Permafrost and landslide activity: Case studies from southwestern Yukon Territory

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ABSTRACT

Five case studies of recent landslides in southwestern Yukon Territory illustrate the role of permafrost in landslide processes of the region. In the Marshall Creek basin, permafrost degradation after recent forest fires caused numerous debris flows near the valley bottom. Similarly, on Haeckel Hill, fire-related deepening of the active layer has facilitated active layer detachment slides on upper hillside slopes. In the Kluane Range, the interface between frozen and unfrozen ground appears to control the depth of movement for active layer detachment slides and debris flows along Silver Creek. The failure mechanism on Mount Sumanik is controlled by a frozen substrate, which contributes to a reduction in drainage and elevated pore-water pressure. Lastly, thawing of segregated ice has caused a thaw slump of fine-grained sediment in lacustrine terraces along Takhini River.

RÉSUMÉ

Cinq études de glissements de terrain récents illustrent le rôle du pergélisol dans les processus de glissement dans la région. Dans le bassin du ruisseau Marshall, la dégradation du pergélisol après des feux de forêt récents a provoqué de nombreuses coulées de débris dans le fond de la vallée. Dans une situation analogue, sur la colline Haeckel, le creusement du mollisol causé par le feu a fait glisser le mollisol sur le haut des collines. Dans le chaînon Kluane, l'interface entre le sol gelé et le sol non gelé semble régir la profondeur du mouvement des glissements par détachement du mollisol et les coulées de débris le long du ruisseau Silver. Le mécanisme de rupture sur le mont Sumanik est régis par un substrat gelé qui contribue à une réduction du drainage et à une pression interstitielle élevée. Enfin, le dégel de la glace de ségrégation a créé des glissements de sédiments à grain fin dans les terrasses lacustres longeant la rivière Takhini.

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INTRODUCTION

A series of case studies of recent landslides within and adjacent to the Alaska Highway corridor were undertaken during the summer field season of 2003 as part of the Yukon Geological Survey's Alaska Highway corridor landslide hazard study. Within the western portion of the project area, between Whitehorse and the Yukon-Alaska border, many landslides relate to permafrost, either due to the degradation of ground ice or the influence of frozen ground on soil drainage. By describing the geologic and climatic controls of five cases of permafrost-related landslide activity, the aim of this paper is to highlight the role of permafrost in landslide processes in this section of the Alaska Highway corridor and introduce the potential influence that climate change has on these processes.

SETTING

PHYSIOGRAPHY

The Alaska Highway corridor between Whitehorse and the Alaska-Yukon border spans nearly 425 km and is a critical region for transportation, settlement, tourism, and resource development. Geology divides the region into two broad physiographic regions: Yukon Plateau and St. Elias Mountains (Fig. 1). Broad upland areas with rounded summits 1500-2000 m a.s.l. (above sea level) characterize Yukon Plateau. Incised into these upland areas are a number of deep valleys with elevations near 600 m a.s.l. The Alaska Highway corridor between Haines Junction and Whitehorse follows one such valley. Shakwak Trench divides Yukon Plateau from St. Elias Mountains and is the physiographic expression of Denali Fault. It is a broad 8- to 20-km-wide valley with a gently undulating floor underlain by thick deposits of till and outwash from a number of glaciations, as well as Holocene alluvium and aeolian material. The Kluane Range (Fig. 1) rises abruptly to 2000 m above Shakwak Trench as a narrow band of steep glaciated peaks.

CLIMATE AND PERMAFROST

The study area 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 southeast of Kluane Lake has a more moderate continental climate than to the north due to its relative proximity to the Pacific Ocean. Local relief modifies climate throughout the entire region; for example, cold air trapped in the valleys of Yukon Plateau frequently causes temperature inversions (Wahl et al., 1987).

The Alaska Highway corridor is underlain by discontinuous permafrost. For much of its length, it lies within the transition from sporadic discontinuous permafrost to extensive discontinuous permafrost (Fig. 1; Heginbottom et al., 1995). Local climate, vegetation cover, and terrain (aspect, material type, drainage condition) are the primary controls on the distribution of permafrost. 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 found the percentage of ground underlain by permafrost varied considerably, comprising 80% of valleys and lowlands north of Kluane Lake, <50% of the area between Kluane Lake and Takhini River, and <20% of the Takhini River valley. By contrast, the distribution and character of permafrost is less constrained on the hillslopes, plateaus and summits adjacent to the corridor. At these locations, temperature inversions and variations in snow depth 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 drainage conditions exist.

MASS MOVEMENTS

A number of studies of mass movements within the Alaska Highway corridor have been completed. These include investigations of rock glaciers (Blumstengel, 1988),

Table 1. *Environment Canada climate normals 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

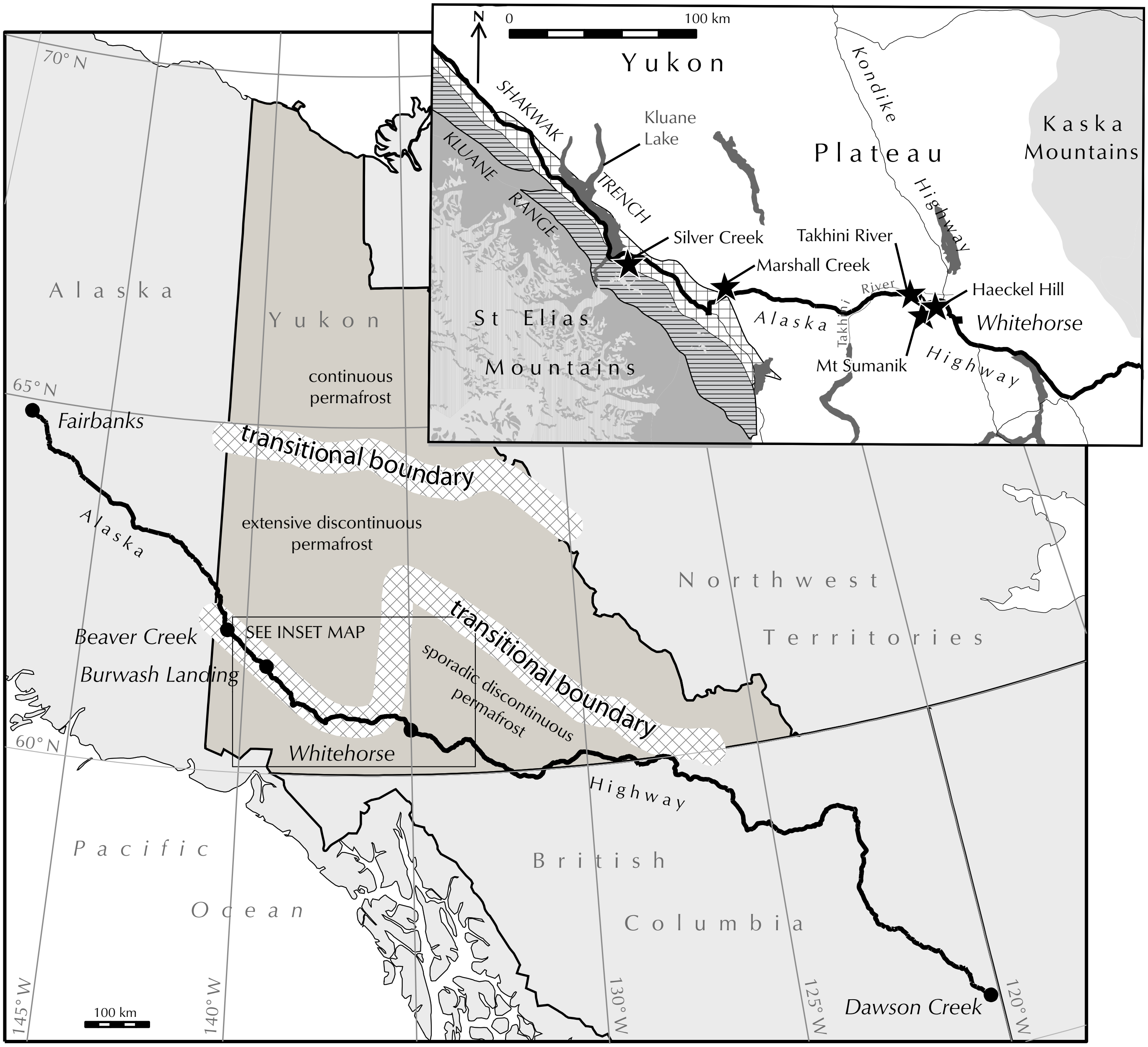

Figure 1. *The Alaska Highway and permafrost distributon of Yukon Territory (after Heginbottom et al., 1995). Inset map displays locations discussed in the text and selected physiographic regions (after Mathews, 1986).*

debris flow fans (Clague, 1981; Harris and McDermid, 1998), large rock slides (Clague, 1981; Everard, 1994), rain-storm-triggered debris flows (Evans and Clague, 1989), and 1:100 000-scale terrain hazard mapping (Gerath and Smith, 1989). These studies focus on activity in the Kluane Range, and do not describe the influence of permafrost on landslide processes in the corridor.

Permafrost-related landslide hazards are explored by three studies. Hugenholtz (2000) describes the morphology of six active-layer detachment slides on an alpine plateau south of Kluane Lake. Based on a ground-heating experiment, he proposed that rapid snowmelt and/or intense pluvial events are required to trigger a detachment. Harris and Gustafson (1993) studied activity on debris flow fans along the Slims River valley, a tributary at the south end of Kluane Lake. They found that debris flows often occur in warm weather, not always as a result of heavy rainfall events, and therefore, speculated that ground ice thaw may contribute water to the failure process. Harris and Gustafson (1988) proposed that retrogressive slumps of icy, unconsolidated sediments produce material for debris flows in the Kluane Range. However, they do not provide a description of the failures or the permafrost conditions that may have contributed to their initiation.

CASE STUDIES

MOUNT SUMANIK

Landslide setting and morphology

A series of ten debris flow channels in a basin draining Mount Sumanik demonstrate how the presence of a shallow frozen substrate may predispose an alpine slope to debris flow activity (Figure 2). 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 moderately steep slopes (24°-29°) and traveled down the more moderate mountain side (15°-25°) scouring gullies up to 47 m wide and 13 m deep, commonly to bedrock (Figure 3). Continued retrogression is evident in the headwalls and on some of the sidewalls. The flows

***Figure 2.** Oblique aerial view of Mount Sumanik debris flow channels. View is to the northeast.*

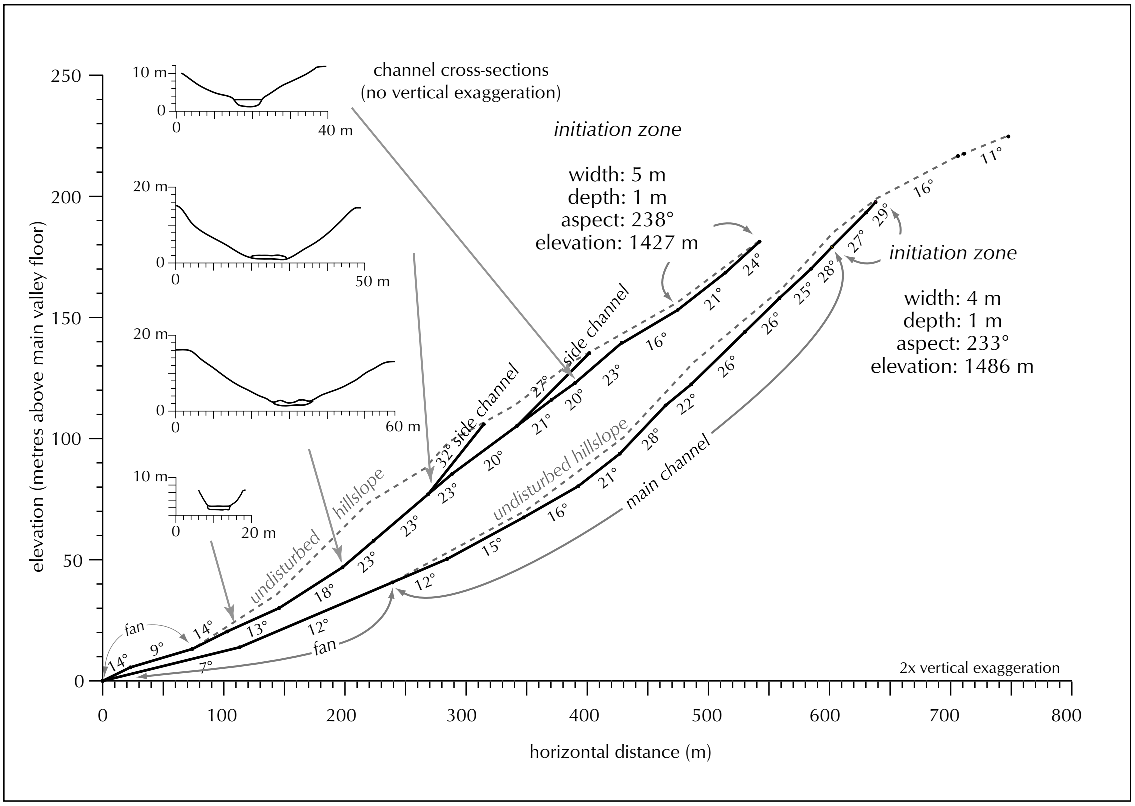

***Figure 3.** Profile and cross-sections of debris flow channels and deposits on Mount Sumanik.*

traveled up to 680 m to valley bottom and produced fans containing boulders up to 2 m in diameter. Individual deposits are less than 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 hill sides had not failed recently. Finally, a lack of vegetation within the landslide debris indicates that failures since 1986 occur with enough frequency to inhibit vegetation growth within the gully systems.

The basin or creek system of the Mount Sumanik debris flow channels do not contain any infrastructure such as roads or buildings. Nevertheless, the impact of the debris flows on the main creek is readily observed. The debris flows and their deposits 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.

Failure mechanism

Shallow slumping and evidence of poor drainage is widespread on the slope above each debris flow headscarp. Soil pits reveal that within this area, frozen ground lies approximately 1.65 m below the surface in late summer. A 60-cm saturated soft plastic layer with low bearing strength was discovered on top of the permafrost table. This stratigraphy suggests that the presence of permafrost promotes poor drainage and may lead to the elevated pore pressures that trigger initial slumping. 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. The structure and ice content of permafrost in the initiation zone could not be ascertained because of pit collapse and inundation at the bottom of the active layer.

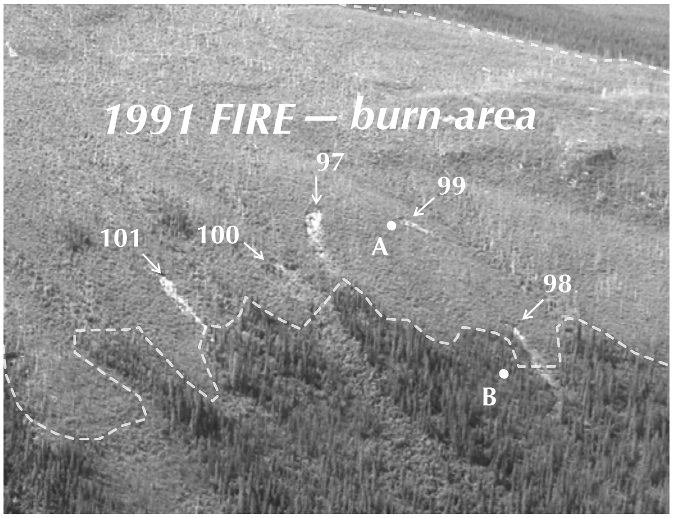

Figure 4. *Oblique aerial view of fire-related active layer detachment slides and secondary debris flow scars on the north-facing slope of Haeckel Hill, stations 97 to 101. Location A and B are hand-dug trenches.*

HAECKEL HILL

Landslide setting and morphology

Five debris slide scars occur in an area burned by a 1991 forest fire on the mid-slopes of Haeckel Hill (Fig. 4). Haeckel Hill is located 7.5 km northwest of Whitehorse and 2 km south of the Alaska Highway. 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 forest canopy. The debris slide scars 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 granules to cobbles with few boulders and a sandy silt matrix. Table 2 describes the morphological characteristics of the landslide scars.

Table 2. *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

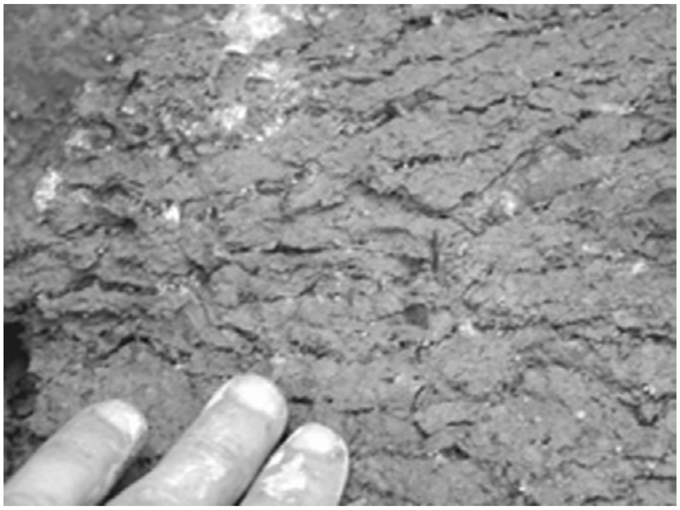

Figure 5. Photograph of frozen soil with stratified ice veins (1-3 mm thick) from Location B, the unburned forest site in Figure 4.

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 track and suggest that the slides translated into debris flows. As well, sloughing beneath intact forest mat and fans of debris overlying compression ridges attest to retrogressive secondary failures. 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 trench adjacent to the headscarp of landslide 99 was excavated in late August (Location A, Fig. 4). However, permafrost was not encountered within the 1.35-m-deep trench. A second pit was dug in the unburned white spruce forest directly below the slide scars (Location B, Fig. 4). Here, permafrost was uncovered at a depth of 70 cm, beneath 25 cm of organic mat and 45 cm of unfrozen mineral soil (Fig. 5). The permafrost contained stratified segregated ice veins, 1-3 mm thick, composing 15% (by volume) of the soil.

Failure mechanism

Comparison of scar depths and the active layer depths in the unburned site suggests that the landslides occurred along a thawing ice-rich zone at 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. Maintenance of high pore pressure was facilitated by poor drainage due to the presence of a frozen substrate. Finally, the presence of a substantial amount of segregated ice suggests that the strata would undergo significant volume and strength reductions as thawing occurred. Three of the five landslide scars appear to have experienced secondary debris flows associated with thaw since the initial failure. These flows travelled much farther than the initial slides. The timing of the failures suggests that the thawing is attributable to the 1991 forest fire.

SILVER CREEK

Landslide setting and morphology

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). Evidence for four recent shallow debris slides was found along the northwest-facing slope of Silver Creek during field surveys in 2003 (Fig. 6). The largest slide (landslide 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 when they were examined during 2003 fieldwork. The source material was a grey colluviated silty till with minor boulders and common cobbles. The scar of

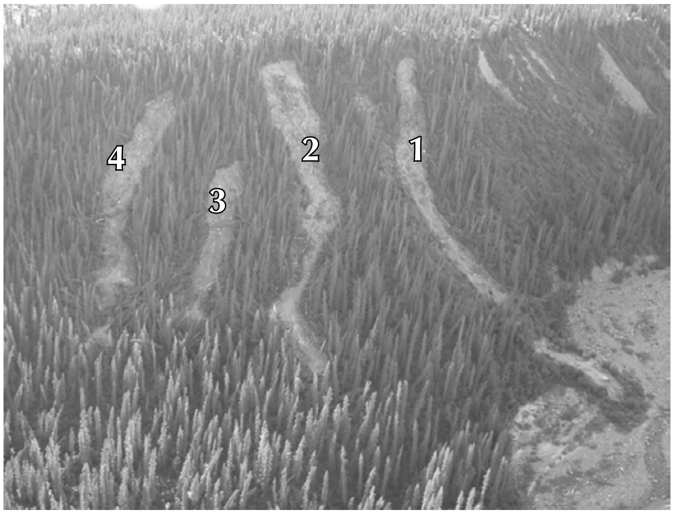

Figure 6. Oblique aerial view of Silver Creek debris slides. Landslide scars are numbered 1 through 4.

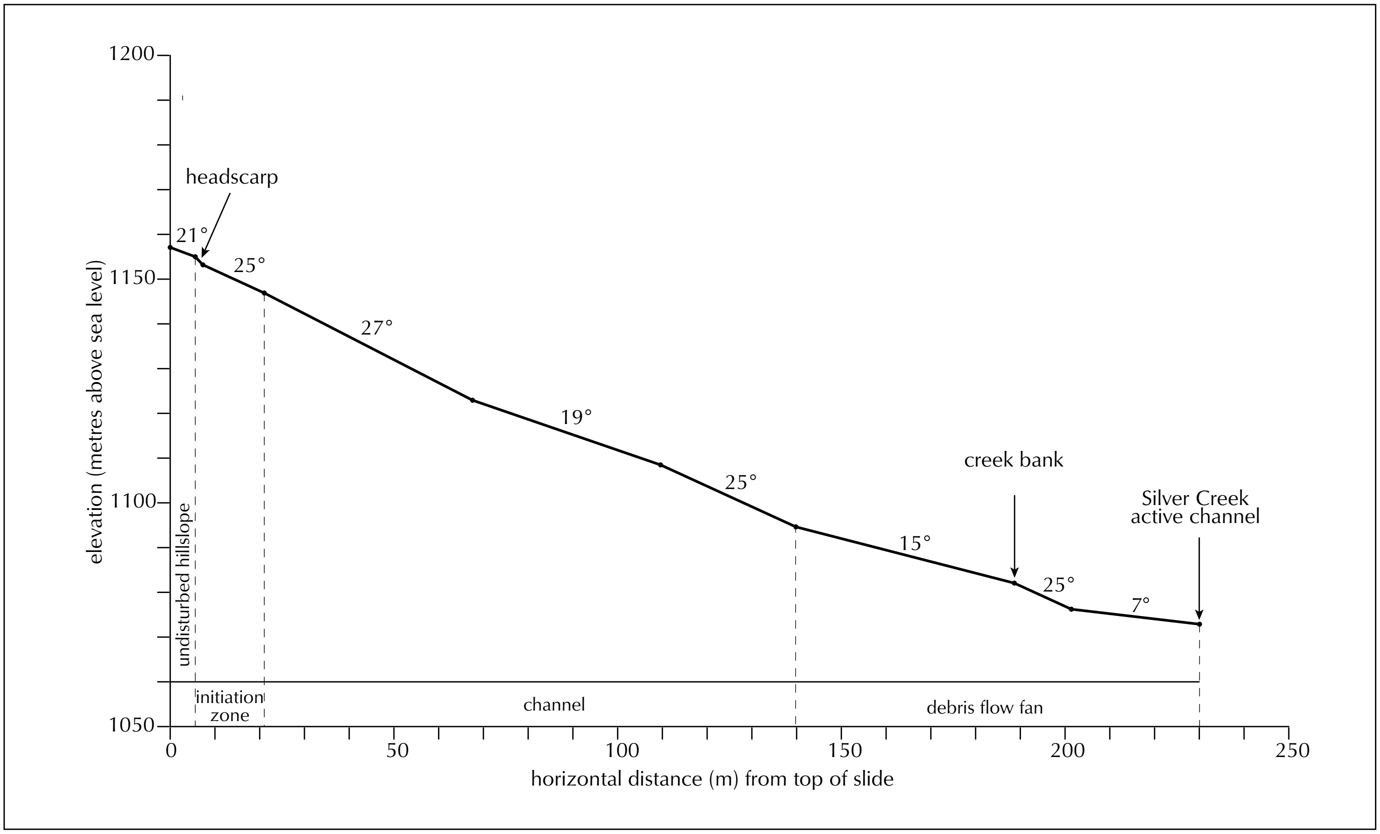

Figure 7. *Longitudinal profile of Silver Creek debris flow (to scale, no vertical exaggeration).*

landslide 1 was surveyed in detail (Fig. 7). The maximum depth of the scar is 1 m. 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. A thick mat of organic material overhangs much of the headwall.

Permafrost conditions

Apart from the areas disturbed by landsliding, 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 encountered 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 clear ice 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 1-17 of that year, Burwash Landing received 209% of its normal rainfall for that period, and 42% of its annual total precipitation (Evans and Clague, 1989). These rainstorms are suspected to have triggered landslide 1 as the 1989 aerial photograph and dendrochronology investigations suggest. Permafrost is very shallow in the undisturbed slope adjacent to the failure. The presence of a shallow frozen substrate likely led to the elevation of 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 suggests 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 has not been established, although a similar mechanism is speculated.

MARSHALL CREEK BASIN

Landslide setting and morphology

Evidence for 41 recent debris flows exists within terraces and valley sides of the Marshall Creek basin, 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. 8). The fires affected an area of approximately 37 km^2 and bordered Marshall Creek for 9 km.

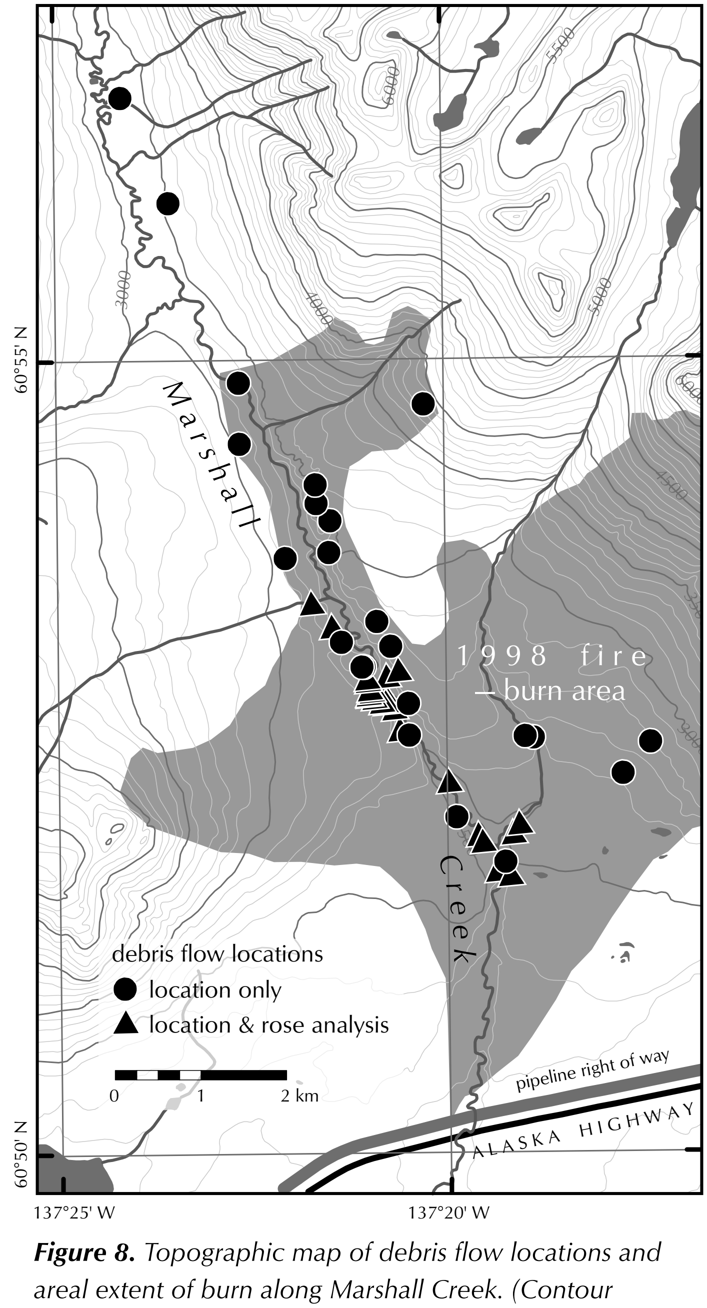

Figure 8. *Topographic map of debris flow locations and areal extent of burn along Marshall Creek. (Contour elevations in feet.)*

The debris flows of the Marshall Creek basin can be divided into two groups based on the landform within which they originated. The majority of the landslides (36) developed on the scarp of high-level terraces composed of glacial and fluvioglacial material (Fig. 9). 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 and glaciolacustrine and glaciofluvial strata was deposited in the valley bottom.

Figure 10 describes the aspect of the debris flow initiation zones that were surveyed by helicopter and on foot. The average aspect of the debris flow headscarps in the high-level terraces was northerly.

The impact of the debris flows includes burial of mining equipment at an unoccupied camp and mining access roads by up to a metre of debris in several locations. Many debris flows traveled directly into Marshall Creek and 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.

Permafrost conditions

In order to compare the depth and character of permafrost within and outside of the burned area, soil pits

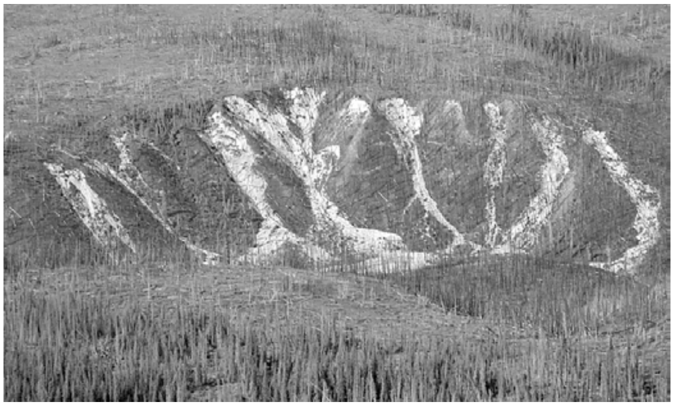

Figure 9. *Oblique photograph of debris flow scars originating from scarp of terraces formed in glacial material along Marshall Creek.*

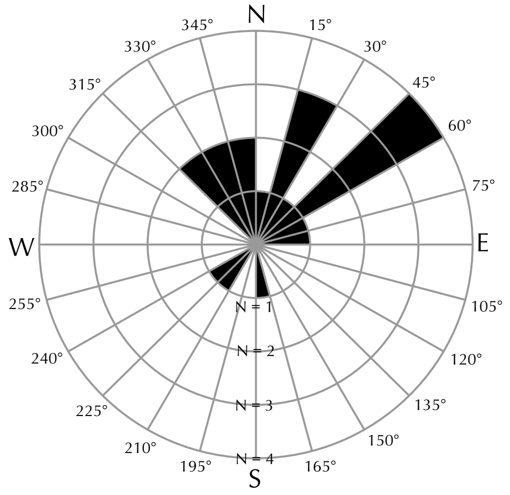

Figure 10. *Rose diagram displaying aspect of visited landslide headscarps in Marshall Creek valley. N is number of samples.*

were dug in burned and unburned terrace gully walls of similar aspect and geometry. At the unburned site, 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 in late summer. Within the frozen soil, ice coatings up to 3 mm thick were observed on granules and pebbles within a silty sand matrix. In total, excess ice is estimated to compose 10% (by volume) of the soil. That is, there may be 10% (by volume) more ice in the sediment than the filling of natural pore space can account for. 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 forest 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, suggests that the landslides occurred along a shallow ice-rich zone at the base of a deepening active layer. Thawing of ice lenses in combination with snow melt and/or rainfall may have contributed water to elevate pore pressure in this zone. High pore pressure was then likely maintained by poor drainage due to the presence of a shallow frozen substrate. Finally, the locally ice-supported structure of permafrost in the Marshall Creek basin suggests that the strata experienced significant strength reduction as thawing occurred.

TAKHINI RIVER

Landslide setting and morphology

A 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 back to the embankment of the Alaska Highway. These features indicate recent retrogressive activity. From the headscarp area, a 132 m, low angle (7°) tongue extends into Takhini River (Fig. 11). 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 on the order of 40 000 m^3.

At the position of the thaw slump, 1971 aerial photographs indicate that stream erosion had removed the vegetative cover on the bank of Takhini River. By 1979,

Figure 11. (a) *Oblique aerial photograph taken in 2003 of Takhini River retrogressive ground ice slump.* ***(b)*** *Inset aerial photograph taken in 1987 of Takhini River retrogressive ground ice slump.*

slumping had caused the terrace scarp to recede approximately 25 m. Between 1979 and 1986, further slumping had caused the headscarp to retreat an additional 112 m to near its present position. Since 1986, the headscarp has retreated several metres and decreased its slope substantially.

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 ranges between 10% and 50%, and averages 24%.

Failure mechanism

River erosion-related thawing of ice-rich sediment caused the failure of fine-grained lacustrine terraces along 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. 11). In general, retrogressive thaw slump development is initiated when the vegetation or active layer materials are removed causing thaw of icy material. The thaw slump under investigation is on the cut bank of a migrating meander of the river; the meander is propagated by a tributary alluvial fan entering Takhini River on the opposite bank.

The Takhini River thaw slump illustrates how thaw-related landsliding can impact infrastructure and streams. In addition, it illustrates the longevity of thaw-related failures. Firstly, 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 and utility cables have been routed above-ground where disrupted by the movement. Finally, the flow of fine-grained material into Takhini River has contributed more fine-grained material to its already high sediment load.

DISCUSSION

IMPLICATIONS OF FUTURE CLIMATE CHANGE

The triggering events in each case study relate to river migration, intense summer rainfall and/or rapid snowmelt, as well as permafrost degradation caused by forest fires. Therefore, any climate change leading to an increase in the frequency and/or magnitude of these events in southwestern Yukon will similarly lead to an increase in the frequency and/or magnitude of periglacial landslides in the region, at least in the short term. Under any change in climate, slopes will be required to re-establish an equilibrium with new conditions.

The range of projections of climate change over the next 50 years for southern Yukon is summarized in Figure 12 and Table 3. Although each scenario projects a slightly different set of future conditions, all projections share several common themes. Firstly, there will be an increase in temperature, more so in the winter than in the summer. There will also be an increase in precipitation. The seasonal timing of this increase is inconsistent between scenarios, but most project that it will occur in winter and

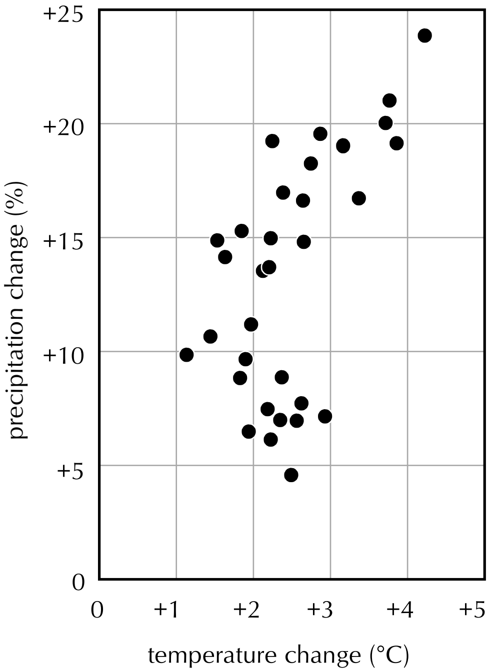

Figure 12. *Projected precipitation and temperature increases (relative to present) for southern Yukon (60.75°N, 135°W) for 2050s. Data provided by the Canadian Institute for Climate Studies, the Canadian Centre for Climate Modelling and Analysis (CCCma) and the IPCC Data Distribution Centre (DDC).*

spring. Although these generalizations may be meaningful at a large regional scale, projections for specific locations are less certain. Many climatic factors important for determining the stability of permafrost or rainfall patterns are dependant on local conditions that are quite complex and poorly modeled. For example, the geometry and orientation of individual valleys influence the local effect of winds on snow depth and the establishment of temperature inversions.

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 over the 21st century. The panel determined that more intense precipitation events

Table 3. *Projected increase (relative to present) in seasonal and annual temperature and precipitation, southern Yukon (60.75°N, 135°W), for the decade 2050. Data for seven general circulation models (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 and the IPCC Data Distribution Centre.*

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

are very likely over many areas around the world. In the study area, this may cause more cyclonic activity in the Gulf of Alaska to penetrate the St. Elias Mountains.

An estimate of how future global atmospheric conditions relate to site-level slope stability requires transcendence of multiple levels of uncertainty and complexity. Therefore, estimates of how landslide processes in the study area will respond to climate change are necessarily qualitative. With this in mind, several suggestions can be made based on the inferred failure mechanisms of the landslides discussed in this paper. Firstly, an increased incidence of forest fire with climate change, and fire-related deepening of the active layer, will certainly lead to more debris flows analogous to those in the Marshall Creek Basin and on Haeckel Hill. Furthermore, the vulnerability of these settings to fire-related ground warming illustrates their susceptibility to thermal disturbance from other causes. Increased annual air temperature or winter snow cover may similarly lead to more widespread deepening of the active layer, and given the local importance of ice near the top of the permafrost zone for soil strength, this ground warming will likewise increase the frequency of debris flows and slides. In addition, an increase in the magnitude or frequency of extreme summer precipitation events will result in an increase in debris flow activity analogous to that near Silver Creek and Mount Sumanik. Finally, increased precipitation may also lead to more runoff, increased river migration and thaw slumps in ice-rich terrain similar to that near the described thaw slump in the Takhini Valley.

SUMMARY

Along the Alaska Highway corridor, various types of landslides relate to the presence and/or degradation of permafrost. The presence of permafrost and its thaw, in various hill slope settings, influences landslide processes via its control on soil drainage and soil strength. The series of debris flow channels on Mount Sumanik demonstrate how poor drainage due to the presence of a shallow frozen substrate may predispose alpine slopes to failure. The recent active layer debris slides and debris flows on Haeckel Hill and in the Marshall Creek basin illustrate the influence of fire-related ground ice thawing on slope stability in valley bottom and mid-slope positions. At these locations, the thaw of soils with moisture contents in excess of saturation caused a reduction of soil strength. Four debris slides along Silver Creek provide examples of permafrost-related failures in an undisturbed, forested setting. At this location, intense rainfall likely induced elevated pore pressures over the permafrost table, thereby reducing the shear strength of the active layer, and triggering at least one of the flows. Finally, a thaw slump within glaciolacustrine silts and clays on the bank of Takhini River initiated when river erosion exposed the icy sediment to thaw, underlining the vulnerability of ice-rich terrain to erosion.

In each case study, failures are induced by thermal disturbance due to river erosion or fire-related removal of vegetation as well as extreme snowmelt and/or precipitation events. If global warming leads to an increased incidence of these events, an increase in landslide frequency and/or magnitude can also be expected within the settings described in this paper.

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