

# Surficial geology investigations in Wellesley basin and Nisling Range, southwest Yukon

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## ABSTRACT

Results of surficial geology investigations in Wellesley basin and the Nisling Range can be summarized into four main highlights, which have implications for exploration, development and infrastructure in the region: 1) in contrast to previous glacial-limit mapping for the St. Elias Mountains lobe, no evidence for the late Pliocene/early Pleistocene pre-Reid glacial limits was found in the study area; 2) placer potential was identified along the Reid glacial limit where a significant drainage diversion occurred for Grayling Creek; 3) widespread permafrost was encountered in the study area including near-continuous veneers of sheet-wash; and 4) a monitoring program was initiated at a recently active landslide which has potential to develop into a catastrophic failure that could damage the White River bridge on the Alaska Highway.

## RÉSUMÉ

Les résultats d'études géologiques des formations superficielles dans le bassin de Wellesley et la chaîne Nisling peuvent être résumés en quatre principaux faits saillants qui ont des répercussions pour l'exploration, la mise en valeur et l'infrastructure de la région. 1) Contrairement à la cartographie antérieure de la limite du lobe des monts St. Elias, aucune indication de limites glaciaires pré-Reid du Pliocène tardif/Pléistocène précoce n'a été trouvée dans la région d'étude. 2) Un potentiel pour les gîtes placériens a été identifié le long de la limite glaciaire de Reid où il y a eu une importante dérivation du drainage pour le ruisseau Grayling. 3) Du pergélisol répandu a été constaté dans la région d'étude, notamment dans les placages quasi continus de ruissellement diffus. 4) Un programme de surveillance a été lancé à l'emplacement d'un glissement de terrain récemment actif qui pourrait évoluer en un effondrement catastrophique risquant d'endommager le pont de la rivière White le long de la route de l'Alaska.

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## INTRODUCTION

Surficial geology mapping provides a foundation for many topical studies into Quaternary history, placer geology, permafrost characteristics and terrain hazards. The aim of this paper is to provide highlights from current research that is being conducted in the Wellesley Basin and Nisling Range of southwest Yukon. These results are part of a multi-year mapping project in the Stevenson Ridge (115J) and northern Kluane Lake map area (115G; Fig. 1). The goal of the project is to provide 1:100 000-scale surficial geology maps, detailed descriptions of the surficial materials, permafrost characteristics and terrain hazards, interpretations on the Quaternary history, and insights into the region's placer potential. Highlights from the 2007 field season are summarized in four sections below that outline the glacial limits, placer potential, permafrost distribution, as well as a landslide case-study.

## GLACIAL LIMITS

### INTRODUCTION

Previous glacial-limit mapping in the southwest Yukon has been undertaken by Rampton (1978a,b,c,d,e), Hughes (1989a, b), Huscroft (2002a,b c) and Jackson (2005) in the areas surrounding Stevenson Ridge and northern Kluane Lake map areas. Duk-Rodkin (1999) produced a glacial-limits map of the entire Yukon Territory based on a compilation of previous work and aerial-photo mapping. The Stevenson Ridge map area straddles the limits of multiple Pleistocene glaciations that advanced northward out of the St. Elias Mountains (Fig. 1). The St. Elias lobe comprised the northwestern portion of the Cordilleran Ice Sheet. Field investigations were conducted in 2007 to confirm and describe the maximum limit of glaciation in this region. Field confirmation of the glacial limits had not been previously completed for this map area. The closest related field-based studies were undertaken by Rampton (1978a, b) and Hughes (1989a, b) in the adjoining Snag (115K) and Aishihik (115H) map areas respectively.

### MAPPING GLACIAL LIMITS

Glacial limits are mapped through a combination of landform identification (moraines and meltwater channels) from aerial photography, and field-based analyses such as the identification of erratics and glacial sediments. Glacial limits have been mapped for three glacial periods in this region: the earliest 'pre-Reid' group of glaciations began in the early Pleistocene, ca. 3 Ma BP;

the penultimate Reid (Illinoian) and Gladstone (early Wisconsinan) glaciations occurred during marine isotope stages 6 (140-190 ka BP) and 4 (55-75 ka BP) respectively; and the most recent McConnell glaciation occurred in the late Wisconsinan during marine isotope stage 2 (ca. 22-10 ka BP) (Fig. 1; Ward *et al.*, 2007b).

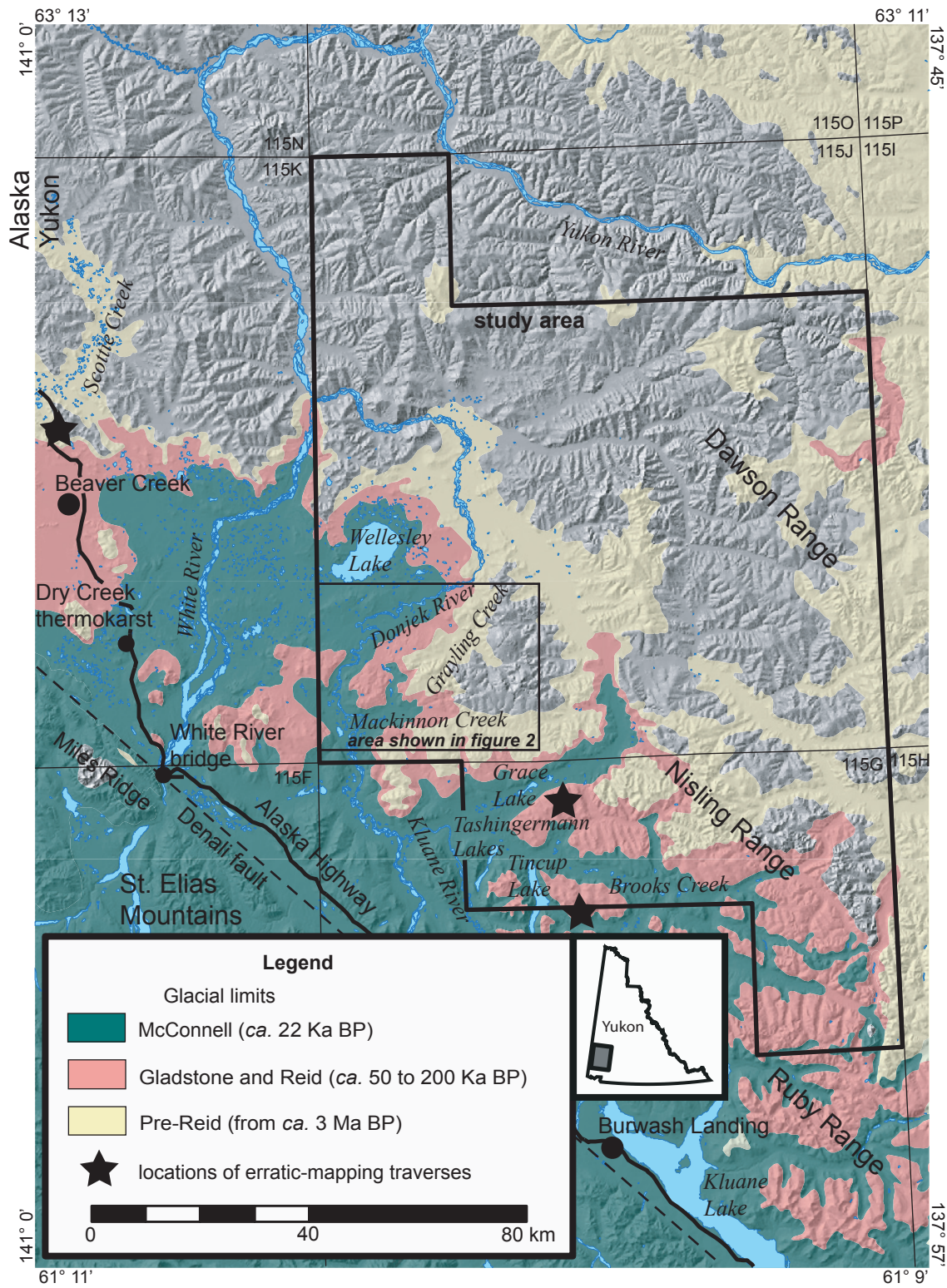
Mapping the limits of glaciations older than the McConnell glaciation can be challenging. Widespread permafrost and colluvial processes are highly effective at eroding glacial depositional landforms, especially in mountainous terrain. Identifiable landforms related to pre-Reid glaciations are almost entirely limited to meltwater channels cut into bedrock, as well as glacial erratics. Depositional landforms such as moraines, kames, or eskers from these earlier glaciations are less likely to be preserved. Moraines from the Gladstone or Reid glaciations are sometimes mappable, but they tend to be discontinuous and preserved only where moraine accumulations were thick and the topography is moderate enough that surface expressions are preserved.

Previous glacial-limit mapping based on aerial photo interpretation in Stevenson Ridge map area (Duk-Rodkin, 1999) shows that the pre-Reid glacial limit extends north of Wellesley Lake to the confluence of the White and Donjek rivers (Fig. 1). In the adjoining Snag map area to the west (115K), Duk-Rodkin (1999) mapped the pre-Reid glacial limit extending north up Scottie Creek (Fig. 1). This contrasts with Rampton (1978a), who previously mapped Scottie Creek as unglaciated.

### METHODS AND RESULTS

In order to better constrain pre-Reid glacial limits in the study area, two foot traverses were completed near Grace Lake and Tincup Lake (Fig. 1) to investigate the distribution of erratics. The traverses were conducted on flat plateau summits that were mapped by Duk-Rodkin (1999) as glaciated during the pre-Reid glaciations and unglaciated during subsequent glaciations. Alpine environments are ideal for mapping the distribution of erratics because organic cover is thin and frost boils are present, resulting in a veneer of exposed pebbles at the surface. Lithologies can be easily identified and distinguished from surrounding local bedrock lithologies. Flat plateau surfaces were targeted for erratic mapping to minimize the potential for downslope remobilization of the pebbles.

Results from both traverses revealed no erratics within the pre-Reid glacial limit, whereas at lower elevations the



**Figure 1.** Location of the Stevenson Ridge and northern Klauene map study area (115J and G) is outlined in black; location of Figure 2 is also displayed. Glacial limits depicted here are after Duk-Rodkin, 1999.

penultimate Reid or Gladstone glacial limit was marked sharply by erratics and meltwater channels. To further investigate the presence of pre-Reid glaciations in this region, a road traverse was completed along the Alaska Highway in the Snag map area (115K) near the border with Alaska (Fig. 1). This traverse also revealed no erratics beyond the limit of the penultimate glaciation.

These initial results suggest that the penultimate glaciation (either Reid or Gladstone) was the most extensive glaciation that originated from the St. Elias Mountains during the Pleistocene. Additional field-based glacial-limit mapping is required near the outer margin of the currently mapped pre-Reid limit (near the Donjek River, for example) to further clarify this potential revision to Yukon's glacial-limit map.

## IMPLICATIONS

The potential absence of relatively extensive pre-Reid glaciations in southwest Yukon is significant for both mineral exploration and our understanding of Cordilleran Ice Sheet history in this region. Mineral exploration relies heavily on soil and stream-sediment geochemistry for locating potential prospects. Different approaches are required to determine the potential source of geochemical anomalies when they are located in glaciated or unglaciated terrain. The maximum Pleistocene glacial limit is therefore critical for determining whether bedrock geochemical anomalies have experienced glacial erosion and subsequent transport.

Recent investigations into the history of the northern Cordilleran Ice Sheet by Ward *et al.* (2007a) have shown that ice extents in areas of limited annual precipitation may not correspond with global glacier extent patterns, both temporally and volumetrically. In addition, the maximum ice extent of different lobes that comprised the northern Cordilleran Ice Sheet may not be synchronous during a single phase of glaciation. In the case of this study, the absence of relatively extensive pre-Reid ice in southwest Yukon contrasts greatly with pre-Reid ice extents in central Yukon. This example raises important and unresolved questions regarding precipitation controls in northwestern North America during the Pleistocene.

## CONCLUSIONS

Previous glacial limit mapping in the Stevenson Ridge and northern Kluane map areas had not been field checked. Two foot traverses on alpine plateaus and a road traverse in the adjoining Snag map area revealed an absence of

pre-Reid glacial indicators beyond the penultimate Reid or Gladstone glacial limit. These results indicate possible revisions to the glacial limits map of Yukon which will have implications for mineral exploration in the area. In addition, refined ice limits provide important information regarding Cordilleran Ice Sheet history and paleo-climatic controls.

## GRAYLING CREEK PLACER POTENTIAL

### GLACIAL DIVERSION OF GRAYLING CREEK

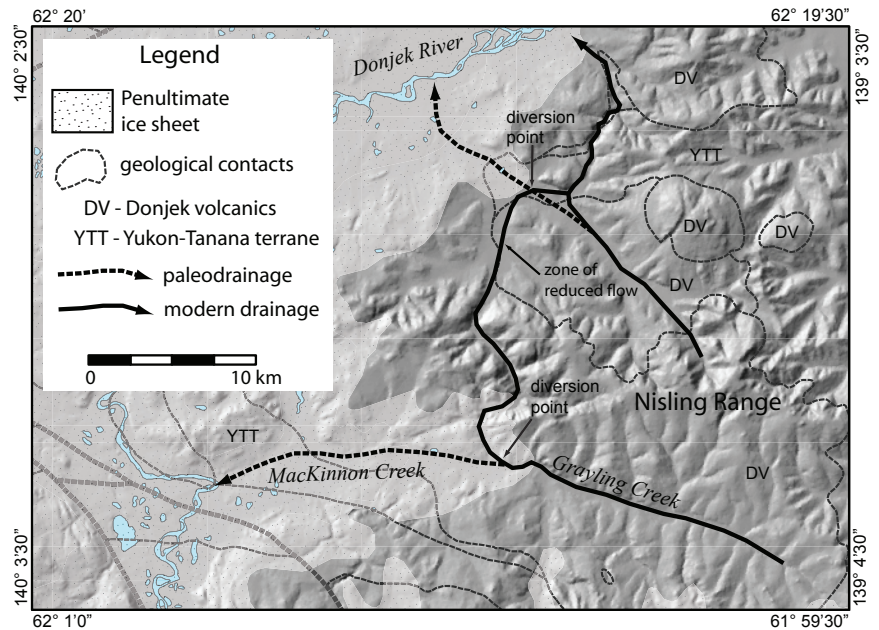
Grayling Creek is located at the northwestern end of the Nisling Range and flows into the Donjek River southeast of Wellesley Lake (Figs. 1 and 2). The indirect modern trajectory of Grayling Creek toward the Donjek River is the result of a glacial diversion that occurred during the penultimate Reid or Gladstone glaciation (Duk-Rodkin, 2001; Fig. 2). Prior to this glaciation, the paleo-drainage of Grayling Creek was westward into the Donjek River via Mackinnon Creek (Fig. 2). Near the height of the penultimate glaciation, ice advancing northward down the Donjek River valley spilled into, and advanced eastward up, the paleo-Grayling Creek valley (Fig. 2). The ice flowing up-valley likely dammed the paleo-drainage and caused a glacial lake to form in upper Grayling Creek. Once the lake reached sufficient depth, it established an outlet to the north, across an unnamed upland of the Nisling Range (Fig. 2). The ice dam held long enough for the diversion channel to downcut and permanently capture Grayling Creek. A second similar diversion occurred further north and extended Grayling Creek's route to the Donjek River, and in doing so, captured additional drainages in the diversion channel (Fig. 2).

### THE LANDSCAPE CHANGE AND PLACER POTENTIAL

The landscape change resulting from the diversion of Grayling Creek enhanced the placer potential for many streams captured by the diversion channel. The diversion channel cut through the northern flank of the Nisling Range, lowering the base level for local streams that it captured. These streams incised their floodplains in order to reach equilibrium with the diversion channel (Fig. 3). The incision process created a narrow, v-shaped valley morphology which is highly conducive for concentrating heavy minerals in fluvial sediment.

The main diversion channel containing Grayling Creek may also be prospective for placer development. The

**Figure 2.** Grayling Creek was diverted northward when the penultimate ice sheet blocked the westward drainage of paleo-Grayling Creek (presently named MacKinnon Creek). Two diversion points indicate the location of ice dams responsible for the deflection of Grayling Creek. A zone of reduced paleo-flow, which may have placer potential, is identified between the diversion points. General bedrock geology for the surrounding area is after Murphy et al., 2007.



high-energy stream responsible for cutting the diversion channel possibly reworked any pre-existing placers and either concentrated them within the drainage, or redistributed them into the Donjek River. Zones of reduced paleo-flow within the diversion channel should therefore be targeted for placer exploration (Fig. 2).

Grayling Creek's paleo-valley, which is now the right-fork tributary of MacKinnon Creek, is less prospective for placer development, compared to the tributaries captured by the diversion channel. During ice recession from the lower part of paleo-Grayling Creek, thick blankets of glacial moraine and lake sediment were deposited over the paleo-valley and would likely reduce the economic viability of any future placer development in the area.

## GEOLOGY

The potential for finding gold-bearing rocks within drainages affected by the diversion channel is favourable. Most of the upland eroded by the diversion channel consists of Cretaceous to Tertiary Donjek volcanics (Murphy et al., 2007). These consist of resistant dacite with massive tuff breccia, olivine basalt and recessive-weathering rhyolite (Murphy et al., 2007). The Donjek volcanics erupted through dark grey carbonaceous phyllite or schist and quartzite belonging to Yukon-Tanana terrane (YTT). These also locally contain felsic metavolcanic rocks (Murphy et al., 2007).

The stream sediment geochemistry for gold in the local area is generally low (8-11 ppb) with the highest values (up to 60 ppb) occurring in YTT rocks. However, caution

should be used when interpreting the gold concentrations from the regional stream sediment geochemistry (RGS) database. It is generally recognized that RGS samples are particularly effective for locating fine-grained gold in bedrock, but they are less consistent in detecting coarse-grained gold sources. The volcanic rocks underlying Grayling Creek would likely produce coarser grained gold



**Figure 3.** A view to the southwest over the Nisling Range and the Grayling Creek diversion channel. The local drop in base level triggered by the diversion is noticeable in the tributary valley located in the bottom left-hand corner of the photograph. The v-shaped morphology of the tributary valley provides an ideal setting for concentrating fluvial deposits.

sources, such as those found in stockwork, lode and brecciated zones.

## RECOMMENDATIONS FOR EXPLORATION

Placer exploration should focus within diversion channel tributaries that have a well defined v-shaped morphology. These drainages should have relatively thin fluvial deposits and therefore an accessible bedrock surface for testing. Geochemical analyses of the local rock units should be completed to further investigate the mineral potential of the volcanic rocks compared to the YTT lithologies. This provides the best guide for locating potentially economic placers in tributaries entering the Grayling Creek diversion channel.

## CONCLUSIONS

The landscape changes resulting from the glacial diversion of Grayling Creek are conducive for enhancing the placer gold potential of the area. The diversion channel established a new base level causing local streams to downcut. This erosion process potentially concentrated heavy minerals in the pre-existing fluvial sediments. The gold potential in the surrounding rocks is relatively unknown and would likely be associated with a volcanic-hosted deposit model. Future placer exploration in this area will benefit from systematic geochemical analyses of the local bedrock to further isolate prospective drainages.

## PERMAFROST DISTRIBUTION AND ICE-CONTENT

### PERMAFROST CONDITIONS IN ADJACENT AREAS

While no regional permafrost mapping or detailed permafrost studies have been carried out within the study area, a variety of localized work has been conducted in surrounding areas. Collectively, this work provides a comprehensive characterization of permafrost in the region, exemplifying the permafrost conditions that would most likely be encountered within the study area itself.

On a national scale, the entire study area has been classified within the extensive discontinuous permafrost zone, in which 50-90% of the land surface is underlain by permafrost with low to medium ground ice content (up to 20% visible ice) in the top 10-20 m (Heginbottom, 1995).

More detailed regional-scale mapping south and west of the study area indicates that continuous permafrost

underlies most of the nearby landscape, particularly within alluvial fans, plains and terraces, and till and colluvial blankets (Heginbottom and Radburn, 1992). These landforms have low to moderate ice contents with ground ice in the form of lenses and reticulate veins. Permafrost is also considered continuous in glaciolacustrine plains, but higher ice contents can be found within these materials (Heginbottom and Radburn, 1992). In contrast, active floodplains of the Donjek and White rivers and glaciofluvial sediments south and west of the study area are shown to support only discontinuous or isolated patches of permafrost with low ice content (Heginbottom and Radburn, 1992).

Rampton *et al.* (1983) used geotechnical drillhole data to characterize the distribution and ice content of permafrost along the proposed Alaska Highway gas pipeline route. Results from this study found that more than 80% of the terrain traversed by the right-of-way north of Kluane Lake (roughly paralleling the Alaska Highway) was underlain by permafrost (Rampton *et al.*, 1983). Permafrost thickness in southwestern Yukon is reported to be up to 15 m near Beaver Creek, 18 m at Burwash Landing, and up to 27 m near Aishihik Lake (115H; Smith *et al.*, 2004). The thickness of the active layer, or the surface layer that seasonally thaws and refreezes, is generally between 0.3 and 2.2 m in the same region (Smith *et al.*, 2004).

Geotechnical work conducted by the Yukon Department of Highways and Public Works (YHPW) along the Alaska Highway south and west of the study area has also been useful for characterizing local permafrost conditions. Since 1997, YHPW has monitored permafrost temperatures in ice-rich silt located beneath and adjacent to the Alaska Highway, 5 km south of Beaver Creek. At this location, borehole data indicate up to 6 m of massive ice (with less than 5% soil inclusions) between 1.8 and 7.9 m below the ground surface (Paine and Associates, 1997a). The active layer at the site varies between 30 and 80 cm and generally corresponds to the thickness of the surface organic horizon. The mean annual temperature of the undisturbed permafrost is -2.4°C at 8 m depth, with ±0.5°C annual variation (YHPW, unpublished data).

YHPW also drilled several shallow boreholes near Dry Creek (approximately 40 km southwest of Wellesley Lake) between 1992 and 1994, prior to the realignment of the Alaska Highway in the area. The borehole data (currently being compiled by YGS) indicate up to 4 m of massive ice between 8 to 12 m below the ground surface within glaciofluvial outwash gravel (YHPW, unpublished data).

Subsequent removal of surface gravel for aggregate use has since caused major thermokarst subsidence adjacent to both sides of the highway. While coarse-textured glaciofluvial materials are commonly assumed to have little or no ice content, this area demonstrates that this is not always the case, and highlights the importance of detailed subsurface investigations prior to development. It also illustrates the potential consequences of ground surface disturbance in permafrost terrain.

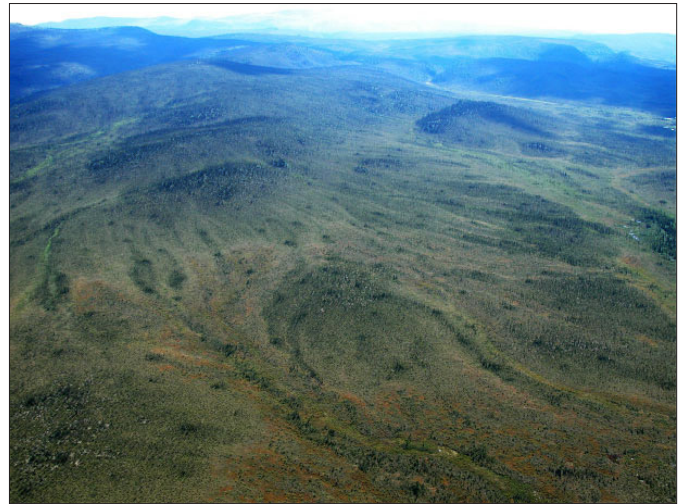
Rampton *et al.* (1983) also highlighted specific sedimentary conditions that are commonly associated with shallow ground ice in the Alaska Highway corridor, all of which relate to the presence of fine-grained sediments and ample groundwater supply. These areas include locations where fine-grained material 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 (Rampton *et al.*, 1983).

## FIELD OBSERVATIONS

Ground and aerial observations from the 2007 field season confirm that permafrost is nearly continuous throughout the study area. In some cases, permafrost was not directly observed in soil pits or cutbanks, but it was generally assumed to be present at greater depth or further back from exposure scarps, based on the morphology of local landforms, or evidence of periglacial processes in the vicinity.

In alpine areas, various periglacial landforms suggest the presence of permafrost. Evidence of frost action, cryoturbation and gelifluction is widespread at high elevations. Stone polygons, stone stripes and frost boils are common along exposed ridge crests and plateaus above approximately 1500 m. Solifluction lobes and nivation terraces were occasionally noted in the Nisling Range, particularly on west-facing slopes. Rock glaciers are also common at the base of steep talus slopes in the eastern Nisling Range.

One of the most notable indicators of permafrost in the study area is the widespread evidence of sheetwash (or slopewash) on gentle to moderately sloped valley sides that are blanketed by till or colluvium. Sheetwash occurs when surface water flows in sheets, rather than in channels, along a shallow impermeable permafrost table. The process gradually transports fine sediment (sand, silt and clay) down to valley bottoms. Evidence of sheetwash is reflected by a diagnostic surface expression in which



**Figure 4.** The flowing surface appearance on many slopes throughout the study area is inferred to be a result of a shallow permafrost table and extensive sheetwash and soil-creep processes. Also note the highly regular pattern of clustered black spruce trees that creates the polka-dot pattern on the landscape; this could be related to the underlying permafrost structure.

the land surface appears to be flowing; this feature is visible from the air on saturated slopes (Fig. 4).

Because the active layer is typically thin and the permafrost table is impermeable, surface soils are commonly saturated and subject to downslope creep through the processes of gelifluction and frost creep. The combined effects of sheetwash and enhanced soil creep may explain why pre-McConnell valley-side glacial features are either highly subdued or absent in the region.

In valley bottoms, permafrost was commonly observed in alluvial terraces, organic plains and glaciolacustrine plains. Frost tables were encountered between 22 and 110 cm below the surface in low, forested alluvial terraces adjacent to the Donjek River. Where peat or thick moss cover existed, frost tables were generally encountered 20 to 40 cm below the surface, commonly beneath highly saturated soils or standing water. In Brooks Creek and Mackinnon Creek valleys, thick, frozen glaciolacustrine sand, silt and clay was exposed along stream cuts (Fig. 1). At one location along Mackinnon Creek, permafrost was at least 11 m thick and contained approximately 40%



**Figure 5.** Jeff Bond with a large piece of clear ice removed from a 50-cm-thick vein within glaciolacustrine silty clay in a cutbank beside Mackinnon Creek. The ice content within the exposure indicates that permafrost is at least 11 m thick in this valley.

visible ice with massive ice lenses up to 50 cm thick (Fig. 5).

Extensive thermokarst terrain was also observed within glaciolacustrine sediments along portions of the Grace Lake and Kluane River valley bottoms. Permafrost is at least 6.5 m thick within clayey silt exposed in Kluane River cutbanks, south of Tashingermann Lakes. At this location, ice content varied between 30-80% by volume (visually estimated) and consisted of small crystals (<2 mm in diameter) and stratified veins up to 10 cm thick. At a thermokarst pond exposure in the Grace Lake valley, ice content within glaciolacustrine sediment was lower (15% by volume) and consisted of thin, stratified and randomly oriented veins with an average thickness of 2 mm.

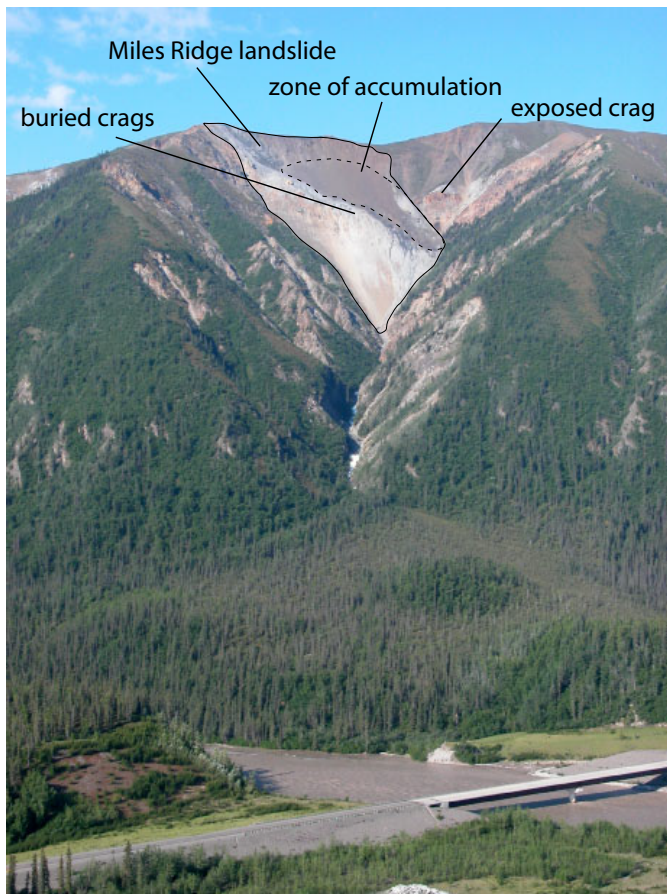
Permafrost-related landslides observed in the area were limited to small retrogressive thaw-flow slides along actively eroding river banks, and small active layer detachments on valley sides. One active layer detachment was documented during the 2007 field season on an 18° west-facing slope in the Grace Lake valley; the landslide

occurred following a large forest fire that burned the area in 2004. This failure was 80 m long, 14 m wide and had a failure plane depth of 70 cm, corresponding to the depth of the local active layer. This morphology is typical of active layer detachments documented in other parts of the Yukon Territory (Lipovsky *et al.*, 2007). Forest fires, river erosion and anthropogenic surface disturbance have been attributed as common triggers for permafrost-related landslides in nearby areas and other parts of southern and central Yukon (Huscroft *et al.*, 2004; Lipovsky *et al.*, 2006; Lipovsky and Huscroft, 2007).

In many locations within the study area, the permafrost table was located near the base of the thick (10-40 cm) layer of coarse-textured White River tephra. This interface has been documented as a failure plane for at least one active layer detachment located just outside the study area (Huscroft *et al.*, 2004). It also forms the failure plane for several other small active layer detachments observed during aerial surveys in the region.

## CONCLUSIONS

Based on ground observations and interpretation of surface landforms, the study area is underlain by nearly continuous permafrost. Ice-rich permafrost in the area is generally associated with fine-grained alluvial and glaciolacustrine sediments in valley bottoms, although massive ice was found in coarse-grained glaciofluvial materials in the region. The frost table is commonly very shallow (<50 cm), resulting in poor drainage and saturated surface soils. Permafrost thicknesses up to at least 11 m were observed. A variety of geomorphological processes related to the presence of permafrost are active at all slope positions throughout the study area, including periglacial processes in high-elevation alpine areas, and sheetwash, soil creep and active layer detachment landslides on valley sides. Retrogressive thaw-flow slides were observed where river erosion has exposed ice-rich glaciolacustrine sediments, and thermokarst subsidence occurs in valley-bottom sediments, usually within glaciolacustrine materials. Forest fires, river erosion and anthropogenic surface disturbance have been attributed as common triggers for thermokarst subsidence and permafrost-related landslides in south and central Yukon (Huscroft *et al.*, 2004).



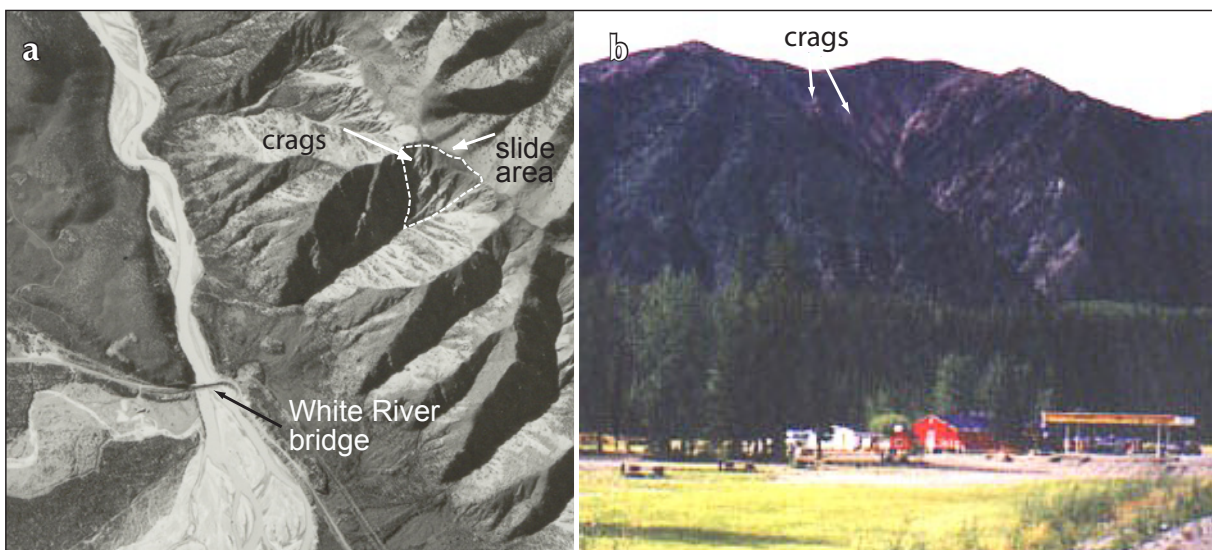
**Figure 6.** The Miles Ridge landslide in relation to the Alaska Highway and White River bridge. View is to the southwest.

## MILES RIDGE LANDSLIDE

A landslide on Miles Ridge has recently developed at the head of an unnamed drainage that flows into the White River, immediately upstream of the Alaska Highway crossing (Fig. 1). The landslide debris has accumulated in the upper reaches of the drainage and is perched over 500 vertical metres above the river (Fig. 6). Catastrophic release of the debris could potentially impact the White River bridge and disrupt transportation in the Alaska Highway corridor.

## HISTORY

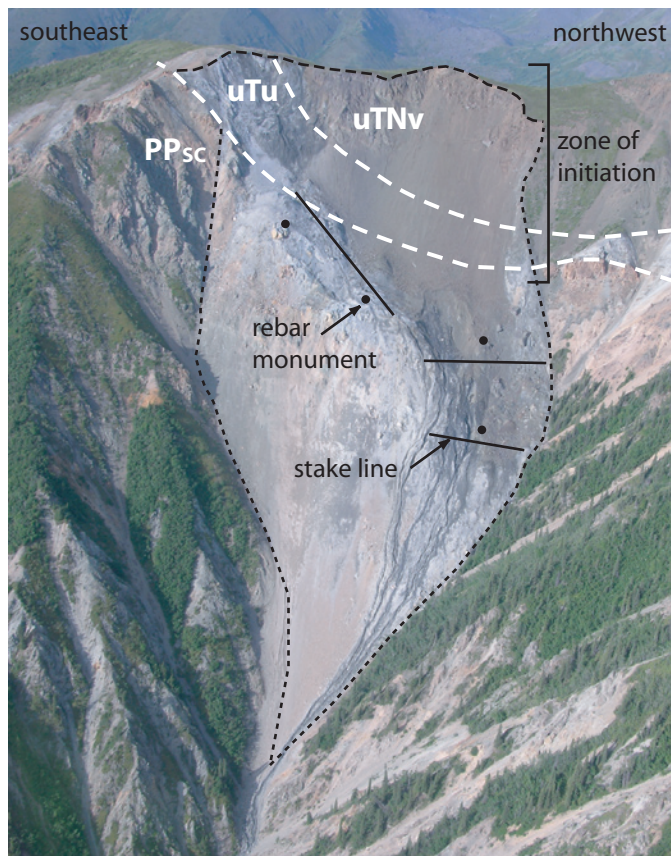
The history of landslide activity at this site has been established using both aerial and historical photographs and reports from local highway maintenance personnel. A 1988 aerial photograph (NAPL A27370-79) displays no evidence of landslide activity in the drainage (Fig. 7a). Likewise, a local pamphlet advertising the White River RV Park in the 1980s contains a photograph of Miles Ridge with no evidence of landslide activity (Fig. 7b). According to Chief David Johnny of the White River First Nation, landslide activity at the head of the drainage was first noticed in the early 1990s. The landslide has continued to expand since then, including distinct changes following the 2002 earthquake on the Denali fault (David Johnny, pers. comm., 2007).



**Figure 7.** Photos illustrating the absence of landslide activity in the drainage in the late 1980s. **(a)** Photo is cropped from an aerial photograph taken in 1988 (NAPL A27370-79). Crag of bedrock line the upper reaches of the drainage and no evidence of slide activity is present. **(b)** Photo is from a pamphlet advertising the White River RV Park in the 1980s. The drainage containing the slide is visible in the background and no landslide scar is present.

## GEOLOGICAL SETTING

Miles Ridge is bound by the Denali fault to the north (Fig. 1) and splays off the main Denali fault system in the south. Several of these secondary splays extend through the source zone of the landslide. Rocks in this zone consist of strike-slip fault-bounded volcanic and altered intrusive rocks. The lowermost rocks within the initiation zone of the landslide consist of interbedded volcanic breccia and volcanoclastic rocks of the Station Creek Formation (Fig. 8; Israel *et al.*, 2007). These rocks are relatively resistant and form erosional remnants (crag) that are visible in 1988 aerial photographs (Fig. 7a). A thin zone of highly altered Late Triassic ultramafic rock lies in fault contact above the Station Creek formation (Fig. 8; Israel *et al.*, 2007). Alteration is significant within the ultramafic unit, and much of the rock has altered to clay.



**Figure 8.** An oblique aerial photograph view looking southwest at the Miles Ridge landslide. The locations of stake lines and monuments for deformation monitoring, as well as geological contacts are shown schematically (after Israel *et al.*, 2007). Bedrock unit labels are defined as follows: PPsc = Pennsylvanian-Permian Station Creek Formation; uTu = Late Triassic Kluane mafic-ultramafic complex; uTNv = Late Triassic Nikolai formation.

Vesicular basalt of the Nikolai formation is in fault contact adjacent to the ultramafic rock and extends to the top of Miles Ridge (Fig. 8; Israel *et al.*, 2007). Localized foliation within the Nikolai formation is parallel to movement along the strike-slip fault and is sub-parallel to the crest of Miles Ridge.

The drainage containing the Miles Ridge landslide is 1.9 km long and is divided into three morphologically distinct sections (Fig. 9). The upper section contains the landslide and is a steep basin filled with talus and bedrock crags. The middle section becomes narrower and contains a canyon at its base. The bottom section is an alluvial/colluvial fan in the White River valley.

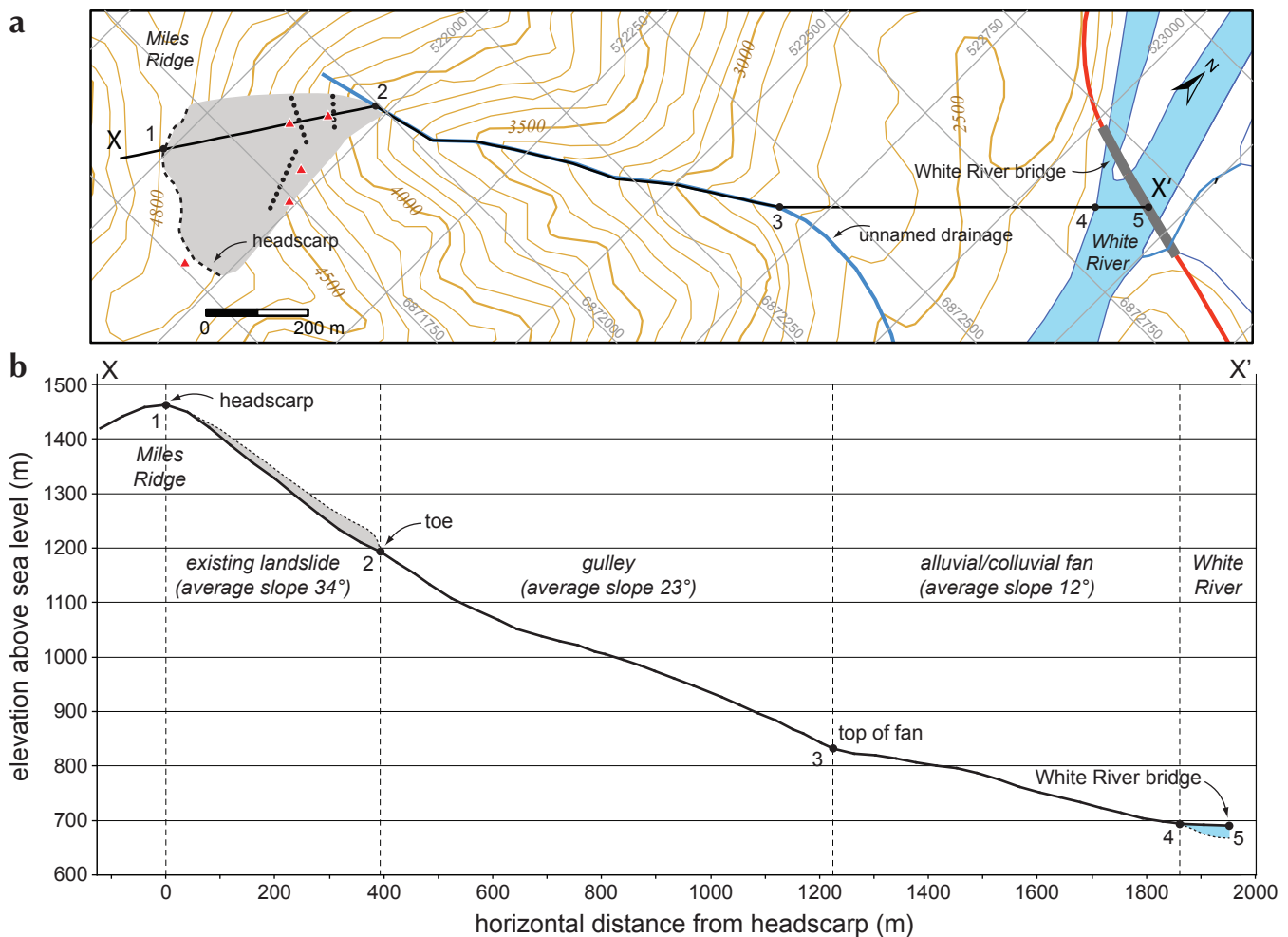
## FAILURE MECHANISM

Initial field observations in 2007 suggest that the Miles Ridge landslide is largely controlled by the character of the local bedrock. The Station Creek Formation appears to be buttressing the extremely incompetent overlying units of altered ultramafic rock and foliated basalt. Partial collapse of the Station Creek Formation has likely triggered failure of the overlying rocks. Active slumping along the headscarp in the Nikolai formation and debris-flow activity in the highly altered ultramafic rock indicates that the landslide is still actively responding to unstable slope conditions (Fig. 10).

The ongoing erosion of the initiation zone has caused a significant amount of fine- and coarse-grained debris to accumulate in the upper part of the drainage basin. This is most noticeable on the southeast side of the slide, where slopes may be stabilized at depth by crags of *in-situ* Station Creek Formation (Fig. 8). In contrast, the northwest side of the slide has no supporting *in-situ* rock and the debris is continually transported away by secondary debris flows and slides (Fig. 8). Further accumulation of debris on the southeast side of the slide will add stress to the supporting Station Creek Formation. With ongoing seismic activity in this area, it is probable that the southeast side of the basin will eventually collapse.

## MONITORING PROGRAM

A monitoring program was initiated so that any future activity in the landslide can be detected and characterized. A series of wooden stake lines and rebar monuments were installed and surveyed using single-frequency differential GPS (DGPS) receivers (Thales Promark 3s) and post processing. A reference base station,



**Figure 9.** (a) Plan view map of cross-section x-x'; triangles represent the rebar monuments and the dotted lines are the wooden stake lines constructed for the monitoring program. (b) Cross-section view of the slide area marking the morphological components and slope changes within the drainage and proximity of the landslide to the White River bridge.

established at the White River RV Park about 2.5 km from the landslide, was occupied for 8 hours using a 1-second collection interval. The position of the base station was then determined by submitting this data in RINEX format to the Geodetic Survey of Canada's online post processing service (precise point positioning). Both the horizontal and vertical coordinates of the base station were fixed to within 10 cm at 95% confidence.

Although the survey was conducted on a steep north-facing slope, good satellite geometry was maintained for the entire survey. Due to time constraints, all GPS point positions were collected using 'stop-and-go' survey mode, where the DGPS rover receiver is leveled over a point using a range pole supported with a bi-pod; wooden stake positions were occupied for 1 minute and rebar

monuments were occupied for 10 minutes. Horizontal and vertical positions were measured to within 8 mm, and most positions had reported accuracies of 5 mm or less (with 95% confidence). The survey lines and monuments were established as follows (Figs. 8 and 10):

1. 17 wooden stakes at approximately 30-m spacing were placed 1 m behind the headscarp in order to provide a reference for ongoing erosion of the initiation zone.
2. 49 stakes with 5-pace spacing were installed along the crest of the southeast debris accumulation zone (Figs. 8 and 9).
3. 26 stakes with 10-pace spacing were installed in two lines across the northwest active debris flow zone (Figs. 8 and 9).



**Figure 10.** A view to the northwest along the headscarp of the Miles Ridge landslide. Active slumping is visible in the foreground. A pogo stick with 25-cm intervals is shown for scale.

4. Four rebar monuments were established throughout the southeast and northwest debris zones as more permanent control points (Figs. 8 and 9).

### POSSIBLE OUTCOMES OF A LARGE-SCALE LANDSLIDE

To date, landslide activity at Miles Ridge has been limited to the upper reaches of the drainage and has had no downstream impact. Preliminary field observations of rock characteristics in the source zone indicate that a larger landslide could occur in the future. If this debris follows a straight trajectory of 1.9 km in the direction of the upper two thirds of the drainage, it will directly impact the White River bridge (Fig. 9). However, near the mouth of the drainage, the stream channel deflects to the east side of the fan, redirecting the flow slightly away from the bridge. Depending on the magnitude of a future landslide,

the run-out could follow the stream channel to the river, or it could abandon the stream channel at the apex of the fan, and continue its straight trajectory toward the bridge.

Four potential scenarios exist if a more catastrophic landslide were to occur:

1. The landslide debris will have limited run-out and settle in the upper reaches of the drainage with no impact to the White River bridge.
2. The landslide debris will lodge near the top of the confined or gullied portion of the drainage, temporarily damming it and causing ponding. Subsequent failure of the dam at a later time could then generate a catastrophic debris torrent into the White River.
3. The landslide debris will reach the White River and subsequently be deposited into the river channel. This could temporarily deflect the White River into the footings of the White River bridge and cause undercutting of the structure.
4. The landslide debris will travel 1.9 km in a straight trajectory, directly impacting the White River bridge.

### CONCLUSIONS

The Miles Ridge landslide is currently active and threatens to impact the Alaska Highway corridor. The landslide is perched in the upper reaches of a steep drainage, less than 2 km from the White River bridge. The landslide source zone occurs within volcanic and highly altered ultramafic rocks that are bounded by strike-slip faults in the Denali fault system. Ongoing slumping and debris-flow activity in the initiation zone of the slide highlights the present instability of the site. A monitoring program was initiated to allow detection of future ground deformation at the site; rebar monuments and a series of wooden stake lines will be used to provide both survey control points and visual measures of ongoing deformation.

## SUMMARY

The 2007 surficial geology mapping program in the Stevenson Ridge and northern Kluane map sheets addressed a number of diverse topics reflecting the complex landscape of southwest Yukon.

1. The study area straddles the glacial limits of four Pleistocene glacial periods. Preliminary results indicate that the earliest (pre-Reid) glacial limits are less extensive than previously thought in this area.
2. Placer gold potential was identified at the margin of the penultimate (Reid or Gladstone) glaciation where a drainage diversion occurred. The resulting change to the morphology of local drainages (e.g., base level change and downcutting) is conducive for concentrating fluvial sediment and therefore potentially increasing placer gold grades.
3. Surficial geology features and stratigraphic exposures suggest that permafrost is widespread in the map area. This is reflected by a diverse number of periglacial landforms and processes that are found at all elevations across the landscape.
4. Finally, a monitoring program was established on a recently developed landslide located on Miles Ridge, above the White River bridge on the Alaska Highway. Future landslide activity at the site has the potential to impact the White River bridge and disrupt transportation along the Alaska Highway corridor. Future field observations will be used to further quantify the hazard at this site.

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