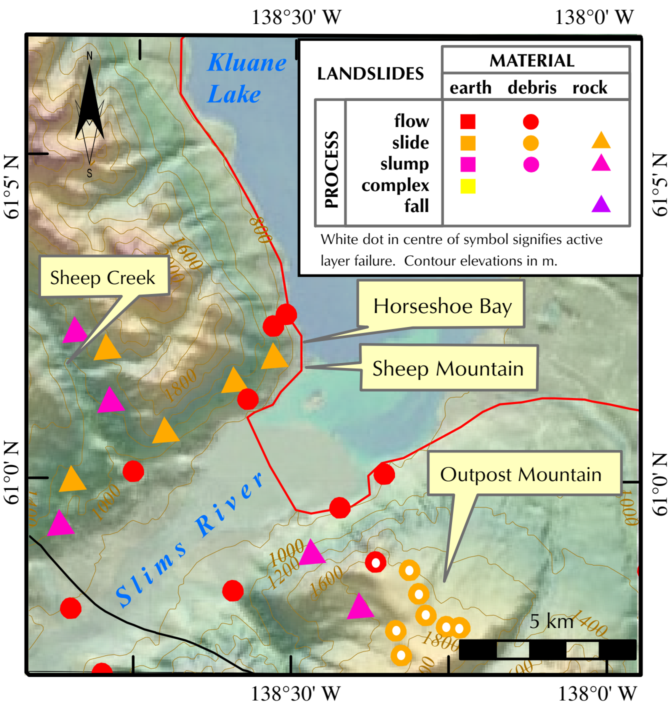


__Figure 13.__ Map of southern Kluane Lake depicting location of various landslide types.

Clague (1981; Fig. 13 and 14). Two super-imposed phases of failure were identified, one between 1950 to 1200 years B.P., and the other 1200 to 490 years B.P. In total, approximately 5 to 10 million cubic metres descended the mountain side in two separate events. These failures involved rapidly moving masses of rock which extended up to 1.5 km from their source (Clague, 1981). Repeated large rock slides from a single small basin illustrate that known instabilities may be reactivated and that areas impacted by prehistoric failures should be evaluated for modern instabilities.

Less than a kilometre north of where Congdon Creek drains into Kluane Lake from the Kluane Ranges, a very large mass of blocky debris was first interpreted as a rock avalanche deposit by Rampton (1978b). The volume of the debris is on the order of 70 million m^3 and extends 3.5 km from a highly modified source area to within 300 m of the Alaska Highway (Gerath and Smith, 1989). Reconnaissance investigations by Gerath and Smith (1989, p. 19) indicate that there was “no evidence of imminent failures of similar nature” along the suspected source area. However, they warn that “more study is needed to gain assurance about the bedrock stability of the nearby mountain front.”

Lastly, a recent rock-slide scar is located near the confluence of Wolf Creek and the main Shakwak Valley (Fig. 15). The scar does not appear in aerial photographs taken in 1988, however, large tension cracks and rock fall debris in the location of the slide indicate that failure did display forewarning signs of instability.

Rock slumps

Deep-seated rock slumps are common in the Kluane Ranges at the rims of erosional plateaus, uplands and bedrock terraces composed of flat-lying sedimentary and volcanic rocks, and also, less commonly, Cretaceous plutons (Fig. 16). In these settings, stream incision and glacial erosion have

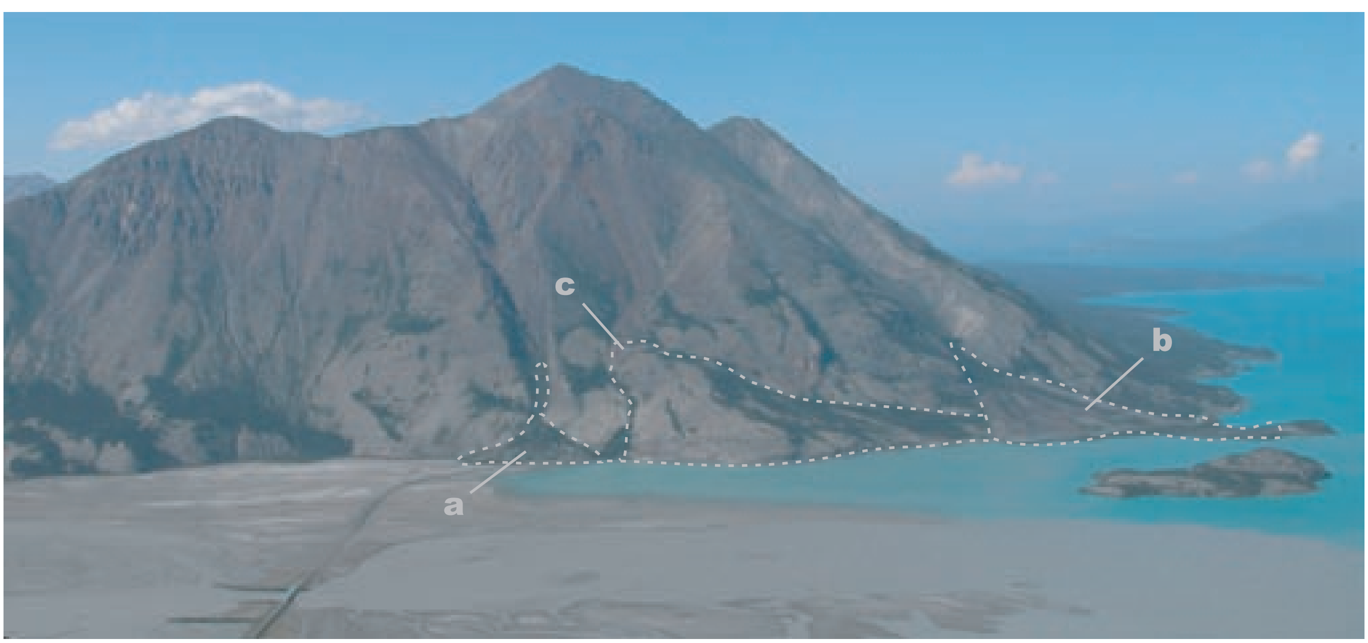


__Figure 14.__ Looking northwest at landslide deposits along the base of Sheep Mountain and the Slims River delta, including __(a)__ debris flow fan, __(b)__ and __(c)__ rock avalanche deposits.

Figure 15. Looking east at Wolf Creek rock slide, Alaska Highway in foreground.

debutressed large rock masses. Large-scale slumping may force the incised stream to the opposite side of the valley where undercutting commonly initiates an opposing slump (Eisbacher, 1979).

Although most rock slumps do not threaten the corridor directly, they do have the potential to dam creeks that drain into the corridor. Breaching and rapid incision of such dams could cause flooding. The probability and magnitude of rock-slump-induced flooding events has not been studied in the corridor.

Movement of large rock slumps may be seismically triggered. Power (1988) attributed movement of a large rock slump in Cement Creek to a modest (magnitude 5.4) earthquake centred near the valley in 1983.

Rock fall

Recent rock fall is ubiquitous on steep rocky terrain of all rock types within the Kluane Ranges and to a lesser extent within the Ruby Range. Rock fall is commonly associated with other types of failures that create over-steepened rock bluffs (Fig. 16b). Rock fall also supplies material to gully systems for subsequent transport by debris flow. For example, frequent rock fall events were observed by the authors in the steep north-facing gullies on the south side of the Slims River delta. These gullies have produced historical debris flows that have blocked the Alaska Highway during intense rain events. Notable locations of frequent rock fall within the Ruby Range are the glacially over-steepened slopes bordering the east side of Kluane Lake and the southwestern slopes of Paint Mountain, northeast of Haines Junction. In

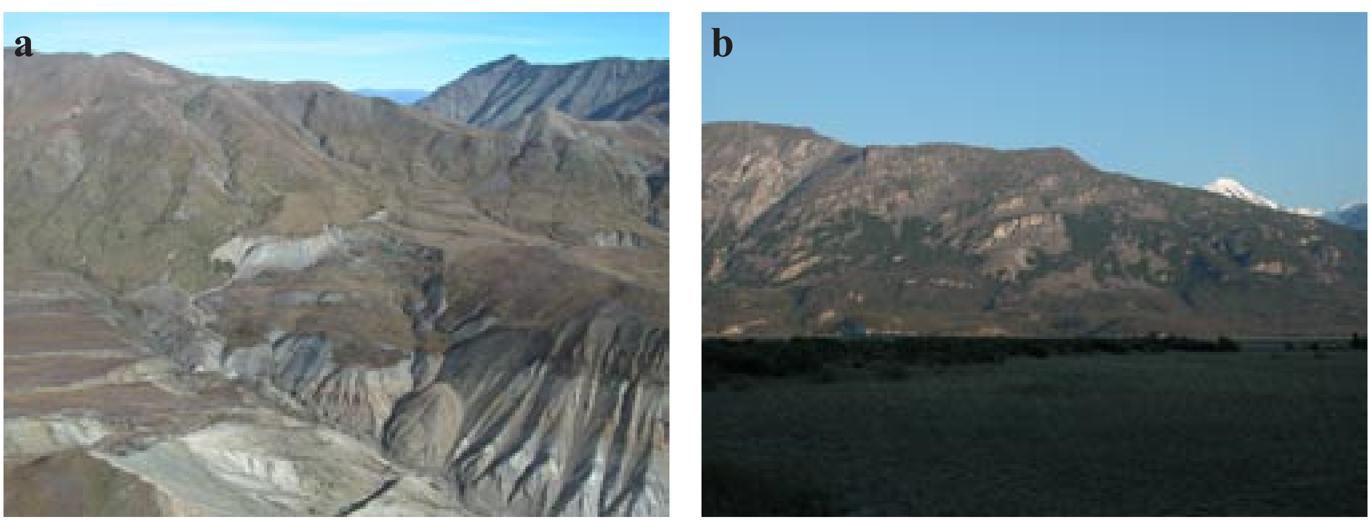


*Figure 16. Examples of large rock slumps within Kluane Ranges. **(a)** Rock slump along upper Sheep Creek; **(b)** Complex rock slump and related rock fall on northwestern slope of Outpost Mountain. Alaska Highway crosses base of the slope along the left-hand side of photograph.*

these locations, repeated rock fall has formed widespread blocky aprons and fans at the base of slopes.

Gravitational spreading

Evidence of gravitational spreading, in the form of uphill-facing scarplets along ridge tops has been recognized in a variety of locations within the Kluane Ranges directly flanking the Shakwak Valley (Eisbacher and Hopkins, 1977; Clague, 1979b, 1982; Fig. 17). These features are likely associated with seismic activity, yet a direct relationship to neotectonic movement has not been confirmed. Gravitational spreading displacements are characteristically very slow (cm/yr), however they have been identified as a precursor to many catastrophic rock failures and debris flows in other mountainous regions (Dramis and Sorriso-Valvo, 1994; Sorriso-Valvo et al., 1999).

Rock, ice and snow flows

The remnants of large suspected rock, ice and snow avalanches are located in the headwaters of Nines Creek (Fig. 18a and b). The fan-shaped deposit consists of a thin, discontinuous layer of angular rubble and originates from a steep catchment composed of near vertical basalt cliffs. Perennial snow patches and glacierettes are common features along the length of the valley side. From the top of the catchment, the debris travelled almost 1 km down a gentle apron, across the floodplain of a small braided stream to the opposite side of the valley. Numerous boulders within the debris exceed 16 m^3 and are most commonly found near the periphery of the deposit.

Several pieces of evidence suggest that the failure responsible for the debris consisted of a combination of snow, ice and rock. Firstly, the thickness of the debris and the frequency of large boulders is greatest near the periphery of the deposit. These features are characteristic of flows of rock and snow in northern Sweden described by Rapp (1959). In addition, vegetation beneath the thin mantle of rubble is locally well

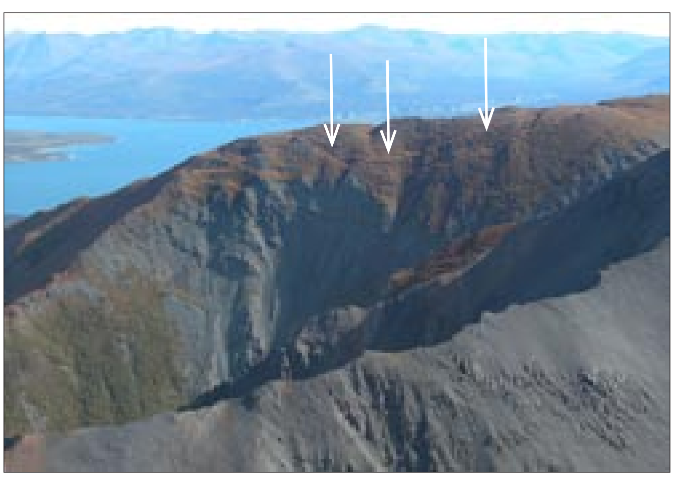


Figure 17. *Uphill-facing scarps (indicated by arrows) related to lateral spreading of bedrock ridges above Kluane Lake (in background) near Nines Creek.*

Figure 18. *Deposits of a large rock and ice avalanche.* ***(a)*** *Arrow points towards boulder photographed in (b). The source of the avalanche is above the steep right-hand rock faces.* ***(b)*** *Boulder with perched stones that travelled over 1 km from the source area. Rock and snow hazards have not been assessed in the corridor.*

preserved (Matthews and McCarroll, 1994; Gardner, 1983) and perched boulders and cobbles are common near the periphery of the debris (Jomelli and Francou, 2000).

Large failures of snow and debris with long run-out distances have not been previously identified as a potential hazard in the Shakwak Valley. The recognition of this type of failure may have implications for hazard analysis in the area. A detailed assessment characterizing the cause, setting, behaviour and impact of this process is recommended to ascertain the risk it may pose to development in the corridor at large.

Retrogressive thaw slumps (earth flows)

Retrogressive thaw slumps are the most common form of earth flow within the Shakwak Valley zone. Retrogressive thaw slumps are noted within the Shakwak Valley where rivers are actively incising ice-rich lacustrine sediment. Terrain vulnerable to thaw slumping commonly displays surface evidence of thermokarst activity. An example of this type of landslide activity is present along the southern bank of the Dezadeash River, 10 km east of Haines Junction (Fig. 19). Here, retrogressive thaw slumps are situated along the cutbank of the river. The most recent flow has an actively ablating headscarp which displays abundant veins of clear ice.

Debris flows and debris slides

Debris flows and debris slides are the most common types of mass movement in the Shakwak Valley and are the only forms of slope failure to have impacted the Alaska Highway directly. They occur on slopes both in the absence and in the presence of permafrost. Where slopes are underlain by permafrost, detachment failures occur. These failures are discussed separately in the following section.

Figure 19. *Retrogressive thaw slump headscarp along the Dezadeash River. Veins of ice were visible within the headscarp. Small flows of lacustrine silt and clay were active during field visit.*

Debris flows and slides are generally triggered by intense rainfall events on steep to moderate colluvial- or till-covered slopes (Gerath and Smith, 1989; Evans and Clague, 1989; Broscoe and Thomson, 1969). Harris and Gustafson (1993) studied the timing of activity on debris-flow fans along the lower Slims River valley. They found that debris flows often occur in warm weather, not always as a result of heavy rainfall events, and speculated that ground-ice thaw may contribute water to the failure process. However, the importance of snowmelt to debris-flow and debris-slide processes was not addressed and has not been studied in the Shakwak Valley zone.

In general, debris flows and debris slides may be channelized by pre-existing gullies, or occur on open slopes. On valley sides, open slopes mantled by till and colluvium over shallow bedrock are particularly vulnerable to debris flow activity (see *Case study 2: Horseshoe Bay*, p. 39). In valley bottoms, stratified glacial deposits containing lacustrine material are also subject to debris flows and slides. Failures are particularly prevalent where valley fill is incised by meltwater channels and modern streams. The numerous debris flows near the Christmas Creek crossing of the Alaska Highway are an example of this type of setting (Fig. 11).

Channelized debris flows are common in rocky gullies that have collected abundant loose colluvium. Channelized debris flows, as with open-slope debris flows, occur on slopes of all aspects, including south-facing xeric slopes and north-facing gullies comprised of variable amounts of frozen soil.

Where portions of such gullies receive restricted amounts of direct sunlight, perennial icings cover and line sections of many debris flow channels. Icings are masses of layered ice formed by freezing of successive flows of water and may incorporate snow (Everdingen, 1998). Due to the observed abundance and geometry of gully icings within the study area, it is suspected that they may be capable of promoting debris-flow activity by plugging debris-flow channels, increasing channel storage, and raising the pore pressure of saturated debris. The melt of debris-covered gully icings may contribute to the occurrence of debris flows after periods of warm weather, as described by Harris and Gustafson (1993). The effect of icings on debris-flow activity has not received study, and their overall influence on landslide processes within the Alaska Highway corridor requires investigation before confidence can be lent to the above suppositions.

Figure 20. *Debris flow fan and catchment on north White River crossing.*

Along the Alaska Highway, areas of high debris-flow and debris-slide risk include the south shore of Kluane Lake from Silver Creek to Slims River, and the western shore of Kluane Lake from Slims River to Congdon Creek. North of Congdon Creek, the highway crosses numerous large alluvial fan complexes further from the mountain front, and the main hazard to the integrity of the route is water- and sediment-laden floods. In addition, notable debris-flow fans exist adjacent to the Alaska Highway and proposed pipeline easement near Koidern Lodge and the north side of White River (Fig. 20).

Between Silver Creek and the mouth of the Slims River, the Alaska Highway has been blocked by debris flows as a result of two separate rainstorm events. During the summer of 1967, a debris flow originating from a north-facing gully blocked traffic with bouldery debris (Fig. 21a and b). Two decades later, during the intense rain storms of 1988, an adjacent catchment produced debris flows that once again blocked the highway. The gully which failed in 1967 did not display evidence of debris flow activity in 1988, probably as a

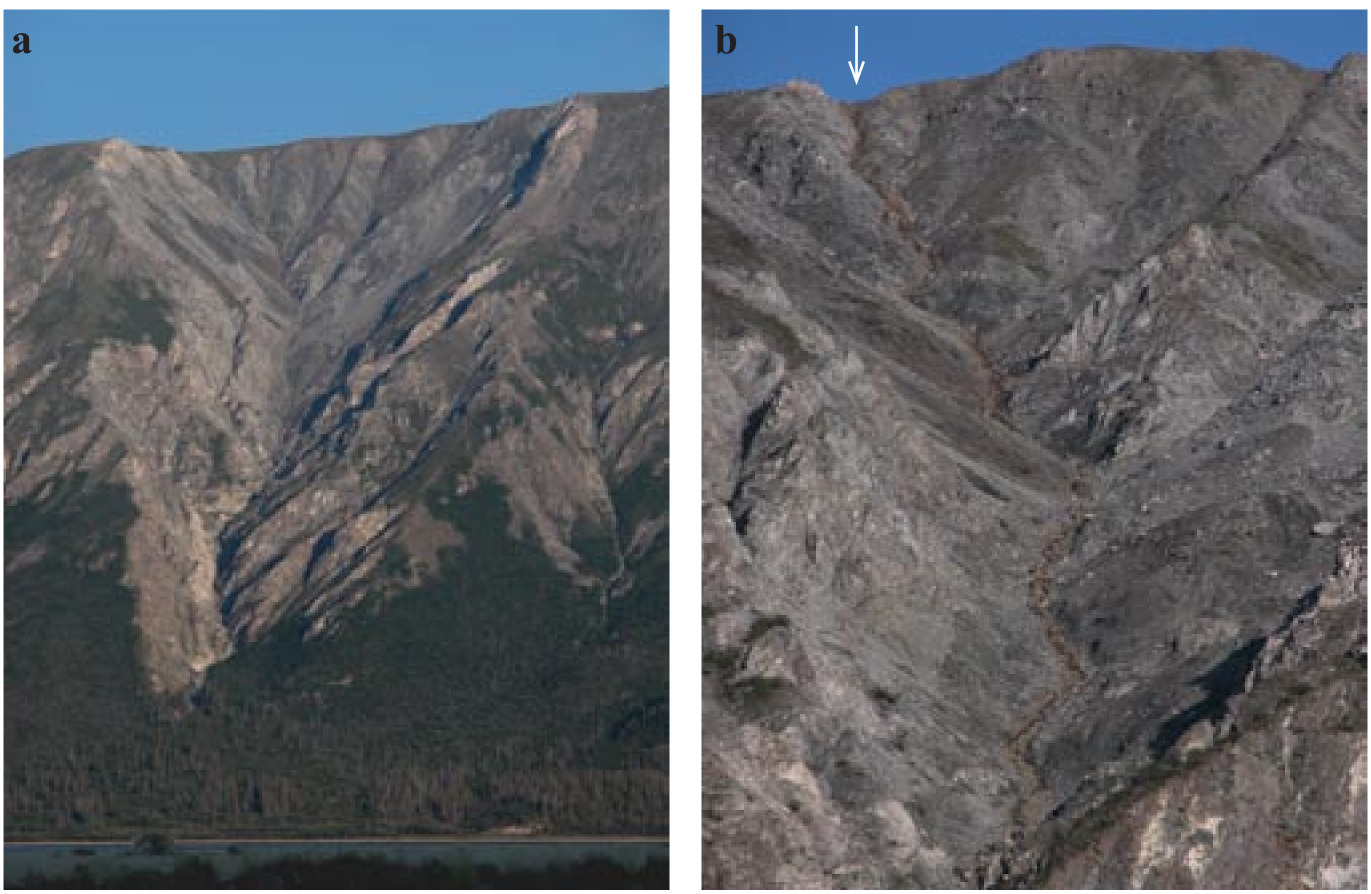


Figure 21. (a) *North-facing gullies along Kluane Lake. These catchments were source areas for debris flows that blocked the Alaska Highway during rainstorm events.* ***(b)*** *The brown-coloured debris in the bottom of the gully is the product of an active-layer detachment failure that occurred on the plateau surface, near arrow.*

Figure 22. *Debris flow scars above Alaska Highway north of Williscroft Creek.*

result of insufficient replenishment of the gully system with material since the previous failure.

During field investigations of this portion of the study area in 2003, active-layer detachment slides were noted at the head of the gully that failed in 1988. Debris from the slides initiated on turf-covered slopes above the gully and then proceeded down the steep and rugged gully channel, creating a 900-m-long flow displaying prominent levees (Fig. 21). This process suggests that active-layer detachment failures may supply some of the material for subsequent transport by larger debris flows.

A colluvial fan, directly north of the Slims River bridge (Fig. 14, location a), was the former location of a park visitor's centre until 1989, when geotechnical investigations (letter from Thurber Consultants Ltd. and Dr. S.G. Evans, dated August 24, 1989) concluded that there was a risk of debris slides to the facility. This risk was confirmed by the discovery of eight debris flow units overlying the White River ash (1200 years B.P.) which suggests an average debris flow return period of 150 years (Harris and McDermid, 1998).

A high debris-flow risk has also been recognized between Horseshoe Bay and the Congdon Creek fan (Gerath and Smith, 1989; Clague, 1982). Along this stretch of shoreline, aprons of debris extend from steep till-veneered slopes underlain by shallow bedrock, directly into Kluane Lake. During a heavy summer rain storm event in 1988, two debris flows occurred in this area, one of which blocked the highway (see *Case study 2: Horseshoe Bay*, p. 39). Older scars and stacked debris-flow deposits exposed in road cuts are evidence of numerous past events along this section (Fig. 22). In addition, Gerath and Smith (1989) suggest that the Williscroft Creek fan, which supports a commercial campground facility, as well as two other colluvial-alluvial fan complexes, present debris-flow and flood hazards in this section. Due to its high risk of widespread and varied slope instability, this stretch of the corridor is bypassed by the proposed pipeline route. The highway and associated public facilities, however, remain vulnerable to debris flows and floods.

Active-layer detachment failures

Failures involving active-layer detachment are relatively common within Shakwak Valley. These failures are influenced by the presence of permafrost due to its control on soil drainage and soil strength. The presence of shallow permafrost may restrict drainage and elevate pore pressure, thereby reducing soil strength. Soil strength may also be physically decreased by the thaw of ice-rich permafrost. Where ice supports soil structure, thaw causes weakening via thaw consolidation associated with structural collapse (McRoberts and Morgenstern, 1974).

Active-layer detachment failures have been noted in all hillslope positions, except south-facing slopes (this study; Hugenholtz, 2000). Settings include valley bottom and mountainous uplands. The predominant source material of the failures is silty morainal deposits containing shallow ground ice. Run-out distances of detachment failures may be long, notably where they enter steep gully systems (Fig. 21). Examples of active-layer detachment slides and flows can be found along Silver Creek (see *Case study 3: Silver Creek*, p. 41), north of Kluane Lake, and on Outpost Mountain.

North of Kluane Lake, flows and slides involving active-layer detachment are common. In this area, locally thick deposits of White River ash and lapilli insulate underlying material and create conditions suitable for the development of shallow permafrost (Fig. 23).

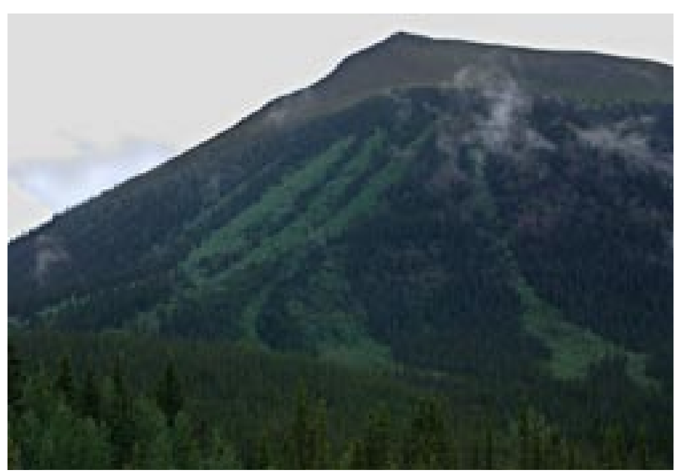


Figure 23. *Overgrown shallow debris flows which initiated due to active-layer detachment failures.*

Hugenholtz (2000) described the morphology of six active-layer detachment slides on the alpine plateau of Outpost Mountain. The slides initiated on slope gradients of 13° to 18° and led to significant secondary retrogressive failures. Based on a ground-heating experiment, Hugenholtz (2000) proposed that rapid snowmelt and/or intense pluvial events are required to trigger a detachment within the study area.

YUKON PLATEAUS ZONE

Physiography and drainage

The Yukon Plateaus zone makes up a vast portion of interior Yukon and consists of several individual plateaus including the Teslin, Kluane and Lewes plateaus (Mathews, 1986). It consists of broad U-shaped valleys and rounded uplands ranging between 800 and 2000 m in elevation. A number of major rivers drain this zone (Fig. 24). The Yukon River flows northward through a series of large interconnected lakes south of Whitehorse. The Takhini River originates from Kusawa Lake and flows eastward into the Yukon River just north of Whitehorse. The Dezadeash River flows westward to Haines Junction, eventually draining into the Alsek River and the Pacific Ocean. The Teslin River drains the north end of Teslin Lake, and eventually flows into the Yukon River.

Surficial geology and glacial history

The Yukon Plateaus zone lies within the limit of the McConnell glaciation. Glacial recession occurred in a number of successive stages separated by periods of ice stagnation. These intervals of stagnation allowed the widespread deposition of thick morainal, glaciofluvial and glaciolacustrine complexes (Bond, 2004). The retreating ice lobes were confined to lower valleys, so that numerous meltwater channels drained along the valley sides and deposited extensive ice contact glaciofluvial deposits (Morison and Klassen, 1991).

Large glacial lakes were impounded in most of the main valleys, leaving them covered with glaciolacustrine deposits that are exposed at surface and in stream terraces. The Alaska Highway corridor, along most of the zone, traverses these glaciolacustrine silts and clays where it passes through the Dezadeash and Tahkini river valleys, and also in the vicinity of Marsh and Teslin lakes. The glaciolacustrine deposits are up to 75 m thick in the Takhini River valley, and 15 m thick along Teslin Lake (Doherty et al., 1994; Mougeot and Walton, 1996a,b,c,d).

Bedrock geology

Numerous lithologies are found within this zone as a result of the accretion of various island-arc assemblages of Yukon-Tanana and Stikinia terranes, the subsequent episodes of regional metamorphism and intrusion of younger plutons (Fig. 2). In general, the distribution of rock types can be characterized as consisting of a variety of oceanic and arc volcanic rocks which are interleaved with deep-sea sedimentary rocks, intruded by younger plutons and separated by faults of uncertain ages.

Along the eastern side of Teslin Lake, Upper Triassic and Lower Jurassic arc volcanic, volcaniclastic and comagmatic intrusive rocks dominate the bedrock (Gordey and Makepeace, 2003). Between northern Teslin Lake and northern Marsh Lake, Mississippian to Lower Jurassic oceanic volcanic and sedimentary rocks, and local accretionary prism mélange lithologies are found (Gordey and Makepeace, 2003).

In the vicinity of Whitehorse, Devonian to Permian arc volcanic and platform carbonate rocks are overlain by Triassic and Lower Jurassic arc volcanic and volcaniclastic rocks, chert, carbonate and arc-derived clastic rocks (tuff, sandstone, siltstone, limestone and chert). These rocks are intruded by mid-Cretaceous plutonic suites (granodiorite, diorite, monzonite and leucogranite). Between Whitehorse and Haines Junction, Early Tertiary plutons (granodiorite, leucogranodiorite, quartz monzonite, quartz diorite and tonalite) and undivided metamorphic assemblages are exposed in upland areas bordering the corridor (Gordey and Makepeace, 2003).

Permafrost

The Yukon Plateaus zone lies within the transition zone between extensive discontinuous and sporadic discontinuous permafrost (Fig. 5; Heginbottom, 1995). Ground ice is commonly found in the lowland between Whitehorse and Haines Junction where groundwater supplies moisture to the fine-grained glaciolacustrine valley fill and hillside deposits of silt-rich till. Ground ice is especially prevalent within fine-grained sediments proximal to bedrock valley walls, or above truncated permeable coarse-grained deposits (Rampton et al., 1983). On valley sides, permafrost is commonly found within 2 m of the surface on north-facing slopes that are blanketed by glacial drift or colluvium, especially in locations overlain by thick organic cover. Solifluction lobes are common at higher elevations.

Throughout the Takhini River valley bottom, sporadic ice-rich permafrost is found within glaciolacustrine silts and clays. At an undisturbed site in the valley, Burn

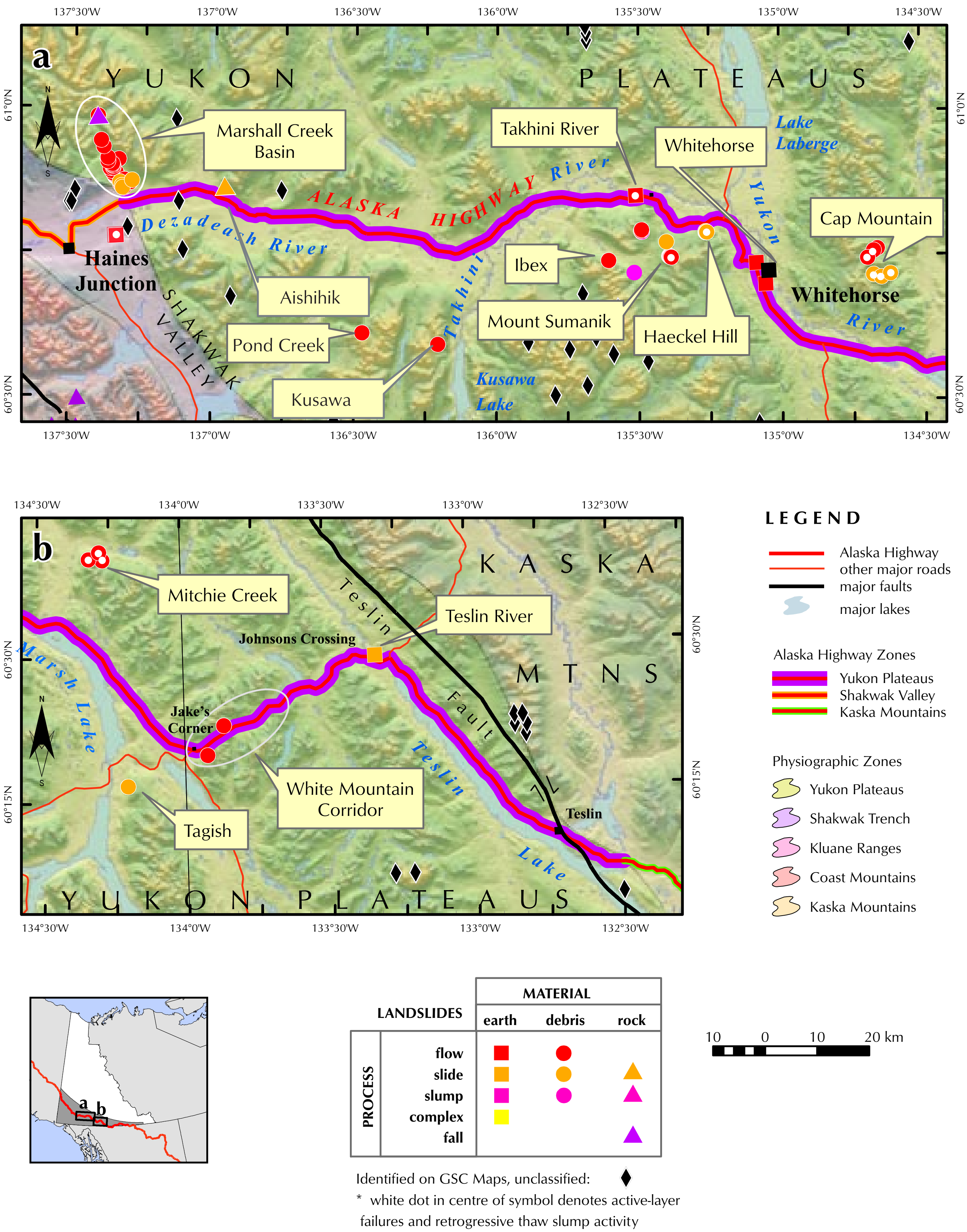


Figure 24. Overview of physiography and locations of noted landslides within the Yukon Plateaus zone. Physiographic zones modified from Matthews (1986).

(1998) reported the active layer thickness as 1.4 m and the permafrost thickness as 18.5 m. At nearby sites that were burned in a severe forest fire in 1958, the thawed layer is at least 3.75 m thick. In addition, numerous thermokarst lakes are active in the valley (Burn, 1982). Where the Alaska Highway traverses the glaciolacustrine deposits of the Takhini River valley area, ongoing road maintenance is required due to permafrost subsidence. Subsidence rates of up to 3 m in the last 15 years have been observed by the Yukon Department of Highways and Public Works (B. Fulcher, pers. comm., 2003).

Landslide processes

Debris flows, debris slides and debris slumps are the dominant landslide processes in the Yukon Plateaus zone, although earth flows, slides and slumps, and rock falls and slides are also common (Fig. 24).

Earth flows, slides and slumps

Earth flows, slides and slumps commonly occur in valley bottoms within glaciolacustrine terraces. Alteration of surface runoff and groundwater regimes by forest fires or deforestation can also concentrate groundwater or surface runoff and lead to instabilities in this material.

In the vicinity of Whitehorse, earth flows are particularly prevalent along the silt and fine-sand bluffs which bound the western edge of the downtown core (Fig. 24a). Numerous earth slides are also found along the banks of the Yukon and Takhini rivers (Fig. 25).

At Johnsons Crossing, earth slumps occur on the eastern bank of the Teslin River. Along the northeastern shores of Teslin Lake, terrain hazards are limited to widespread piping and gully erosion of glaciolacustrine terraces, but changes in hydrological regime could trigger larger earth flows within these materials.

Figure 25. *Earth slide due to river erosion and undercutting of glaciolacustrine silts in the Takhini Valley.*

Retrogressive thaw slumps

Retrogressive thaw slumps commonly occur in valley bottoms where the basal parts of ice-rich fine-grained glaciolacustrine terraces are disturbed by river erosion. Ice lenses preferentially form in fine-grained lacustrine sediment, where ample groundwater supply was available during periods of permafrost aggradation. Where river erosion, fire or human activity disturbs insulating vegetation, failures may occur. River erosion has been the primary cause of retrogressive thaw slumps within the Takhini and Dezadeash river valleys (see *Case study 6: Takhini River*, p. 46).

Rock falls and slides

Rock falls and slides are frequent on mid to upper slopes within the Yukon Plateaus zone. Small volume rock falls occur primarily where frost action has loosened steep weathered bedrock faces. In the Ibex River valley, rocks falls along glacially over-steepened intrusive valley walls have led to rapid accumulation of colluvium in steep source areas. These materials are then easily mobilized in large debris flow events that are triggered by heavy precipitation or snowmelt. Rock falls are common along the White Mountain corridor.

Large volume rock slides are rare within the Yukon Plateaus zone and occur where joints or bedding structures daylight in areas of steep, high relief and shear deformation has been parallel to potential sliding directions. For example, the Aishihik rock slide east of Haines Junction occurred in prehistoric times in highly fractured metamorphic rocks, and travelled 1.5 km from its source area (see *Case study 5: Aishihik rock slide*, p. 44). Rock slides are likely seismically triggered.

Debris flows, slides and slumps

Debris flows occur in a number of settings within the Yukon Plateaus zone. They most commonly occur within saturated colluvium and till deposits on moderate to steep valley sides. During the waning stages of the McConnell Glaciation, several pauses in deglaciation left thick, and commonly silty, kame deposits between 1600 to 2000 m a.s.l. and near 980 m a.s.l. The highest deposits generally sit above steep valley walls (Fig. 26), commonly contain extensive permafrost, and are a source of abundant material to debris flow channels (Lowey, 2002). These debris flows mobilize large volumes of material and can characteristically

Figure 26. *Upper catchment of Kusawa Lake debris-torrent system. Permafrost was encountered within 1 m of the surface within the undisturbed hillslope, 20 m behind the headscarp. The landslide scar is approximately 300 m wide.*

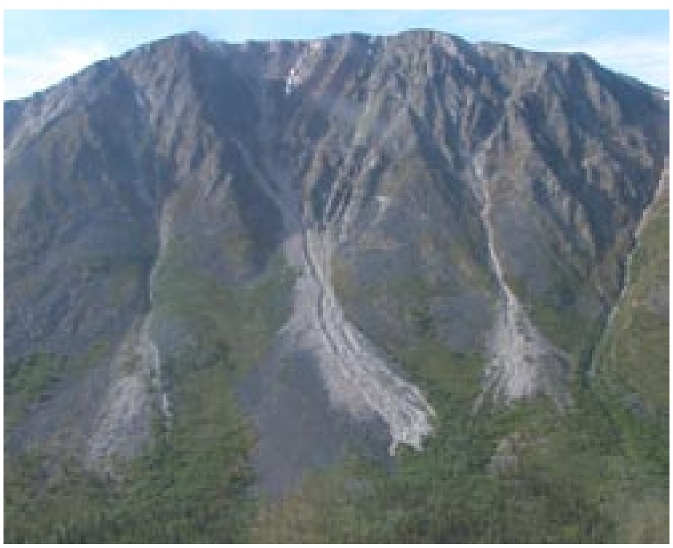


Figure 27. *Pond Creek debris flows.*

travel distances of up to a kilometre to valley bottom. Where debris flows initiate in valley-bottom settings, they are confined to the flanks of glaciofluvial and morainal terraces incised by modern day streams.

Debris flows may also be derived from catchments of mostly weathered bedrock (Fig. 27). In the Ibex River valley, large debris flows entrain weathered bedrock and colluvium that accumulate in gullies along steep intrusive mountain sides (see *Case study 7: Ibex Valley*, p. 48). Debris flows are also frequent in the White Mountain corridor along the base of prominent, near-vertical limestone bluffs, on north-facing till-covered slopes (see *Case study 10: White Mountain*, p. 54). On Mount Sumanik, the presence of thawing permafrost in colluviated till has created unstable and saturated source materials that have mobilized in a series of large debris flows (see *Case study 9: Mount Sumanik*, p. 52).

Active-layer detachment failures

Permafrost-related debris slides are also common in this zone. Active-layer detachment debris slides occur on gentle to moderate (10° to 25°) north-facing slopes where permafrost degradation has occurred either naturally (Cap Mountain and Mitchie Creek), or following forest fires (Haeckel Hill and Marshall Creek). On Haeckel Hill (see *Case study 8: Haeckel Hill*, p. 50), 5 debris slides were initiated following a forest fire that burned the area in 1991. In Marshall Creek (see *Case study 4: Marshall Creek basin*, p. 42), a large forest fire in 1998 led to permafrost degradation and triggered 41 debris flows within 5 years of the fire.

KASKA MOUNTAINS ZONE

Physiography and drainage

The Kaska Mountains zone of the Alaska Highway corridor is an area of rounded relief ranging between 800 and 2000 m in elevation. Within this zone, the highway passes primarily through the Cassiar Mountains, following the Morley, Swift and Rancheria rivers (Fig. 28). The Kaska Mountains zone straddles a major drainage divide which separates the headwaters of the Teslin/Yukon rivers and the Liard/Mackenzie river systems.

Surficial geology and glacial history

During the McConnell Glaciation, the Cassiar Mountains formed a major ice centre from which ice lobes flowed to both the east and west. Exposed bedrock was left covered in a veneer of till and colluvium at high elevations and along valley sides. Valley bottoms are filled with variable thicknesses of modern day alluvium underlain by glaciofluvial meltwater complexes, particularly along Rancheria River (Klassen, 1982; Mougeot and Walton, 1996a). Closer to Teslin, valley bottoms are blanketed in lodgment and ablation till as well as glaciolacustrine deposits, some of which are subject to thermokarsting (Morison and Klassen, 1997).

Bedrock geology

The bedrock geology of the Kaska Mountains comprises folded and faulted continental platform sedimentary rocks that have been displaced by movement along the Tintina Fault (Fig. 2). From Teslin, south to the British Columbia border, bedrock geology along the Alaska Highway consists of metamorphosed early (?) to mid-Paleozoic continental margin sedimentary rocks of the Yukon Tanana–Nasina Subterrane, as well as superposed Late Devonian and early

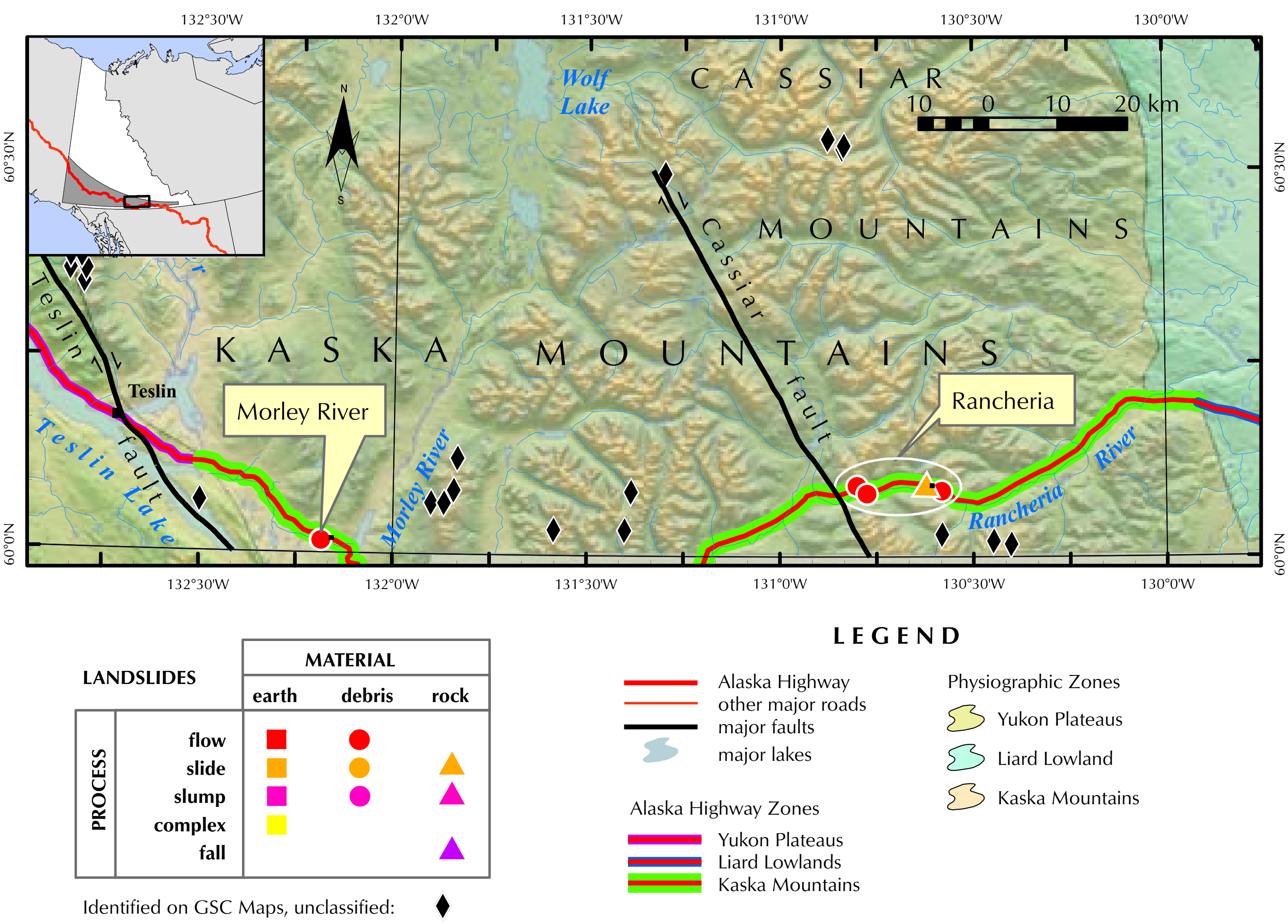


Figure 28. *Overview of general physiography and the location of landslides observed within the Kaska Mountains zone. Physiographic zones modified from Matthews (1986).*

Figure 29. *Typical setting of debris flows on steep till-covered slopes of the Kaska Mountains zone. Note how scars extend from upper hillslopes to valley bottom.*

Mississippian arc volcanic and plutonic rocks. Moving eastward from where the highway re-enters the Yukon, rocks in the corridor are Carboniferous to Permian oceanic marginal basin Slide Mountain Terrane volcanic and sedimentary rocks. In the Rancheria area, east of the Cassiar fault, locally sheared mid-Cretaceous plutonic rocks are prevalent. Pleistocene columnar jointed basalts are also found along stretches of the highway along the valley bottom. Further east, following the highway along the Rancheria River, are Lower Cambrian rifted and passive continental margin sedimentary rocks of the Cassiar Terrane.

Two major northwest-trending transcurrent faults dissect this zone: the Teslin fault bounds the western edge of the zone, while the Cassiar fault cuts through the centre of the zone. Pre- to mid-Cretaceous displacement along the Teslin fault may have been as much as several hundred kilometres (Fig. 2; Gordey and Makepeace, 2003).

Permafrost

The Kaska Mountains lie within the sporadic discontinuous permafrost zone (Heginbottom, 1995). Frozen soils commonly occur on north-facing slopes and in poorly drained valley-bottom areas beneath thick organic cover, and also in higher elevation alpine areas where rock glaciers and solifluction lobes are common.

Landslide processes

Landslides within the Kaska Mountains zone are predominantly debris flows and small rock failures (Fig. 28). No permafrost-related landslides were observed in this zone. The absence of retrogressive thaw slumps is probably due to the paucity of lacustrine material in valley bottoms. However, it is likely that ground warming leading to permafrost degradation on north-facing slopes could lead to isolated active layer detachment failures.

Debris flows

The most significant and potentially hazardous landslides in this zone are debris flows on moderately steep slopes where surface runoff concentrates during periods of heavy rainfall or snowmelt. Numerous debris flows of this type were initiated after a period of intense rainfall in 1988 in the Rancheria area. At this location, the Alaska Highway closely follows the base of a moderately steep and long hillside. One of the debris flows blocked the Alaska Highway, and the largest one travelled nearly 1 km (see *Case study 12: Rancheria Message Post*, p. 56). Numerous other debris flows occurred in the uplands surrounding the corridor (Fig. 29).

Smaller scattered debris flows also initiate along river terraces underlain by till, as observed at Morley River, where a river meander caused undercutting of a terrace close to the Alaska Highway (see *Case study 11: Morley River*, p. 58).

Rock slides and falls

Rock slides and falls are rare but occur sporadically in alpine areas where structural controls and jointing patterns predispose bedrock outcrops to slope failure, and where significant frost shattering has occurred on steep bedrock faces.

LIARD LOWLAND ZONE

Physiography and drainage

Liard Lowland zone includes a large area of subdued relief near 760 m a.s.l. lying entirely within the watershed of the Liard River. Where the Alaska Highway corridor traverses the Liard Lowland zone, it crosses a broad, gently rolling, till and outwash plain incised by Pleistocene meltwater channels and modern streams (Klassen and Morison, 1981).

Surficial geology and glacial history

The advance of the Liard Lobe of the McConnell Glaciation is responsible for most of the deposits in the area, although older, preglacial and glacial deposits are found sporadically. During the McConnell Glaciation, glacial flow was primarily to the east, roughly paralleling the Alaska Highway. Isolated areas of hummocky stagnant ice complexes flank younger proglacial meltwater channels in various locations adjacent to the corridor. Where modern streams, such as the Little Rancheria and Liard rivers, flow within incised v- and box-shaped valleys, interstratified fluvial gravel, lacustrine silts and moraine deposits may be exposed for a thickness of up to 25 m. In sporadic locations, glacial material is intercalated with Quaternary basalt flows (Gabriesle, 1967; Klassen, 1987). Much of the landscape adjacent to the Alaska Highway is veneered by up to 50 cm of eolian silty loess.

Bedrock

The bedrock geology of Liard Lowland is not well constrained due to the scarcity of exposed bedrock. Scattered outcrops of bedrock comprise Lower Tertiary terrestrial clastic rocks, soft Paleozoic shales and more resistant Paleozoic carbonate rocks (Gabrielse, 1967). The distribution of rock types is complicated by the southern extension of the Tintina Fault and associated conjugate faults, which strike northwest and are inferred to intersect the Alaska Highway between the Liard River crossing and the British Columbia border.

Permafrost

The Alaska Highway corridor contains only sporadic occurrences of permafrost within the Liard Lowland zone. Fewer than 3% of holes drilled in association with the proposed Alaska Highway gas pipeline intersected permafrost in the area (Rampton et al., 1983). Perennially frozen ground is isolated to north-facing terrace slopes as well as poorly drained low-lying areas adjacent to lakes, swamps and ponds, where thick organic mats may be underlain by till or glaciofluvial material.

Landslide processes

Due to the low relief of the area, slope instabilities are not widespread within the Liard Lowland zone (Fig. 30). The two dominant types of landslides in the area are rock slumps

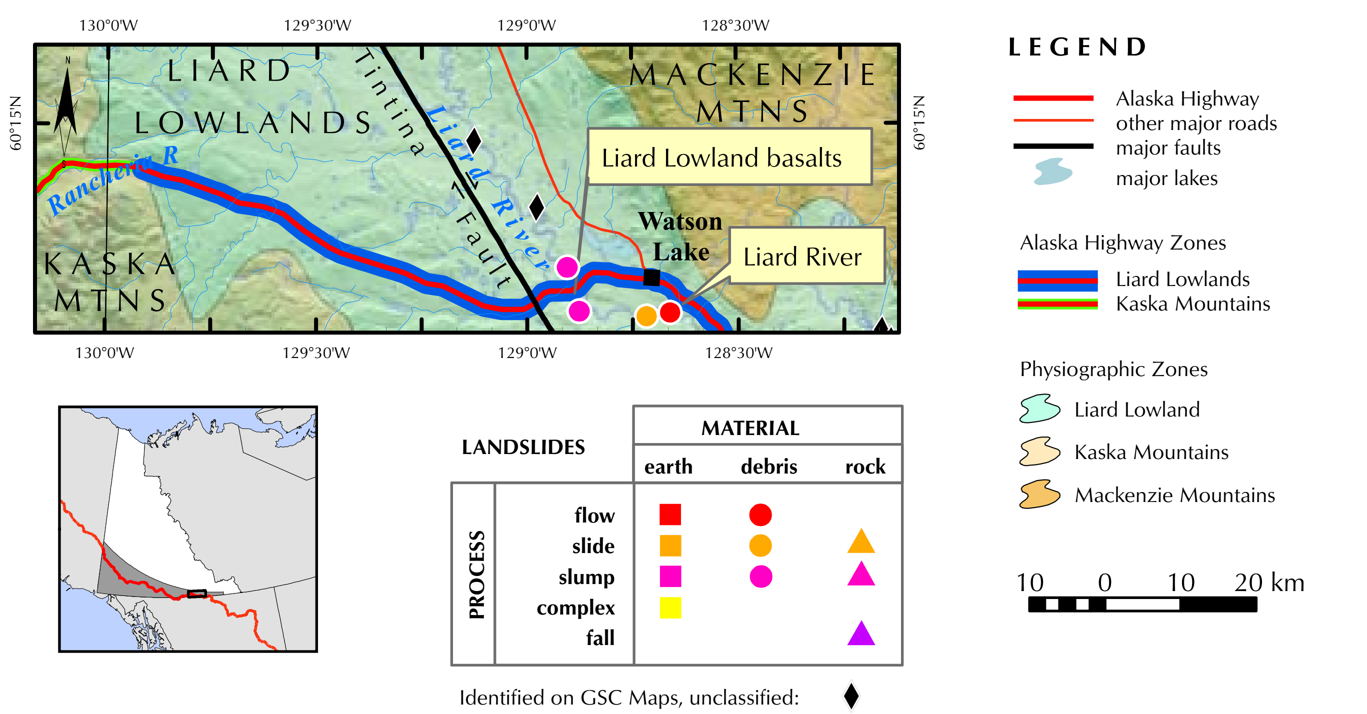


__Figure 30.__ Overview of general physiography and the location of landslides observed within the Liard Lowland zone. Physiographic zones modified from Matthews (1986).

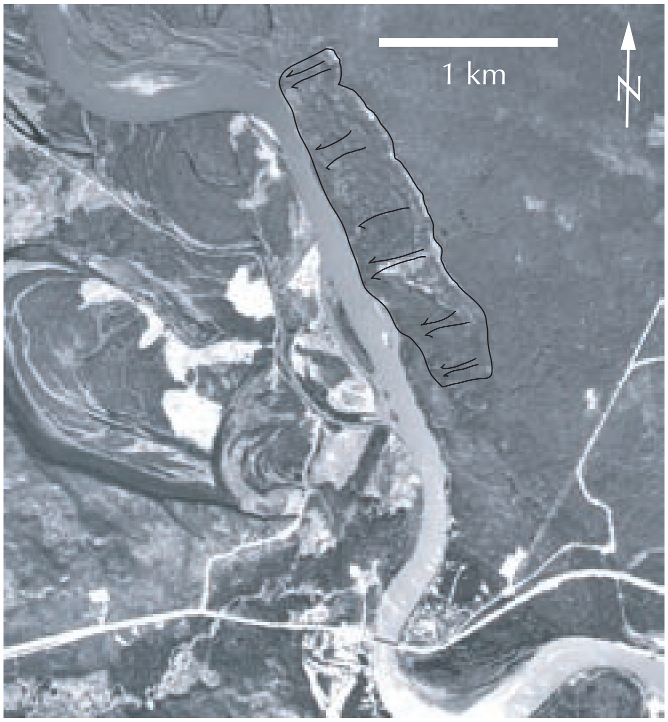


***Figure 31.** Aerial photograph of large rock slumps (outlined in black) within Pleistocene basalt and till adjacent to the Alaska Highway's crossing of the Liard River (National Air Photo Library number A27829-56, Natural Resources Canada).*

and debris flows. Both of these landslide types are related to river and meltwater incision of weak stratified sediment and intercalated lava flows.

Rock and debris slumps

Multiple retrogressive rock slumps are characteristic where thick deposits of flat-lying glacial material and lava flows rest on less resistant strata. For example, along the Liard River, within 10 km north and south of the Alaska Highway, retrogressive slump scars cover approximately 6 km^2 (Fig. 31). The age and activity state of these failures are unknown, although, their positions coincide with locations of active undercutting of till and basalt terrace surfaces by the Liard River. These surfaces are generally 60 m above river level.

Debris flows

Debris flows are observed commonly along the banks of incised rivers and the gullied rims of Pleistocene meltwater channels. Numerous shallow and narrow debris-flow scars are located along entrenched meanders of the Little Rancheria River (Fig. 32), which is incised 60 to 80 m into a till plain. Most debris flows occur along north-facing stream banks, suggesting that the thickness of the active-layer may play a role in their initiation. Shallow debris flows are also characteristic of terraces underlain by lacustrine sediments along the Liard River (see *Case study 13: Liard River*, p. 59). This type of debris flow may occur cyclically as colluviation and revegetation impede drainage by capping exposed scarp faces. The primary means of mitigating future events of this type is to ensure adequate groundwater drainage of permeable strata. Inland from river valleys, debris flows occur along the gullied rims of Pleistocene meltwater channels that are typically incised 20 to 30 m into rolling silty till plains. A possible example of this type of activity is found along the meltwater channel currently occupied by Albert Creek, where evidence of old debris flow scars may exist.

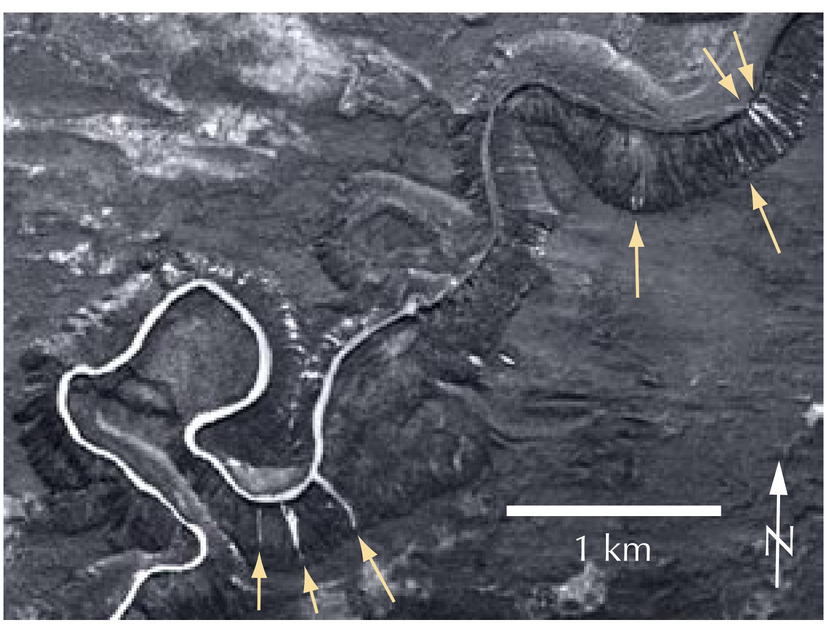


***Figure 32.** Aerial photograph of debris flows (arrows) along the Little Rancheria River. Note that the majority of the failures occur on north-facing slopes (National Air Photo Library number A27829-10, Natural Resources Canada).*

DISCUSSION

POTENTIAL IMPACT OF CLIMATE CHANGE ON LANDSLIDE HAZARDS IN THE ALASKA HIGHWAY CORRIDOR

As illustrated in the previous section, climatic factors play a central role in slope stability along the Alaska Highway corridor. Most landslides in the region are related to river migration, intense summer rainfall, rapid snowmelt, forest fires and permafrost degradation. Any change in climate leading to increased frequency and/or magnitude of these events and processes will therefore similarly influence the frequency and/or magnitude of landslides, until slopes can re-equilibrate with new thermal and hydrologic conditions.

Climate change projections in southern Yukon

Knowledge of anticipated climate change is still emerging and at present is only sufficient to characterize the direction, not magnitude, of future climate trends. To illustrate this point, a range of climate change projections for southern Yukon over the next 50 years, is summarized in Figure 33 and Table 2. Although each scenario projects a slightly different set of future conditions, all projections share two common themes. Firstly, there will be an increase in air temperature, with more warming occurring in the winter than in the summer. Secondly, there will be an increase in precipitation, which is most likely to occur in winter and spring, however the seasonal timing is somewhat inconsistent between scenarios.

Although these generalizations may be meaningful at a regional scale, projections for specific locations are less certain. Many climatic factors important for determining the stability of permafrost and rainfall patterns can be significantly altered by complex local conditions that are unaccounted for in global circulation models. For example, the geometry and orientation of individual valleys influence the local effect of winds on snow depth as well as the establishment of temperature inversions. These factors strongly affect the distribution of permafrost, and in turn control permafrost-related landslide activity.

Not only are seasonal climatic trends important for the initiation of landslides, but individual synoptic events, such as forest fires and rainstorm events, may also initiate failures. In its third Assessment Report, the Intergovernmental Panel on Climate Change (IPCC, 2001) undertook a systematic analysis of the predicted changes in extreme weather and climate events for the 21st century. The panel determined

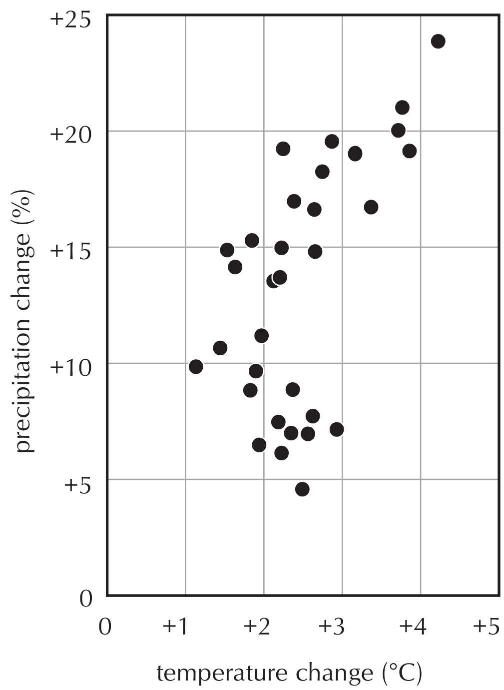


Figure 33. *Projected precipitation and temperature change for southern Yukon (60.75º N, 135ºW) for 2050s. Each dot represents one scenerio. Data provided by the Canadian Institute for Climate Studies, the Canadian Centre for Climate Modelling and Analysis (CCCma) and the IPCC Data Distribution Centre (DDC).*

that more intense precipitation events are very likely over many areas around the world. In the study area, this may mean that more cyclonic activity in the Gulf of Alaska would penetrate through the St. Elias Mountains to the corridor, bringing more frequent storms or warm spells.

Implications for future landslide activity

Local and global uncertainties surrounding future atmospheric emissions and circulation patterns compound the uncertainty of the potential influence of climate change on site-level landslide processes. The complexity of the relationship between climate and slope instability makes discussion of the effects of future climate change necessarily qualitative.

Snow melt and rainstorm events

Numerous landslides have been attributed to heavy rainfall events and intense periods of snowmelt in the Alaska Highway corridor (Hughes et al. 1972; Harris and Gustafson 1988; Evans and Clague 1989; Gerath and Smith 1989; Hugenholtz 2000; this study). During these synoptic events, precipitation and meltwater rapidly saturate the

Table 2. *Projected changes in seasonal and annual temperature and precipitation, southern Yukon (60.75º N, 135ºW), for 2050s. Data for seven GCMs using IPCC (2000) Special Report on Emission Scenarios. Data provided by the Canadian Institute for Climate Studies, the Canadian Centre for Climate Modelling and Analysis (CCCma) and the IPCC Data Distribution Centre (DDC).*

Experiment	Temperature change (°C)					Annual precipitation change (%)
	Annual	Winter	Spring	Summer	Fall	
cgcm2 a21	2.9	3.9	3	3.2	1.5	7
cgcm2 a22	2.4	3	2.4	2.9	1.1	9
cgcm2 a23	2.6	3.9	2.2	3	1.1	7
cgcm2 b21	1.9	2	1.8	2.6	1.4	7
cgcm2 b22	2.2	3.3	1.8	2.4	1.2	8
cgcm2 b23	2.5	4.1	2	2.6	1.3	5
csiromk2b a11	4.2	3.5	4.7	4.4	4.2	24
csiromk2b b11	3.7	3.4	4.2	4	3.2	20
csiromk2b a21	3.4	3.1	3.2	4.1	3	17
csiromk2b b21	3.8	3.1	4.5	4.1	3.7	19
hadcm3 a21	1.8	0.6	1.4	2.8	2.4	9
hadcm3 a22	2.4	2.2	1.1	2.4	3.8	17
hadcm3 a23	2.2	2.3	0.8	2.6	3	15
hadcm3 b21	1.1	0.1	0.6	1.8	2	10
hadcm3 b22	1.9	1.6	1.1	2.1	3	11
hadcm3 b11	1.5	1	0.5	1.9	2.4	11
hadcm3 a1fi	2.6	2.8	1.5	2.6	3.6	15
ccsrnies a21	2.2	2.6	2	1.9	2.5	19
ccsrnies b21	2.9	3.2	2.5	2.6	3.1	20
ccsrnies a11	3.7	4.5	3.6	3.1	3.8	21
ccsrnies b11	1.5	1.4	1.1	1.5	2.1	15
ccsrnies a1fi	2.6	2.8	2.2	2.2	3.2	17
ccsrnies a1t	3.1	3.8	2.7	2.7	3.4	19
echam4 a21	1.8	2.2	0.8	2.3	2.1	15
echam4 b21	2.2	2.6	0.6	2.7	2.8	14
gfdlr30 a21	2.8	2.9	2.5	2.1	3.6	18
gfdlr30 b21	2.3	3.2	2.1	2.2	1.9	7
ncarpcm a21	1.9	2	1.9	1.4	2.1	10
ncarpcm b21	1.6	2.4	1.4	1	1.7	14
cgcm2 a2x	2.6	3.6	2.5	3	1.3	8
cgcm2 b2x	2.2	3.1	1.9	2.5	1.3	6
hadcm3 a2x	2.1	1.7	1.1	2.6	3.1	14

ground. Saturation may lead to increased shear stress and pore-water pressure to the point of failure. Locations where groundwater is concentrated (e.g., gullies), or where shallow permafrost and bedrock impede drainage, are particularly susceptible to rainstorm and snowmelt-triggered failures. Therefore, increased landslide activity can be expected in these settings if climate change heralds an increase in the magnitude or frequency of heavy precipitation, increased snowpack, and intense periods of thaw.

In some settings, the frequency of landslides does not relate directly to the frequency of extreme climatic events because a primary precondition, the availability of material for transport, is not met (Church and Miles, 1987). In these cases, if the frequency of rainstorms or intense snowmelt events increases, there would not necessarily be a corresponding increase in landslide frequency. However, in settings where there is a readily available supply of material, such as in areas underlain by permafrost, an increase in the frequency and/or magnitude of rainstorm-triggered landslides may occur. Specific locations where these situations are likely include north-facing gullies in the White Mountain area and the southern shore of Kluane Lake.

Permafrost degradation

Anticipated climate conditions will likely lead to the eventual overall warming of permafrost, deepening of the active layer, and a decrease in the areal extent of permafrost throughout southern Yukon (Smith and Burgess, 1998). This regional degradation of permafrost is likely to take place gradually due to the buffering effect of seasonal snow cover, vegetation and soil (Burn, 1994). However, the precise response of permafrost at a given site will be complex due to the importance of site conditions such as soil moisture, snow cover, vegetation cover, and ice content of permafrost at the base of the active layer (Smith and Riseborough, 1983).

Permafrost plays an important role in landslide activity in the corridor via its control on soil moisture, drainage and strength. Thawing

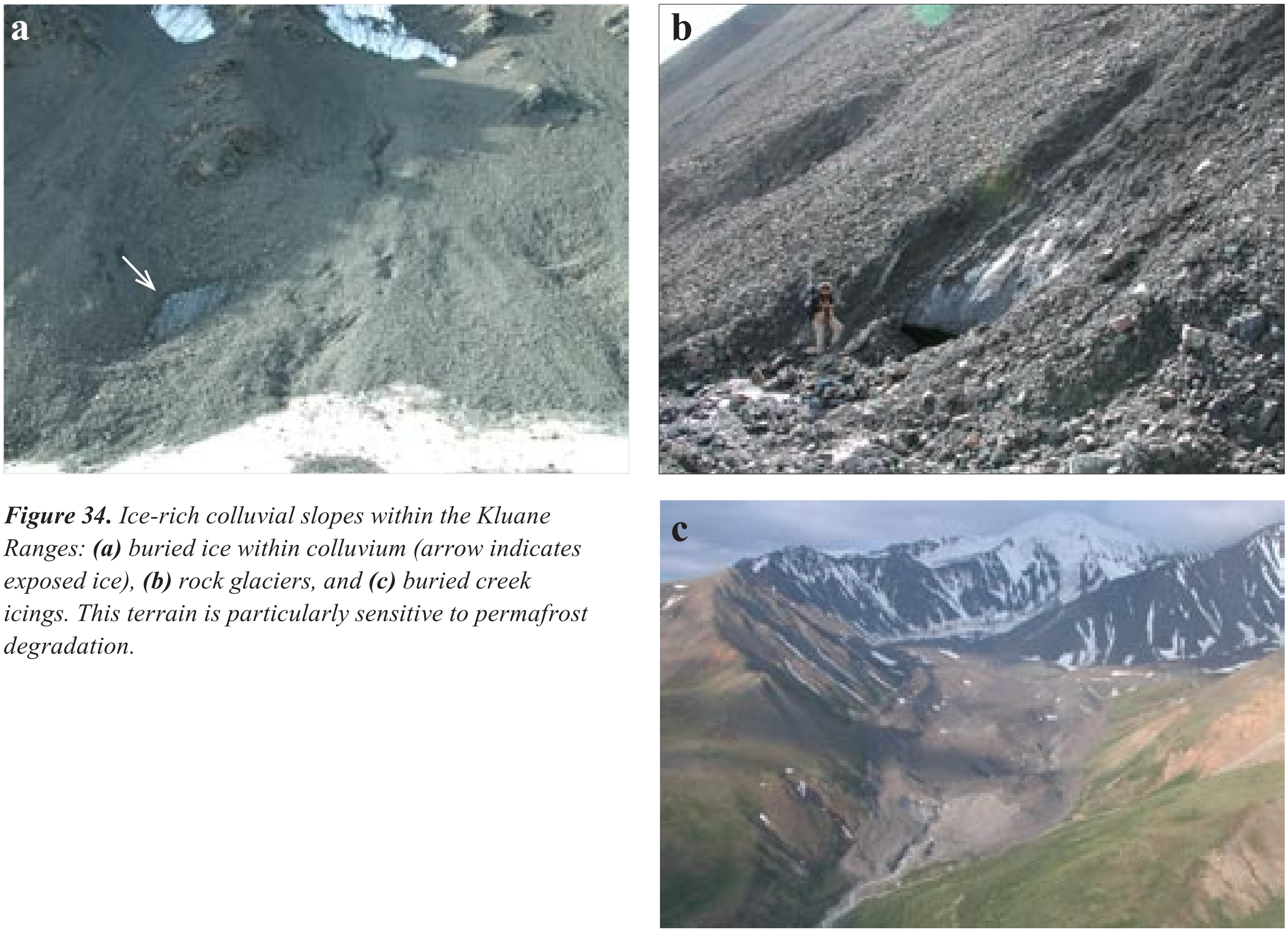


Figure 34. *Ice-rich colluvial slopes within the Kluane Ranges:* ***(a)*** *buried ice within colluvium (arrow indicates exposed ice),* ***(b)*** *rock glaciers, and* ***(c)*** *buried creek icings. This terrain is particularly sensitive to permafrost degradation.*

ice-rich permafrost contributes water to soil moisture while the presence of an impermeable shallow permafrost table restricts drainage of moisture. When rapid thaw occurs in soils containing more ice than would fill the soil pores, excess pore-water pressures are created, resulting in reduced cohesion, and possibly a complete loss of internal friction (McRoberts and Morgenstern, 1974).

Regionally, permafrost degradation may give rise to opposing effects on slope stability. Ice content at the base of the active layer is characteristically high within silt-rich tills and lacustrine sediment throughout the corridor (Rampton et al., 1983; this study). Given the local importance of permafrost and icy sediments for soil strength near the top of the permafrost zone, ground warming leading to the deepening of the active layer will likely increase the frequency of active-layer detachment failures in these settings. In contrast, where sediment is not ice-rich, deepening of the active layer may increase drainage and actually reduce the likelihood of snowmelt- and rainstorm-induced active layer detachment failures.

The impact of permafrost degradation may be especially acute on the alpine slopes of the Kluane Ranges. Ice-cored moraines, rock glaciers, buried river icings and ice-rich colluvium are all commonly found in the upper catchments of the region (Fig. 34). Permafrost constitutes a significant portion of soil strength in these periglacial settings (Zimmermann and Haeberli, 1992), and permafrost degradation could lead to extensive slope failures in this terrain. The primary impact of this type of landslide activity on the corridor would be increased sediment input and channel instability on the large alluvial fans which drain the Kluane Ranges and cross the Alaska Highway and pipeline right of way.

Fire frequency

Current estimates of forest fire frequency in boreal forests range between 30 to 500 years (Hinzman et al., 2003; Yoshikawa et al., 2002), and in the last 20 years, the annual burn area in Canadian boreal forests has doubled (Kasischke and Stocks, 2000; Stocks et al., 2002). In Yukon, it is uncertain whether or not the seasonal timing and magnitude of increased precipitation will be great enough to offset the drying influence of increased evaporation. Attempts at modeling future changes in Canadian forest fire activity project increases of 40% in size and 46% in severity, for a climate with twice present day carbon-dioxide levels (Van Wagner, 1988; Flannigan and Van Wagner, 1991). This increase in activity is related to increased regional aridity and drier fuel, more frequent convective air movements leading to lightning strikes, and changing wind patterns.

An increase in fire frequency will certainly lead to an increase in landslide activity in the Alaska Highway corridor. Even under current climate conditions, landslide activity can be clearly attributed to the occurrence of forest fires. Forest fires severely disturb hydrological and thermal regimes on slopes. Immediately following a forest fire, soil moisture increases due to reduced evapotranspiration and the thaw of ice-rich permafrost. In addition, ground thermal conductivity can increase by up to ten times with the destruction of organic mats, and surface albedo may decrease by 50% with reduced shading from vegetation and darkening of the ground surface by charcoal (Yoshikawa et al., 2002). These changes in ground thermal conductivity and surface albedo lead to rapid permafrost thaw. The resultant increased soil moisture elevates pore water pressure and decreases soil strength. In addition, increased runoff promotes gully erosion, and sets up slopes for potential failure by creating new channels for the concentration of water.

River migration

Increased channel instability can be expected if global warming causes changes in the amount and timing of precipitation, snowmelt or sediment supply to streams (Ashmore and Church, 2001). Enhanced bank erosion rates may occur as rivers adjust their gradients to accommodate changing flow levels and sediment loads.

A clear relation can be established between bank erosion and slope failures under the current climate regime. Channel migration leads to over-steepening of banks and has initiated debris slides and debris flows throughout the study area by undermining the foot of river banks and terrace slopes. In addition, the removal of streamside vegetation and soil has led to retrogressive thaw slumps in ice-rich terrain. Therefore, if climate change causes enhanced river migration, the frequency of debris flows, debris slides and retrogressive thaw slumps in the corridor can be expected to increase.

Glacier mass balance

The impact of climate change on glacier extent in the region is expected to be complex. The location and size of glaciers and perennial snow patches in any area is determined by the amount of annual snowfall and summer temperatures. Although warmer temperatures are anticipated in Yukon, increased precipitation in the form of snow is expected to cause most glaciers in the study area to advance (Brugman et al., 1997). Glaciers and snow patches with low elevation accumulation zones, however, would likely recede or disappear completely.

Locally, this retreat may lead to increased landslides due to the exposure of previously ice-covered sediment on steep slopes or due to the unloading of rock slopes (Eisbacher and Clague, 1984; Haeberli et al., 1992; Zimermann and Haeberli, 1992; Holm, 2002). Newly exposed sediment is especially vulnerable to debris flows because it is characteristically unvegetated, forms steep slopes, and may be ice-rich or ice-cored. Glacier recession may also debutress rock slopes and thereby lead to slope instabilities ranging in size from deep-seated failures of valley walls to small-scale rock falls.

Although few glaciers reside directly adjacent to the Alaska Highway corridor, many glacially fed streams drain into the study area. Therefore, the direct impact of increased landslide activity due to glacial recession would be mainly restricted to upper catchments in the Kluane Ranges. However, increased landslide activity would likely supply more sediment for subsequent fluvial transport and lead to increased channel migration in valley bottoms.

Changes in regional distribution and setting of landslides

Although the frequency and/or magnitude of landslides may increase with climate change, the regional distribution of landslides will not likely change significantly from present because several of the primary controlling factors, such as geology and physiography (material and slope), will remain relatively stable. In other words, those areas currently subject to landslide activity will continue to be affected in the future, but perhaps at an increased rate/intensity. Potential new settings for landslides in the corridor would be those areas most susceptible to thermally and climatically induced slides. These areas include locations underlain by icy silt-rich till and lacustrine material in the Yukon Plateaus, Shakwak Valley and Wellesley Depression zones. The greatest uncertainty of the implications of global warming for landslide activity is found where there is the least amount of information regarding the distribution, depth and ice content of permafrost, namely within the Kaska Mountains.

CONCLUSION AND RECOMMENDATIONS

A wide variety of landslide mechanisms and settings have been recognized within the Alaska Highway corridor. This variability reflects the diverse geologic, geomorphic and climatic environments in the region. In the northernmost zone, the Wellesley Depression, shallow permafrost and its subsidence has an important influence on landslide processes. The most common forms of failure in this region are thaw-induced debris slides and topples. The Shakwak Valley zone has the highest concentration of landslides in the corridor due to the abundance of steep slopes, high relief, and widespread discontinuous permafrost in the area. The most common types of landslides in the Shakwak Valley are rock slides in weak bedrock, channelized and open-slope debris flows, and active-layer detachment failures. Landslides in the Yukon Plateaus primarily relate to the presence of silt-rich and locally ice-rich tills on steep valley sides and the incision of fine-grained lacustrine terraces in valley bottoms. Climatic triggers commonly lead to the creation of active-layer detachment failures, debris flows and earth slides in these settings. In ice-rich terrain of the Yukon Plateaus zone, river migration may also initiate the formation of retrogressive thaw slumps by removing vegetation and soil and exposing permafrost to seasonal thaw. In contrast, debris flows after intense rainfall events are the most common type of landslide in the Kaska Mountains. Finally, in Liard Lowland, failures associated with modern stream incision into glacial meltwater channels, stratified sediments and lava flows are the most common landslide events. The slopes adjacent to the incised streams and meltwater channels are subject to slumping, debris slides and debris flows which characteristically terminate in the stream channels. Throughout the entire corridor, fire-initiated instabilities pose a significant hazard due to rapidly altered hydrologic and thermal regimes following loss of vegetation.

Climate change will likely have the greatest impact on landslide processes where climatic and thermal factors control the strength and availability of material that is subject to failure. The classes of landslides most strongly influenced by climate are active-layer detachment failures and retrogressive thaw slumps. An increased frequency of rainstorm- and snowmelt-triggered debris-flow events may be moderated by the availability of material for transport.

Regionally, the areas most susceptible to changes in landslide activity due to climate change are those underlain by ice-rich colluvium, till and glaciolacustrine material in the Wellesley Depression, Kluane Ranges and Yukon Plateaus. Within the Kaska Mountains the implications of global warming for landslide activity is largely unknown because there is little information regarding the distribution, depth and ice content of permafrost in the region.

At a regional scale, perhaps the most significant impact of climate change-related landslide activity may be the indirect impact of increased sediment inputs into drainages from landsliding activity leading to increased stream channel instability. This would be particularly acute on alluvial and colluvial fan complexes along Kluane Lake where highway maintenance is already a challenge.

Historical data concerning landslide frequency in the corridor is sparse, therefore, estimates of the recurrence probability of future events are necessarily vague. Clague (1982) estimated the probability of threshold destructive events (events large enough to cause damage to settlements or infrastructure) for various natural hazards in the Shakwak Valley. He estimated the annual probability of recurrence for threshold destructive events to be between 0.2 and 0.05 for debris flows and debris torrents, and between 0.001 and 0.01 for large rock slides, slumps and complex landslides. These figures were based on estimates of past recurrence intervals for events of comparable size, using the position of infrastructure at the time of the report, which has changed very little to date. These probability estimates did not take the effects of climate change into account and therefore may be slightly low for debris flows and debris torrents.

With respect to permafrost-related landslides, existing development can be expected to suffer continued direct impacts, the extent of which will depend on the degree of long-term climate change, seasonal climatic variability and fire frequency. In any location with ice-rich soils on sloping ground, anthropogenic or forest-fire related removal of ground cover will almost certainly either initiate new failures or accelerate the rate of pre-existing failures within a very short time frame (1 to 10 years). Risks to future development can only be minimized by ensuring thorough management plans that carefully identify and avoid sensitive terrain.

REQUIREMENTS FOR FURTHER STUDY

The Alaska Highway corridor is critical to settlements, tourism, economic development and transportation in Yukon, and is the focus of several proposed development projects. Several aspects of slope stability require further study before a course of action for the management of landslide hazards in the Alaska Highway corridor can be implemented and an informed regulatory policy drafted. Those most immediate aspects requiring investigation are summarized within the following paragraphs.

1. Detailed investigations of hillslope and mountain permafrost distribution and character to support land-use, fire-management and regulatory policies.

Increased knowledge of permafrost conditions and their sensitivity to development is required for safe, economic and sustainable development in the Alaska Highway corridor. Accurate maps of permafrost and ground ice conditions are needed to support environmental assessment, land use planning and cumulative effect assessment processes, as well as climate change vulnerability appraisals.

The distribution of permafrost on the hillsides and mountainous terrain adjacent to the Alaska Highway is largely unstudied. Where anticipated developments are proposed, permafrost mapping would enable the avoidance of sensitive terrain. If development is proposed to cross below, above, or over potentially frozen slopes, regulators will be required to determine the location and level of detail of geotechnical study they require from project proponents. Regional permafrost mapping and studies of mountainous permafrost would encourage safe, economical and environmentally sustainable design of these evaluations.

Improved characterization of permafrost conditions would also support land use planning processes. Adjacent land uses are not compatible due to the presence of perennially frozen ground. For example, where ice-rich permafrost conditions exist, clearing of agricultural fields adjacent to the Alaska Highway may correlate with high subsidence rates of the highway. At present, adequate maps of permafrost distribution, ground ice content, and ground temperature information do not exist.

Adequate permafrost mapping could also support land management decisions. Fire management plans could consider the vulnerability of development to fire-related failures in the allocation of resources for fire prevention and fighting.

Finally, an understanding of the distribution and character of permafrost and ground ice is essential for determining the sensitivity of a landscape to climate change. For example, reconnaissance observations indicate that many slopes in the Kluane Ranges are underlain by ice-rich debris and that permafrost contributes significantly to their present stability. The sensitivity of this landscape to projected climate scenarios is presently poorly understood. Permafrost mapping would enable a more accurate characterization of the magnitude of the potential impacts of climate change in permafrost terrain.

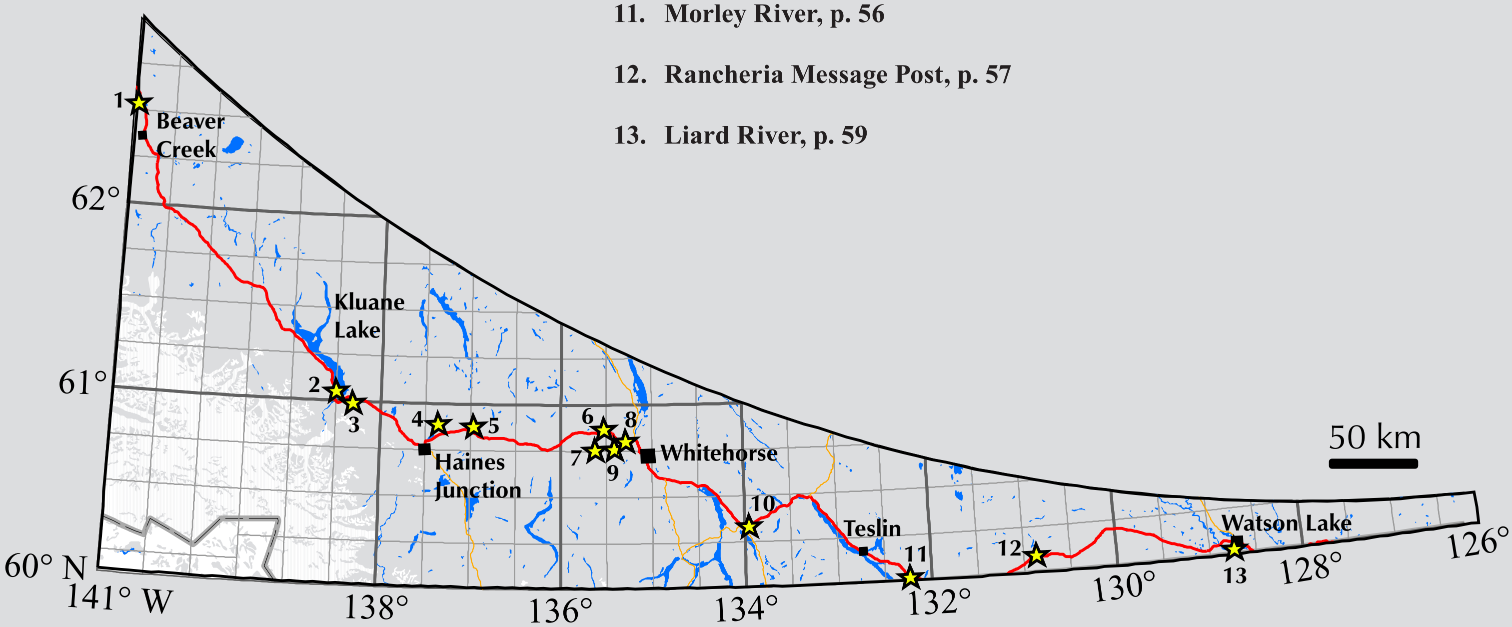
2. Establishment of a regional landslide inventory

An inventory of landslides in the study area was not performed due to the reconnaissance nature of the study. However, inventories are important for characterizing the range of geological conditions susceptible to the various landslide processes operating in the region. This type of database would be particularly useful for permafrost-related detachment failures which occur on exceptionally low slopes and for which conventional analysis cannot predict onset of failure. In addition, the incorporation of temporal and climatic information into the database could aid in defining the relationship between the occurrence of slope failures and annual or seasonal climatic variables. The relative importance of landslide-triggering factors such as rainstorm intensity and duration could then be ascertained. Unfortunately, recording relevant climatic factors is made challenging by the limited number of weather stations in the corridor, particularly in mountainous environments.

3. Comprehensive study and frequency analysis of debris-flow fans to establish risk

Debris flows have historically posed the highest risk to low-lying regions and are capable of causing severe damage to settlements and transportation routes. This study characterized the setting of debris flows within the Alaska Highway corridor but discussed the timing, magnitude, and exact location of very few debris-flow events. Dating of debris flow deposits needs to be done to establish past frequencies and likelihood of future events. These detailed investigations are particularly recommended before increased development proceeds on colluvial fans at the south end of Kluane Lake between Slims River and Silver Creek, in the Ibex valley, on the northeastern side of the Shakwak Trench near Koidern River, and adjacent to the White River bridge crossing.

CASE STUDIES



Case study 1: Beaver Creek embankment

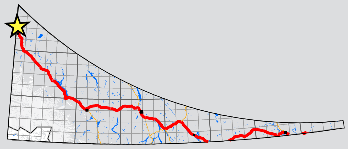
Location: *62°31'48"N,140°58'48"W*

Elevation: *639 m*

Age: *ongoing*

Aspect: *southwest*

Landslide type: *active, translational, debris slide*



Translational sliding of a highway embankment fill at km 1955 of the Alaska Highway, 41 km north of Beaver Creek (Fig. 8), illustrates the sensitivity to disturbance of landscapes that are underlain by ice-rich permafrost. The failure initiated when the highway was repositioned closer to the toe of a till covered slope in 1995. Continued subsidence has caused a 150-m length of the embankment to slide downhill and form an asymmetrical graben (Fig. I and II). Several boreholes were drilled and analysed by J.R. Paine and Associates Ltd. (1997) under contract by Community and Transportation Services, Transportation Engineering Branch, Yukon Territorial Government. A borehole in the maximum settlement zone found approximately 8 m of fill material consisting of silty sand overlying, from top to bottom, 3.7 m of ice-rich silt and 1.3 m of gravelly sand. The silt contained a combination of ice crystal inclusions and stratified/oriented ice formations up to 30 cm thick. In another borehole, the greatest amount of visible ice was observed at the base of the silt unit.

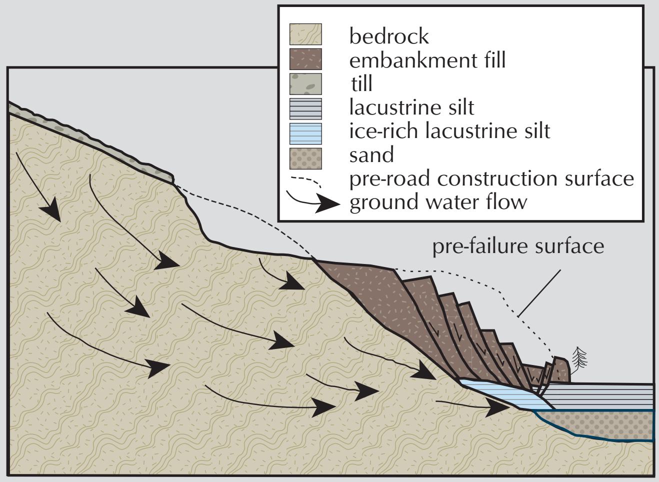


Figure II. *Schematic cross-section, derived in part from testhole data, displaying stratigraphy, ground ice and inferred failure conditions. Ground-ice accumulations in lacustrine silts commonly occur at the base of bedrock slopes throughout the Alaska Highway corridor (Rampton et al., 1983).*

Failure mechanism

Ground-ice aggradation at the base of bedrock slopes is typical in the Alaska Highway corridor (Rampton et al., 1983). Ice lens growth in these locations is promoted by groundwater flow through fractured bedrock, discharged at the base of the valley walls. At this site, the presence of sandy layers could have enhanced the movement of the groundwater towards the aggrading permafrost by providing a permeable layer for groundwater flow. Ongoing permafrost degradation is likely related to disruption of groundwater movement in the local area due to excavation of the highway cut or the placement of fill at the base of the slope and adjacent valley bottom

Figure I. *Initiation area of failure caused by subsidence due to permafrost thaw at the base of the slope. Note car parked on Alaska Highway shoulder for scale. View looking southeast.*

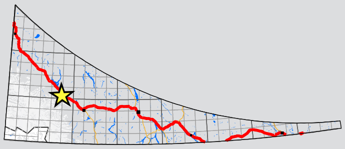
Case study 2: Horseshoe Bay

Location: *61°2'33"N,138°30'14"W*

Elevation: *1050 m*

Age: *July, 1988*

Aspect: *northeast*



Landslide type: *dormant debris flow*

During July 1988, rainstorms triggered debris flows, debris torrents and floods that severed the Alaska Highway in numerous locations between southern Kluane Lake and Burwash Landing. In Horseshoe Bay (kilometre 1710), on the southwestern shore of Kluane Lake, a debris flow was triggered on an open east-facing slope.

The shallow failure initiated immediately below a bedrock-controlled bench within (silty) till deposits and colluvium. Glacially smoothed greenstone was exposed in the 1-m-deep floor of the headscarp area. In the headwall, a grey clay-rich till was exposed below a 30-cm loose weathered horizon. From the initation zone, the debris travelled over steep bedrock scarps onto a more moderate colluvial apron (Fig. III). The maximum depth of the scar is 2 m and the width of this scar ranges between 6 m at its headscarp, to 55 m across its fan (Fig. III). Flow levees and gullies are common features within deposits in the channel. In total, the flow travelled 650 m to the shore of Kluane Lake and buried the highway (Fig. III). Directly above where the debris flow crossed the Alaska Highway, the debris is only 40-60 cm thick and composed of gravelly, silty sand with few boulders. The surface expression of the transported material is very subdued and displays few signs of waves, lobes or levees. Near the toe of the slide, snags of trees, roots, and logs up to 0.5 m in diameter reach a height of 2.5 m.

continued…

Figure III. *Oblique aerial photograph of Horseshoe Bay debris flow which occurred in 1988 after heavy rains.*

continued… Case study: Horseshoe Bay

Failure mechanism

The Horseshoe Bay debris flow failed on July 12, 1988, after an extended period of heavy rainfall. Although daily rainfall was not exceptional, the cumulative rainfall over the first half of the month was extraordinarily high. From July 1-17, Burwash Landing and Haines Junction received 95.8 mm and 36.3 mm, respectively, of rainfall, which accounts for 209% and 264% of their normal rainfall for that period (Public Works Canada, unpublished sources).

The storm events caused rapid infiltration of rainfall, soil saturation and a temporary rise in pore-water pressures. In the area of the initiation zone, this rise in pore pressure was enhanced by groundwater concentration due to the presence of a bedrock lip (Fig. IV). Shallow bedrock beneath the upper reaches of the flow channel also helped to concentrate water and facilitated the long runout distance. Permafrost was not found on the slope in the area of the failure.

Impacts

The Horseshoe Bay landslide blocked the Alaska Highway with debris including tree trunks and boulders for a distance of 50 m. The failure contributed to the closure of the highway for five days, trapping motorists and cargo. Repairs to the highway included clearing, resurfacing and ditch restoration.

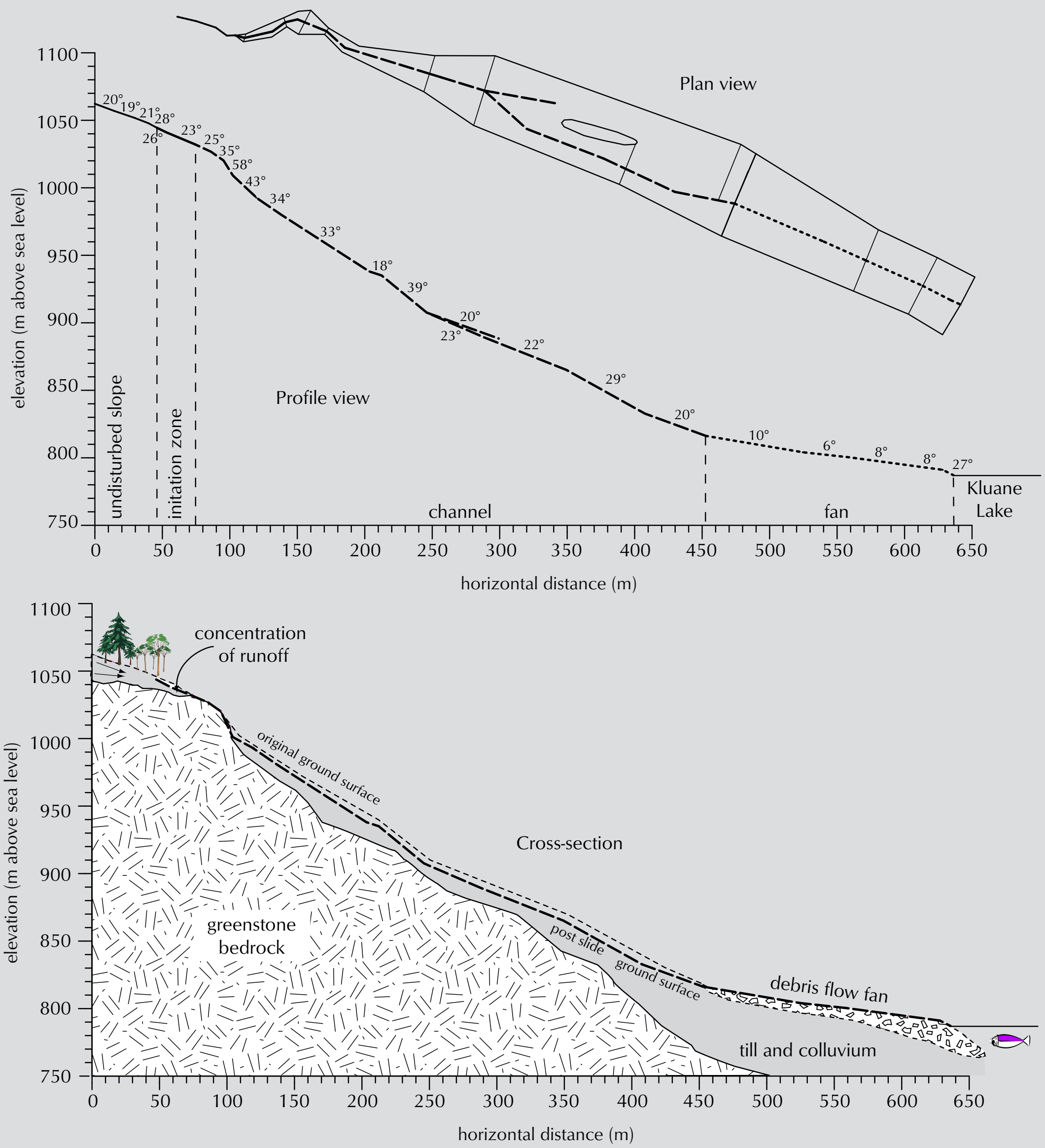


Figure IV.
***(a)** Surveyed cross-section and plan view of Horseshoe Bay debris flow.*
***(b)** Schematic cross-section of surface and inferred subsurface conditions of Horseshoe Bay debris flow.*

Case study 3: Silver Creek

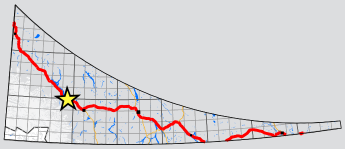
Location: *60°58'39"N,138°18'44"W*

Elevation: *1155 m*

Age: *July, 1988?*

Aspect: *northwest*

Landslide type: *dormant active layer detachment failure (debris flow)*



As Silver Creek flows eastward from the glaciated peaks of the Kluane Range and enters Shakwak Trench, it incises 80 m into an undulating and fluted plain composed of till, lacustrine and outwash sediments from a number of glaciations (Denton and Stuiver, 1966). Four recent shallow debris slides were found along the northwest-facing slope of Silver Creek during field surveys in 2003 (Fig. V). The largest slide (slide 1) occurred in 1988, according to aerial photos taken in 1989, and the age of willows in the landslide scar. The remaining three slides occurred between 1989 and 2003. All four slides initiated on middle to upper planar slopes that displayed indications of only minor concentration of runoff or groundwater flow. The source material was a grey colluviated silty till with common cobbles and minor boulders. Slide 1 was surveyed in detail (Fig. VI). The width of this scar ranges between 10 m at its headscarp, to 26 m across its fan. Overlapping flow lobes and flow levees are common features within the deposits in both the headscarp area and the channel. The maximum depth of the scar is 1 m. A thick mat of overhanging organic material is present above the headwall. Debris from the slide extends 45 m into the floodplain of Silver Creek.

Figure V. *Oblique aerial view of Silver Creek active layer failures (debris flows). Landslides are numbered 1 through 4.*

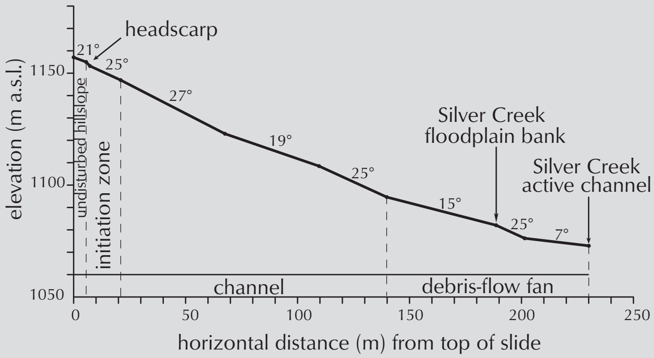


Figure VI. *Diagrammatic profile of Silver Creek debris flow.*

Permafrost conditions

Apart from the areas disturbed by landslides, the southern bank of Silver Creek is occupied by mature white spruce forest. Typically, the ground is covered by lichens and feather mosses ranging from 25 to 30 cm thick. Frozen soil was found in mid-August at a depth of approximately 40 cm below the mineral soil surface. The top 15 cm of the frozen soil contained visible ice in the form of coatings on clasts, ice grains, and ice veins up to 1 mm thick. The visible ice content was estimated to be less than 10% by volume.

Failure mechanism

In July, 1988, heavy rainfall triggered numerous failures, some severing the Alaska Highway, in the Kluane Lake area (Evans and Clague, 1989). From July 1 to 7, Burwash Landing received 209% of its normal rainfall for that period, and 42% of its annual total precipitation (Evans and Clague, 1989). These rainstorms in 1988 are suspected to have triggered landslide 1, as airphoto interpretation and dendrochronology investigations suggest. The permafrost table is very shallow in the undisturbed slope adjacent to the failure. The presence of a shallow, frozen and impermeable substrate likely caused the intense rainfall to elevate pore water pressure to the point of failure. Comparison of the depth of the landslide scar and the depth of permafrost on the undisturbed slope suggests that the permafrost table also controlled the depth of failure. Sloughing from beneath the organic mat and the presence of overlapping flow lobes in the landslide debris suggest that the present depth of the scar (1 m) has been modified by thaw and reactivation since the initial failure. A triggering event for landslides 2, 3 and 4 was not established although a similar mechanism is speculated.

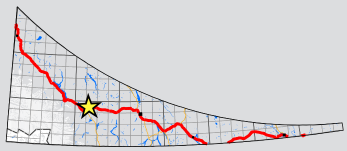
Case study 4: Marshall Creek basin

Location: *60°52'51"N,137°20'46"W*

Elevation: *910-1200 m*

Age: *1998-2003*

Aspect: *north (average)*



Landslide type: *dormant debris flows (active layer)*

Forty-one recent debris flows exist within terraces and valley sides of Marshall Creek, 14 km northeast of Haines Junction. The vast majority of the instabilities were initiated within an area burned by forest fires during the summer of 1998 (Fig. VII). The fires affected an area of approximately 37 km^2 and bordered Marshall Creek for 9 km.

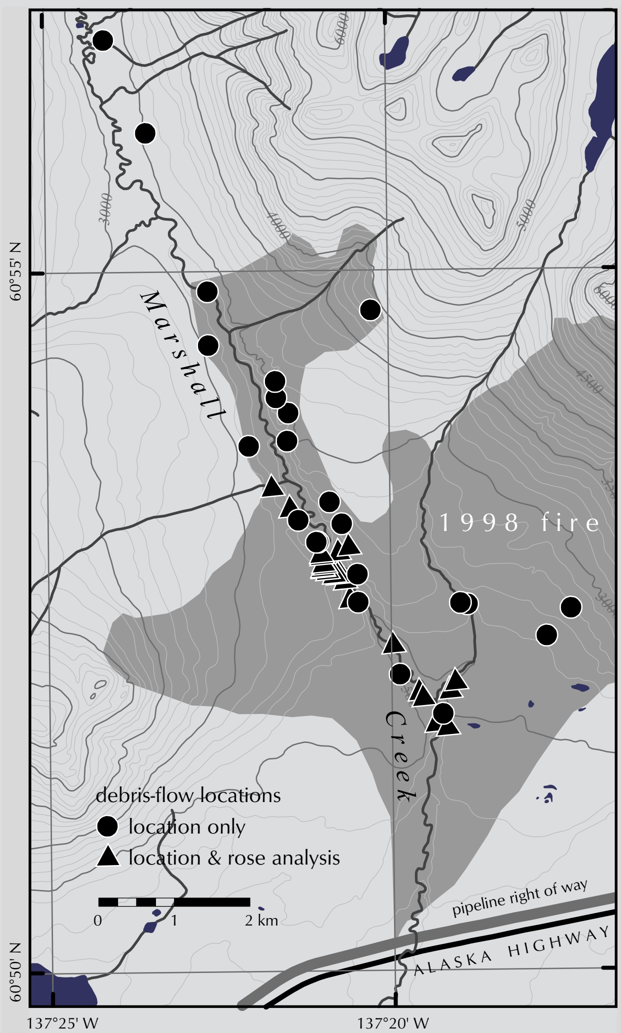


Figure VII. *Topographic map of debris flow locations and aerial extent of burn along Marshall Creek. Dark grey is 1998 fire-burned area.*

The debris flows in the Marshall Creek basin can be divided into two groups based on the landform within which they originate. The majority of the landslides (36) developed on the scarp of high-level terraces composed of glacial and glacial-fluvial material (Fig. VIII). In comparison, a lesser number (5) of the landslides occurred on gentle till-blanketed valley sides. Much of the valley fill was deposited as ice advanced and retreated from the Marshall Creek valley during the late Wisconsinan McConnell Glaciation. During this advance and subsequent retreat, silt-rich till blankets were deposited on valley sides and a thick fill of silt-rich till, glaciolacustrine and glaciofluvial strata were deposited in the valley bottom. Figure IX describes the aspect of the debris flows that were surveyed by helicopter or by foot. The average aspect of the debris flow headscarps in the high-level terraces was north-facing.

Permafrost conditions

In order to compare the depth and character of permafrost within and outside of the burned area, soil pits were dug in an unburned terrace gully wall and in a second gully of similar aspect and geometry within the burn. At the unburned site, in late summer, ice was found at a depth of 60 cm, beneath 25 cm of moss and lichen, 20 cm of black humic organic soil, and 15 cm of unfrozen soil. Within the frozen soil, up to 3-mm-thick ice coatings were observed on granules and pebbles within a silty sand matrix. In total, visible ice is estimated to compose 10% (by volume) of the soil. In contrast, at the burned site, ground temperatures were 6.4°C at 1.05 m depth.

Failure mechanism

Comparison of soil organic horizons and canopy cover inside and outside of the burned area indicate that the forest fires burned most of the organic mat and canopy. Removal of the vegetative cover has led to changes in surface energy balance and caused the active layer to increase in thickness. Examination of the northerly aspect of the landslide initiation zones, as well as comparison of scar depths and the active layer depths in the unburned site suggest that most landslides occurred at the base of the active layer. Thawing of ice lenses in combination with snowmelt and/or rainfall may have resulted in elevated pore-water pressure in this zone. The presence of segregated ice near the permafrost table also suggests that the strata would undergo some strength reduction as thawing occurred. Lastly, maintenance of high pore pressure was likely facilitated by poor drainage due to the presence of the impermeable permafrost table, which would have been shallowest on north-facing slopes.

Impacts

The impact of the debris flows near Marshall Creek includes burial of mining access roads and mining equipment by up to a metre of debris. Many debris flows travelled directly into Marshall Creek and have contributed sediment ranging in size from clay to boulders. The creek is still actively eroding this material. The Alaska Highway and the proposed Alaska Highway pipeline right of way cross Marshall Creek 3 km downstream from the failures. These crossings remained unaffected by the failures.

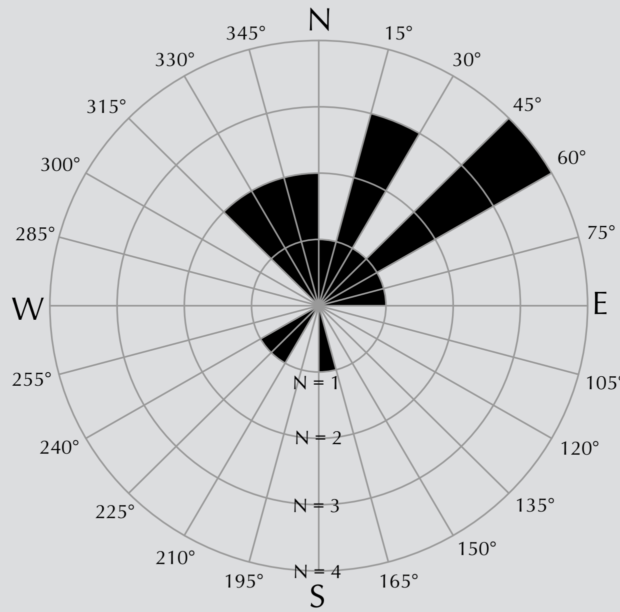


Figure IX. *Rose diagram representing the aspect of visited landslide headscarps in Marshall Creek valley.*

Figure VIII. *Oblique photograph of debris flows originating from the scarp of a terrace formed in glacial material along Marshall Creek.*

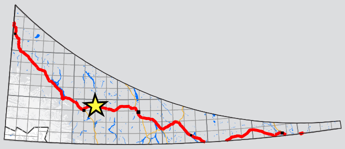
Case study 5: Aishihik rock slide

Location: *60°52'8"N,136°57'43"W*

Elevation: *1283 m*

Age: *Early Holocene*

Aspect: *southwest*



Landslide type: *dormant rock slide*

A large rock slide deposit is located on the north side of the Dezadeash River valley, 35 km northeast of Haines Junction. The failure involved gneissic rock of Proterozoic to Mesozoic age (Gordey and Makepeace, 2003), which at the site, is highly fractured. The source displays an average slope of 37° and ranges from approximately 150 to 320 m in height. Within the southwesterly facing headscarp, the dip direction of several major sets of joints is sub-parallel to the direction of failure. Two vertical fault zones approximately 2 m wide were observed near the centre of the headscarp. Along the western flank of the headscarp, toppling features were noted (Fig. X). Behind the headscarp, tension cracks and sackung features (ridge-parallel troughs formed by surficial creep) were observed and have torn the roots of live vegetation. From the source area, the debris extends 1.75 km onto a glaciolacustrine terrace (Fig. XI) resulting in an height/length ratio of 0.31 and a travel angle of 17.5°. The debris has an approximate volume on the order of 22x106 m^3, a maximum thickness of 36 m and is dominated by large (1 m) subangular boulders. Its surface expression is generally hummocky and supports several small ponds.

Constraints on the age of the landslide to the early Holocene are provided by the presence of lacustrine deposits overlying the deposit. Glacial lake shorelines deposited atop and eroded into the debris can be traced between 810 and 850 m in elevation. This lake level correlates with the early-Holocene glacial lake Champagne (Rampton and Paradis, 1982). Debris below 850 m contains rare pebbles of erratic lithology, which are suspected to be dropstones, but may alternatively be clasts derived from the adjacent slope that were entrained in the failure. The presence of 1250-year-old White River Ash in surface aeolian sand overlying the landslide debris corroborates with an early-Holocene age.

Figure X. *Active toppling on western flank of Aishihik rock slide. The toppling movement has disturbed roots of live vegetation in adjacent hillslope.*

Failure mechanism

The preconditions of the rock slide are unknown, although the age of the deposit and geometry of the remnant failure surface suggest that the slide is related to thinning and retreat of the Pleistocene ice tongue which occupied the Dezadeash valley during the late Wisconsinan. Preliminary measurements of major joint sets suggest that the geometry of the head wall was steep, possibly wedge-shaped and that movement was facilitated by failure along shallowly dipping joints day-lighted by glacial erosion of the Dezadeash valley. Only a thin discontinuous veneer of lacustrine material over the slide debris suggests that the slide entered Glacial Lake Champagne. Moist lacustrine deposits in the flat valley bottom have little frictional resistance and are suspected to have supported the mobility of the flow. Seismic shaking may have also contributed to triggering the failure.

The presence of disturbed vegetation along tension cracks indicates recent movement. Such signs of modern instability have implications for hazard assessment within this region of the Alaska Highway corridor. Prior to further development below the slopes of this upland, a more detailed assessment of the area is recommended.

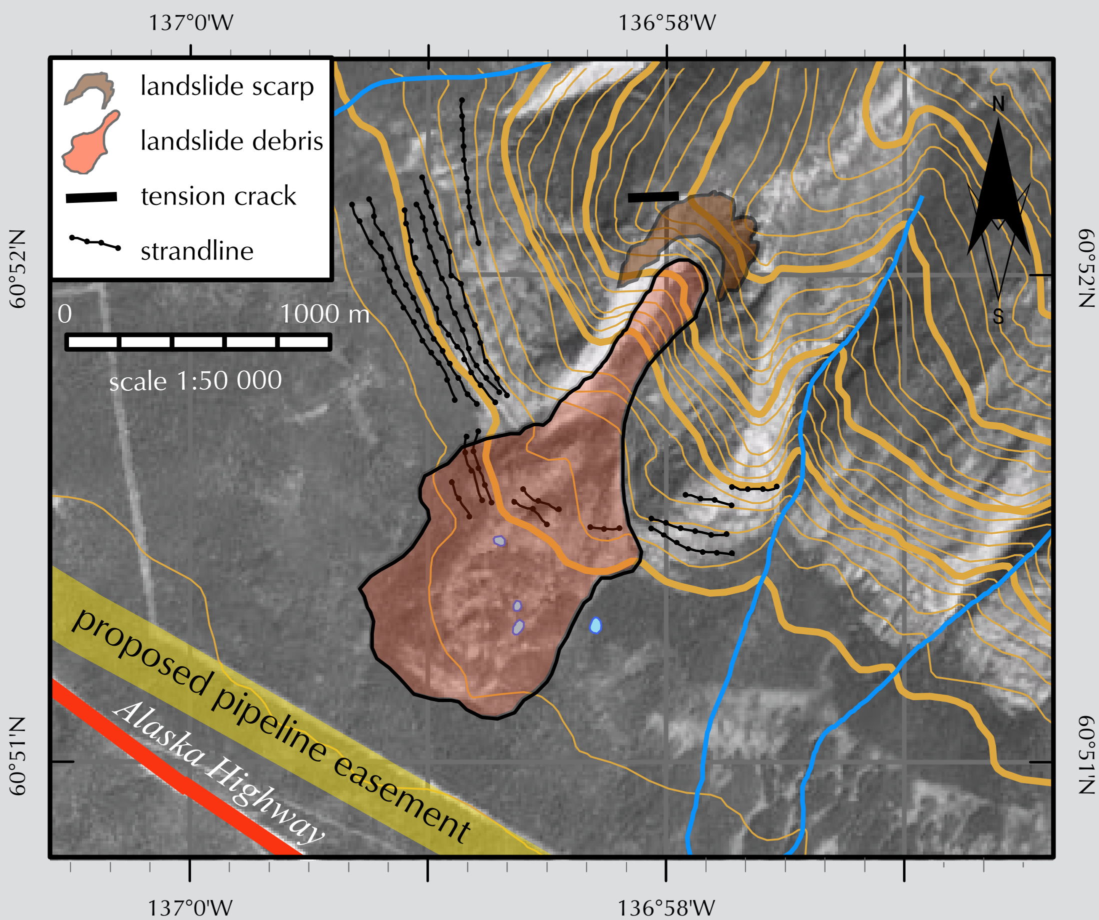


Figure XI. *Topographic map underlain by an ortho-corrected aerial photograph (A25275-14) depicting location of Aishihik rock slide.*

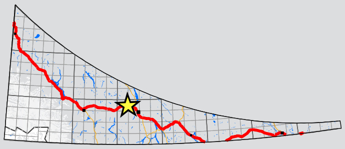
Case study 6: Takhini River

Location: *60°51'24"N,135°30'40"W*

Elevation: *680 m*

Age: *1979-present*

Aspect: *north*



Landslide type: *retrogressive ground-ice slump (earth flow)*

A partially stabilized retrogressive thaw slump is located adjacent to the Alaska Highway, 25 km west of Whitehorse. The failure occurred in a terrace composed of laminated silt and clay and is representative of eight other failures that have occurred within 6 km of this location. The terrace's surface lies 11 m above the river, is locally ice-rich, and hosts numerous thermokarst lakes. The slump has an approximately 7-m-high, 107-m-wide semi-circular headscarp. During field visits in the summer of 2003, the western portion of the headscarp was near vertical, and the remainder of the headscarp exhibited a slope of 25° with fresh terracettes extending to the embankment of the Alaska Highway. These features indicate that retrogression continues. From the headscarp area, a 132-m, low-angle (7°) tongue extends into the Takhini River (Fig. XII). The river has eroded the fine-grained material leaving a 1.7-m stream cut at the landslide toe. The volume of the failure is calculated to be in the order of 40 000 m^3.

At the position of the thaw slump, 1971 air photographs indicate that stream erosion had already removed the vegetative cover on the bank of the Takhini River. By 1979, slumping had caused the terrace scarp to recede approximately 25 m. Between 1979 and 1986, further slumping had caused the headscarp to retreat 112 m to near its present position. Since 1986, the headscarp has retreated several metres and decreased its slope substantially.

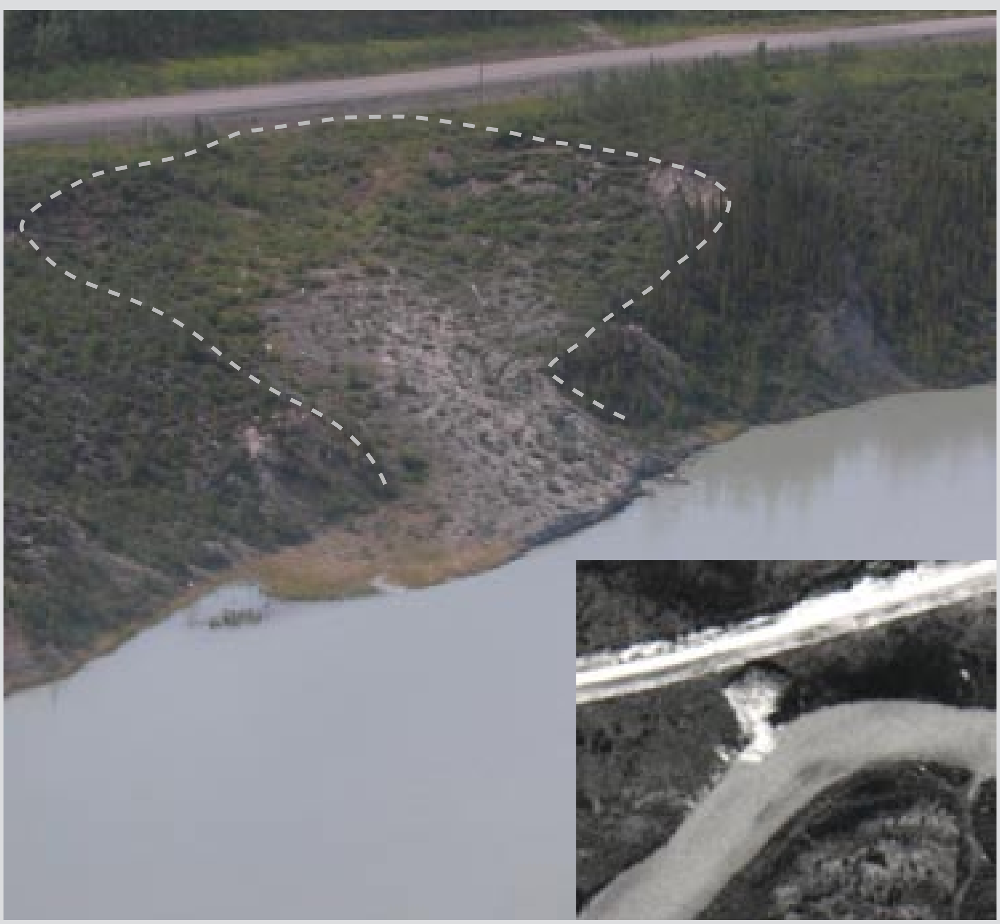


Figure XII. (a) *Oblique aerial photograph taken in 2003 of Takhini River retrogressive ground ice slump adjacent to the Alaska Highway. Cracks in highway embankment propagated during summer 2003. Permafrost thaw was triggered by river undercutting. Forest fire, proximity to highway, and forest cover removal in adjacent agricultural fields all contribute to continued subsidence in the area. Dashed line highlights remnant headscarp.* ***(b)*** *Inset aerial photograph (A27217-257) of Takhini River retrogressive thaw slump in 1987.*

Permafrost conditions

Extensive forest fires during the summer of 1958 burned most of the vegetation and soil organic horizon in the area surrounding the slump. Burn (1998) found that the active layer is 1.4 m thick in unburned sites, whereas at burned locations 39 years after the fire, the permafrost table may be more than 3.75 m below the ground surface. Burn (1998) also found that the excess ice content of permafrost in the valley may range between 10% and 50%, and averages 24%. That is, when thawed, there may be on average 24% more ice (by volume) in the sediment than the filling of the porosity would predict there would be.

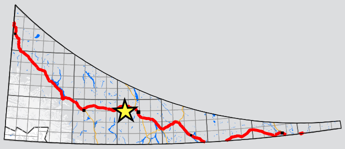
Failure mechanism

Thawing of segregated ice has caused the failure of fine-grained lacustrine terraces along the Takhini River. The morphology of the thaw slump is characteristic of bi-modal flows (McRoberts and Morgenstern, 1974). It has a semi-circular, amphitheatre-like headscarp and biangular profile. The flow has a low-angle tongue (7°) and, when active, had a steep headscarp (Fig. XII). In general, retrogressive thaw-slump development is initiated when the vegetation or active-layer materials are removed, causing thaw of icy material. Likewise, the Takhini River thaw slump is on the cut bank of a migrating meander of the river, and the meander is propagated by a tributary alluvial fan entering the Takhini River on the opposite bank.

Impacts

The Takhini River thaw slump illustrates how thaw-related landsliding can impact infrastructure and streams. In addition, it illustrates the length of time that instabilities can continue after initiation. Highway fill is subsiding and causing the roadbed to slope towards the slump. Cracks in the road surface are also propagating parallel to the scarp as the headscarp stabilizes. Utility cables have been routed above ground where disrupted by the movement. Finally, ongoing river erosion at the toe of the slump contributes to the addition of fine-grained material into the Takhini River.

Case study 7: Ibex Valley



Location: *60°44'42"N,135°36'25"W*

Elevation: *2000 m*

Age: *recent (1991-2001)*

Aspect: *north*

Landslide type: *multiple dormant debris flows*

On the south side of the Ibex River valley, several debris-flow tracks emanate from a single gully system and are characteristic of mass movements within the U-shaped valley. The Ibex River valley is located approximately 30 km east of Whitehorse and contains the easement for a potential pipeline route.

The debris flows originate from a north-facing catchment area which drains steeply into the Ibex valley with an average gradient of 39° and over 1100 m of relief (Fig. XIII). The local terrain has been glacially steepened and slopes within the basin are composed of bedrock mantled by a discontinuous veneer (<1 m) of colluvium composed of gruss and sandy rubble. Bedrock within the basin is dominated by granodiorite, although metabasite composes the uppermost ridge of the basin. The failures initiated within multiple bedrock-lined tributary gullies at a slight bench whose geometry favours the accumulation of debris and snow (Fig. XIV).

Figure XIII. *Oblique photograph of debris-flow catchment and fan. A debris flow in the early 1990s came within 60 m of a proposed pipeline easement situated in the valley bottom (foreground).*

The tributary gullies converge to form a main bedrock-lined channel. The roughly 25-m-wide and 750-m-long gorge has a slope of 35°, and is incised into bedrock and older debris flow deposits near its terminus. The walls of the channel are approximately 18 m high and are cut into granitic bedrock. The floor of the channel is bouldery and flanked by subdued levees 1-2 m high. At the lowermost end of the channel, stream incision exposes the reversely graded deposits of three flow events, each less than 1.2 m thick.

Below the mouth of the channel, the flows travelled to a maximum of 550 m towards the valley bottom and deposited boulders up to 2.5 m in diameter on the fan. The longest tongue cleared a 25- to 15-m-wide swath through an immature (dating from earlier than 1958) lodgepole pine forest and reached within 60 m of a proposed pipeline easement.

Individual lobes are composed of an unsorted mixture of sand and rubble. The largest clasts are characteristically observed along the lateral periphery of the flows; there is a down-fan trend in grain size (boulder- to cobble-dominated) and the deposits lack well defined levees on the fan. Cobbles were found sporadically perched upon boulders well above the general fan surface. Incision and reworking of the debris into channel forms was noted. Since 1958, approximately 45 % of the surface area of the fan has been active. Dendrochronological dating of the most recent scars indicates that debris flow events occurred in 1991, between 1998-1999 and between 2000-2001. The pattern of the last undisturbed trees ring of the samples indicate that scarring probably occurred in winter.

Failure mechanism

Due to the shallow residual soils and impermeable bedrock found in the catchment basin, large amounts of runoff and snowmelt may quickly proceed into channels and saturate loose colluvial material. Such conditions are conducive to the formation of debris flows during rainfall and snowmelt events. Loosening of rock by freeze-thaw cycles enhanced by chemical weathering of the granitic bedrock are suspected to be the primary processes supplying debris to the gully systems for subsequent transport by debris flow. The presence of perched clasts, and the pattern of truncated tree rings suggest that snow composed a significant portion of the debris and supports the hypothesis that snowmelt may have contributed water to the failure process.

Figure XIV. *Catchment area of Ibex valley debris-flow system displaying light coloured fresh-looking channels, where debris and snow are able to accumulate.*

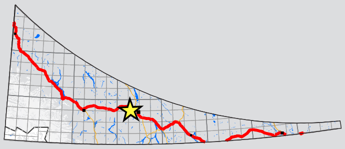
Case study 8: Haeckel Hill

Location: *60°47'34"N,135°15'50"W*

Elevation: *1041–1104 m*

Age: *1991-2003*

Aspect: *349°–046° (NNW–NE)*



Landslide type: *abandoned, composite, retrogressive active layer detachment failures*

Five recent active-layer debris slides and secondary debris flows within matrix-supported diamictons on Haekell Hill are examples of mid-slope landslides resulting from fire-related ground-ice thawing.

Five failures occurred in an area burned by a 1991 forest fire on the mid-slopes of Haeckel Hill (Fig. XV). Haeckel Hill is located 7.5 km northwest of Whitehorse and 2 km south of the Alaska Highway. Within the burn, loss of organic mat and tree canopy was complete. The debris slides are located on the north-facing slope of the hill at approximately 1000 m a.s.l. The source material was till and colluviated till composed of a sandy silt matrix containing granule- to cobble-sized clasts and rare boulders. Table I describes the morphological characteristics of the landslide scars. Transverse compression ridges were commonly observed at the toe and along the sides of the scars. These features indicate that sliding was the initial failure mode. Flow levees up to 1 m in height commonly flank the landslide tracks and suggest

Table I. *Morphological characteristics of landslides on Haeckel Hill.*

Station	Elevation (m)	Aspect	Initiation Slope	Scar length (m)	Scar width (m)	Scar depth (m)
03AH097	1104	46°	20°	167	14	1.3
03AH098	1098	349°	19°	51	15	1.2
03AH099	1041	27°	21°	105	9	1.5
03AH100	1080	352°	24°	-	10.5	2
03AH101	1077	14°	18°	-	10	1

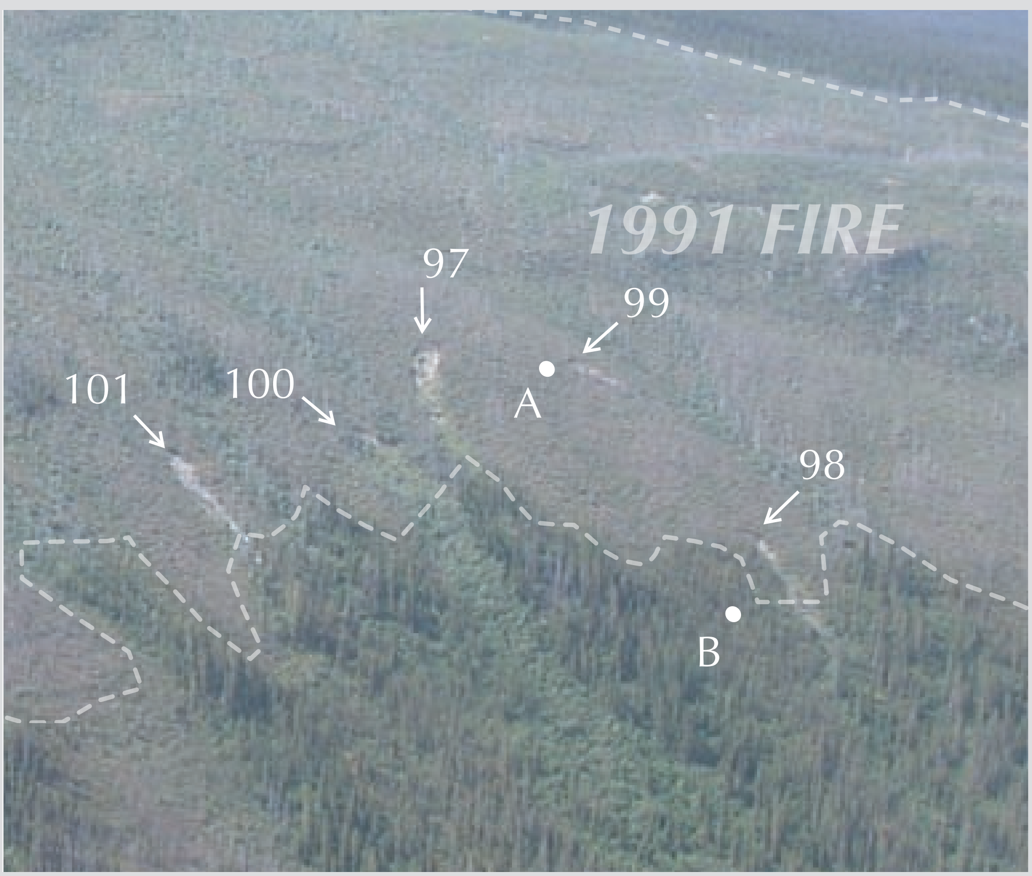


Figure XV. *Oblique aerial view (2003) of active layer detachment slides and secondary debris flows on the north-facing slope of Haeckel Hill.*

that the slides translated into debris flows. As well, sloughing beneath intact forest mat and fans of debris overlying compression ridges attest to secondary retrogressive failures. These flows travelled much farther than the initial slides. Aerial photographs taken in 1995 demonstrate that three of the five landslides had occurred within four years of the fire.

Permafrost conditions

In order to gain insight into the depth and character of permafrost within the burned area, a 1.35-m-deep trench adjacent to the headscarp of landslide 97 was excavated (Location A, Fig. XV). However, permafrost was not found in the pit. A second pit was dug in the unburned white spruce forest directly below the slides in late August (Location B, Fig. XV). Here, permafrost was located beneath 25 cm of organic mat and 45 cm of unfrozen mineral soil (Fig. XVI). The permafrost contained stratified segregated ice veins, 1-3 mm thick, composing approximately 15% (by volume) of the soil.

Failure mechanism

The timing of the failures suggests that the thawing is attributable to the 1991 forest fire that burned most of the organic mat and canopy. Comparison of scar depths and the active-layer depths in the unburned site suggests that the landslides occurred along the base of the active layer. Elevated pore-water pressure in this zone may have resulted from thawing ice lenses, in combination with snowmelt and/or rainfall. Thawing of ice lenses would have also reduced the structural strength of the base of the active layer, and high pore pressure could have been maintained by poor drainage due to the presence of a frozen substrate. Three of the five landslides appear to have experienced secondary debris flows associated with thaw since the initial failure.

Figure XVI. *Soil from beneath the permafrost table from unburned forest site displaying stratified visible ice. Thawing of ice-rich soil causes a significant loss of soil strength.*

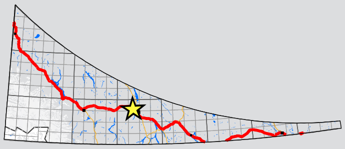
Case study 9: Mount Sumanik

Location: *60°45'0"N,135°23'13"W*

Elevation: *1427-1483 m*

Age: *recent*

Aspect: *west- to southwest-facing*



Landslide type: *multiple dormant debris flows*

A series of ten debris-flow channels in a basin draining Mount Sumanik demonstrate a potential effect of ground-ice thawing on undisturbed alpine slopes (Fig. XVII). Mount Sumanik is located 15 km west of Whitehorse. The basin containing the landslides drains westward. Instabilities are confined to the southwest-facing slopes of the drainage basin, and occur on the apex of convex alpine slopes in silty till deposits and colluvium. The failures were initiated on fairly steep slopes (24°-29°) and travelled down the more moderate mountain slope (15°-25°), scouring gullies up to 47 m wide and 13 m deep, commonly to bedrock (Fig. XVIII). In several locations, gullies follow bedrock structures. Continued retrogression is evident in the headwalls and on some of the sidewalls. The flows travelled up to 680 m to the valley bottom and produced fans containing boulders up to 2 m in diameter. Individual deposits are up to 2 m thick. The source material was a colluviated till composed of subrounded granules to boulders in a sandy silt matrix.

The frequency with which the debris flows occur was not ascertained. However, the oldest willows growing on the freshest flow deposits are two years old. Aerial photographs of the debris-flow gullies from 1986 display well vegetated subdued V-shaped forms, indicating that the hillsides had not failed recently when the photos were taken. Finally, a lack of vegetation within the landslide debris indicates that failures since 1986 have occurred frequently enough to inhibit vegetation growth within the gully systems.

Permafrost conditions

Soil pits reveal that within this zone, frozen ground lies approximately 1.65 m below the surface in late summer. The thickness, ice content and structure of the permafrost was not ascertained.

Figure XVII. *Oblique aerial view of Mount Sumanik debris-flow channels, looking east.*

Failure mechanism

Shallow slumping and evidence of poor drainage is widespread on the slope above each debris-flow headscarp. A 60-cm-thick saturated soft plastic layer was discovered on top of permafrost within this zone. This stratigraphy suggests that the presence of permafrost promotes poor drainage and may lead to the elevated pore pressures that trigger slumping on the hillside, thereby supplying debris to the gully system. Once failures initiate in the upper alpine slopes, shallow bedrock beneath the lower gullies concentrates water and facilitates long runout distances into the valley bottom.

Impacts

Infrastructure does not currently exist within the basin or creek system of the Mount Sumanik debris flows. Nevertheless, the impact of the debris flows on the main creek is readily observed. The debris flows contribute a large supply of sediment ranging from clay to large boulders to the creek system. Multiple abandoned channels mark the resultant lateral instability of the creek during flood up to 3 km downstream from the debris flow fan.

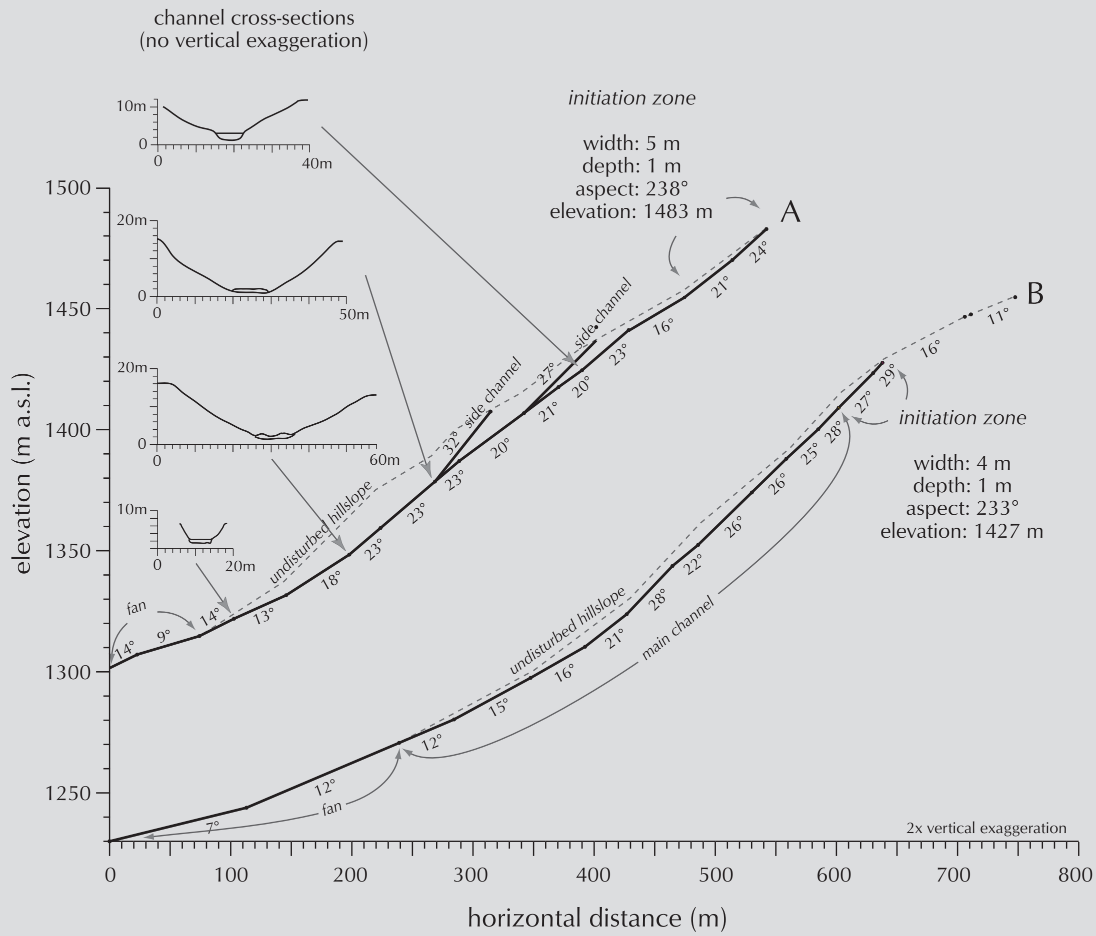


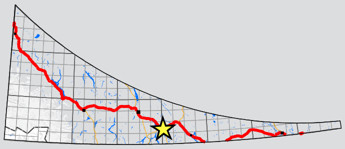
__Figure XVIII.__ Longitudinal profile and transverse cross-sections of a debris-flow track on Mount Sumanik

Case study 10: White Mountain

Location: *60°19'36"N,133°55'19"W*

Elevation: *1245 m*

Age: *>1723 B.P. to recent*



Aspect: *northeast*

Landslide type: *multiple dormant debris flows*

In the area of White Mountain, the Alaska Highway corridor traverses a deep U-shaped valley bordered to the south by steep, 300-m-high, limestone bluffs (Fig. XIX). Many debris-flow catchments and channels are incised into till and colluvium below the rock faces. One debris-flow system preserves a record of multiple-flow events and gives an estimate of the frequency of debris-flow events along these slopes.

The system consists of an upper catchment, channel and fan. The catchment originates at the base of the smooth glaciated limestone bluffs within glacial valley fill at 1245 m. The underlying material within the catchment is primarily composed of a bouldery till with a silty sand matrix and an average slope of 37 degrees. Permafrost was not encountered within the unvegetated gully walls, but extensive permafrost was found to lie within 80 cm of the mineral surface on the forested slopes immediately adjacent to catchment. The permafrost contained only trace amounts (<3%) of visible ice.

From the initiation zone, the debris travelled down a 600-m-long and 2- to 12-m-wide channel bordered by 1.3-m-thick levee, to a fan. The apex of the fan preserves a series of four nested levees (Fig. XX).

Figure XIX. *Catchment area of White Mountain debris flows originating from north-facing slopes of White Mountain. Permafrost was encountered within 1 m of the surface within forested slopes adjacent to the catchment. Photograph taken looking south from Alaska Highway.*

Figure XX. *Deposits from two youngest debris flows (occurred between 1980-1991 and 1952-1980, based on dendrochronology).*

The levees display a decreasing average clast size with decreasing channel diameter. The largest pair of levees contained abundant boulders to a maximum diameter of 1.3 m, and the smallest pair of levees contained primarily poorly sorted gravel with rare small boulders in a sandy matrix. The minimum age of the individual levees are (from youngest to oldest) 12, 23, 51, and 120 years old based on the maximum age of white spruce trees rooted in the material. It is assumed that debris flows occur more frequently than the record of levees would suggest because large events are capable of erasing smaller, more frequent events, so that the remaining levees only preserve a partial record.

Failure mechanism

The debris transported by flows to the fan is supplied by failures within till. The presence of permafrost in the undisturbed hillslope adjacent to the catchment indicates that permafrost melt must occur in order to supply loose debris in the catchment available for debris flows during rain or snowmelt events. Once debris flows remove overlying insulating material, thaw may then progress further into the slope, making additional debris available for transport. In summary, thaw of permafrost within the undisturbed hillslope is suspected to control the expansion of the catchment basin and the availability of sediment for transport by debris flows.

Case study 11: Morley River

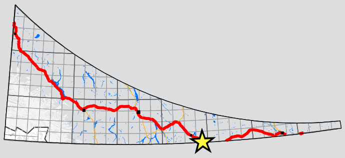
Location: *60°0'58"N,132°11'6"W*

Elevation: *817 m*

Age: *recent (1-2 years)*

Aspect: *south*

Landslide type: *debris flow, active*



A series of five debris flow gullies are situated within the Alaska Highway corridor, 35 km southeast of Teslin (Fig. XXI). The gullies are incised into a 45-m terrace along the Morley River underlain by till. The most recent debris flow occurred down a 120-m-long gully with a steep 10-m-high headwall. The headwall exposed grey, stiff, and prismatically jointed till with a silty loam matrix and rare lenses of gravelly sand. The debris flow initiated within saturated colluvium at the base of the headwall. During field visits in the summer of 2003, a spring emanating from the debris was observed. Excavations in the initiation zone revealed a 20-40 cm sandy gravel lense as the source of water feeding the spring. From the initiation zone, debris travelled down a 25°, 100-m-long channel into the Morley River. Within the 5- to 7-m-wide channel, debris was deposited with an average thickness of 0.5 m.

Failure mechanism

The occurrence of debris flows along the bank of the Morley River is attributed to stream incision of poorly drained source material. The debris flows are situated along the cut-bank of a meander of the Morley River, where undercutting by the river at this location leads to over-steepening of the glacial valley fill, colluviation, and accumulation of debris at the base of steep scarps. The presence of springs at the base of gully headwalls suggests that groundwater may saturate, increase pore pressure, and then cause failures within the saturated debris. In turn, these failures undermine the headwall and prevent its stabilization. This cyclical behaviour leads to retrogression of the gully headwall and widening of the gully.

Figure XXI. *Oblique aerial photograph of Morley River debris flows. The Alaska Highway crosses at the top of the photograph.*

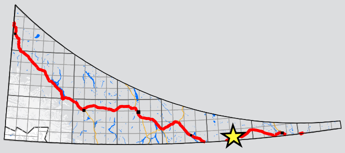
Case study 12: Rancheria Message Post

Location: *60°5'31"N,130°48'4"W*

Elevation: *1225 m*

Age: *July, 1988*

Aspect: *south*



Landslide type: *dormant debris flow*

During July, 1988, prolonged rainstorms affected southern Yukon and triggered debris flows in the Cassiar Mountains 11 km west of the settlement of Rancheria. Three debris flows occurred on the slopes above the Alaska Highway and one impacted the highway directly. The largest slide occurred on a gullied, broadly concave slope above the historic location of Rancheria Message Post.

The failure initiated in a mid-slope position within silt-rich bouldery till near the position of a small spring feeding an ephemeral stream (Fig. XXII). The till varies from compact to loose, and the matrix displayed a vesicular texture, attesting to the susceptibility of the deposit to intense freeze-thaw action. The eastern portion of the headscarp is characterized by minor active slumping. From the initiation zone, the debris travelled down a generally open slope, incising up to 3 m into till. Below the open slope, the flow travelled onto a gentler, gullied slope segment composed of sandy till. Accumulations of large woody debris up to 3 m in height line the lateral margins of the flow channel and may have confined the width of the

continued…

Figure XXII. *Debris flow induced by intense rainstorm in 1988 on south-facing slope near Rancheria Message Post. Alaska Highway in foreground.*

continued… Case study: Rancheria Message Post

failure. Individual trunks are a maximum of 30 cm in diameter. On a gentle apron below the gullied slope section, the debris spread into two arms that cleared two 20-m-wide paths through mature subalpine fir forest. The main arm of the flow extended into a marsh on a terrace adjacent to the Alaska Highway. The debris on the fan attains a maximum observed thickness of 1.5 m. The total length of the slide is 905 m and the width of the scar ranges from 10 m at its headscarp, to 50 m across its fan (Fig. XXIII).

Flow lobes, discontinuous levees and gullies are common features within the deposits on the upper fan. The debris on the upper fan is characterized by gravelly, silty, sand with few boulders up to 30 cm in diameter. The lower fan is characterized by a smooth gravelly sand plane.

Failure mechanism

The Rancheria Message Post debris flow failed on July 12, 1988 after an extended period of heavy rainfall (Public Works Canada, unpublished sources). Although daily rainfall was not exceptional, the cumulative rainfall over the first half of the month was extraordinarily high. From July 1 to 17, Whitehorse and Watson Lake received 99.3 mm and 120.1 mm of rainfall respectively, which accounts for 292% and 206% of their normal rainfall for that period (Public Works Canada, unpublished sources).

The storm events caused rapid infiltration of rainfall, soil saturation and a temporary rise in pore-water pressures. Above the area of the initiation zone, this rise in pore pressure was enhanced by concentration of the groundwater collected in the upper alpine basin due to the amphitheatre-like concave form of the slope. Permafrost was not found on the slope in the area of the failure.

Impacts

The Alaska Highway narrowly escaped impact from the Rancheria Message Post debris flow, with debris having travelled to within tens of metres from the highway alignment. Just 30 km east of this failure, a second smaller debris flow that was triggered by the same rainfall event blocked the road with debris that included tree trunks and boulders up to 1 m in diameter. Repairs to the highway there included clearing, resurfacing and ditch restoration.

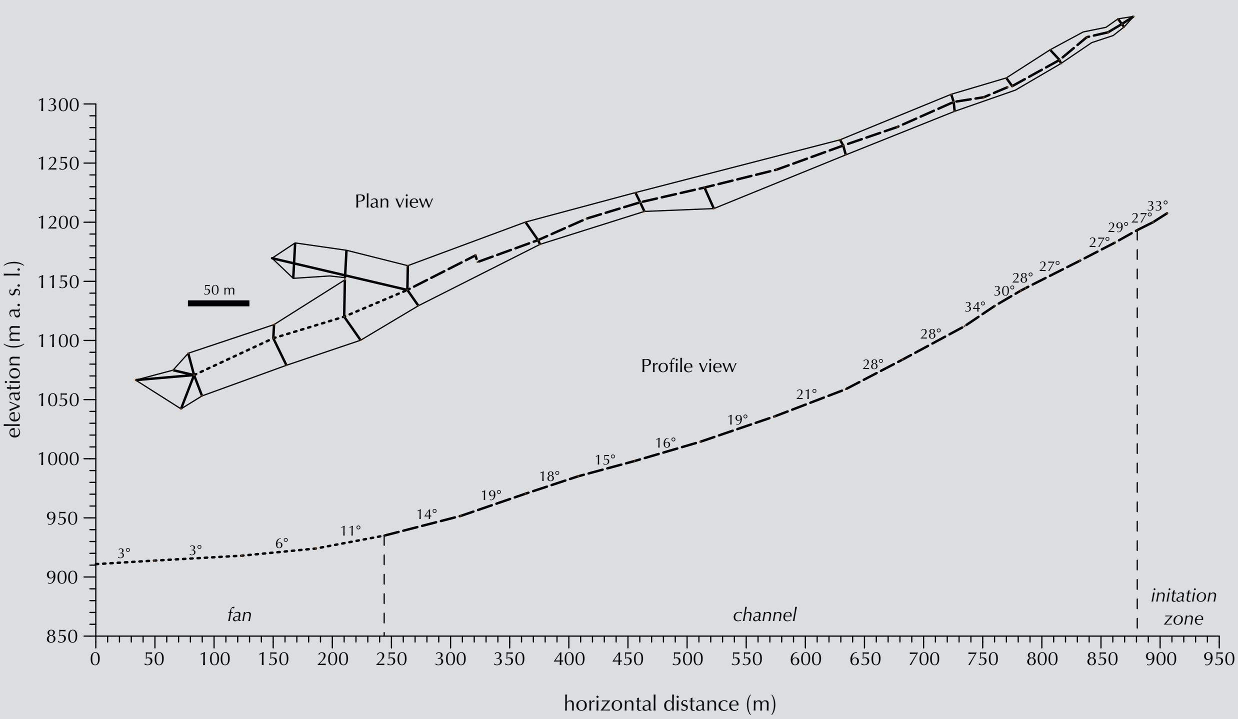


Figure XXIII. *Long profile and plan view of Rancheria Message Post debris-flow track.*

Case study 13: Liard River

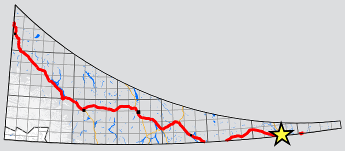
Location: *60°1'40"N,128°39'40"W*

Elevation: *639 m*

Age: *recent*

Aspect: *south*

Landslide type: *complex dormant debris slide*



Along the forested banks of the Liard River, bedded sediments with contrasting permeability have lead to translational sliding (Fig. XXIV). Approximately 10 km southeast of Watson Lake, the Liard River incises a glaciofluvial terrace underlain by stiff laminated lacustrine clay and silt, with common beds of diamicton and gravel approximately 20-35 cm thick. The shallow (1-1.5 m) failure scar extends from the top of the 35-m-high terrace bank to river level (Fig. XXV). The average width of the scar is 23 m. Undisturbed slopes adjacent to the failure are veneered with 50 cm of colluvium and a thick forest mat. Debris, composed of equal amounts of soil and organic debris, slid directly into the Liard River. A spring issuing from the interstratified base of glaciofluvial gravels was noted.

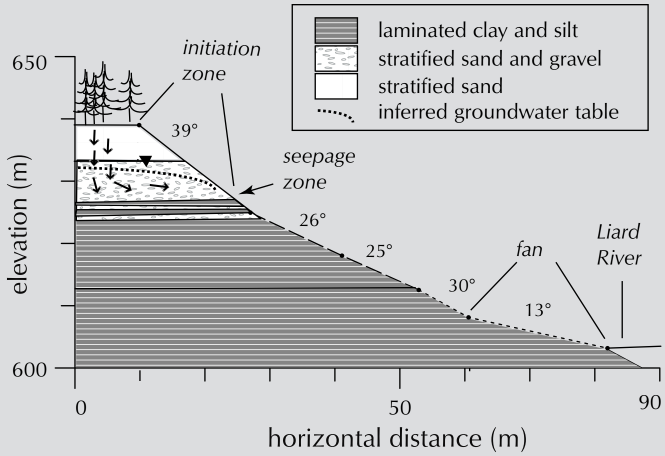


Figure XXV. *Surveyed long profile of Liard River debris slide with inferred sub-surface conditions which contributed to failure.*

Failure mechanism

Creation of the Liard River slide is attributed to high groundwater storage combined with restricted drainage resulting from colluviation of bedded fine sediment. Colluvial processes and vegetation growth disturb the stratification of bedded sediment and result in a less permeable veneer of colluvium capping underlying undisturbed sediment. The impermeable cap restricted drainage at the base of the outwash gravel and increased groundwater storage. The resulting rise in pore pressure during a suspected snow melt or rainstorm event decreased effective stress and initiated translational sliding within the colluvial layer.

Figure XXIV. *Oblique aerial photograph of debris slide along Liard River.*

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