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2011

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doi:10.4095/288647

Recommended citation:
Dyke, L.D., Sladen, W.E. and Robertson, L., 2011. Colluvium flows as a hazard to pipelines in northeastern British Columbia, Geological Survey of Canada, Open File 6696, 1 DVD. doi:10.4095/288647

INTRODUCTION

This open file is the final report for the field work portion of PERD Pipeline POL project B52.001, titled Cyclic Loading of Pipelines on Unstable Slopes in northeastern British Columbia. The project started in 2001 under the direction of Dr. Ibrahim Konuk of the Geological Survey of Canada. Ongoing distress to buried pipelines on slopes in western Alberta and northeastern British Columbia drew the major pipeline owners and the Geological Survey of Canada together to develop numerical models that can predict large pipeline deformations that accumulate with slope movements over time. The companies have supplied extensive data from field monitoring and laboratory work for comparison with modeling results. The model formulation is advanced and has been reported elsewhere (eg. Konuk et al., 2006). This report documents field studies between 2001 and 2008 to identify the geologic setting of the slope movements and characterize their magnitude and frequency. The results are intended to help pipeline regulators and owners to recognize problematic terrain and provide background information for pipeline routing, design, and maintenance planning in this particularly landslide-prone region of the country.

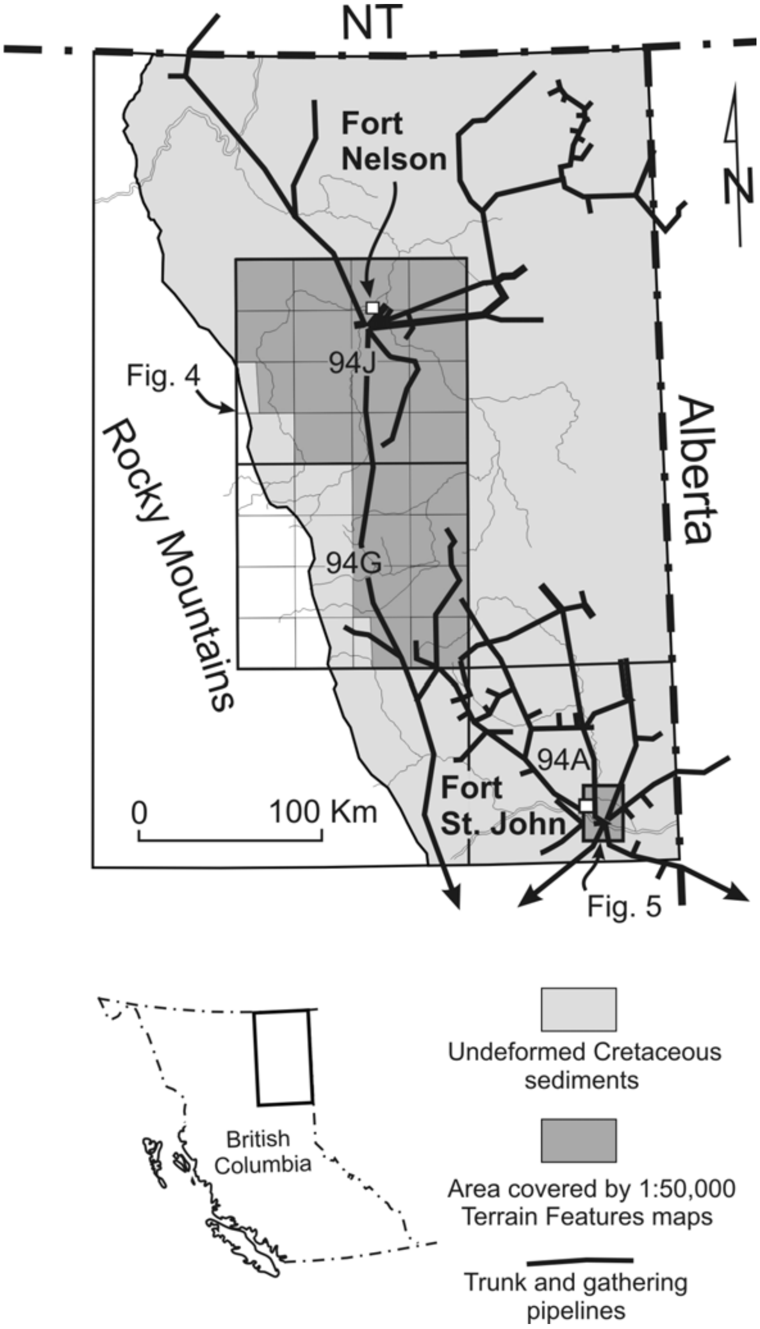

Figure 1. Northeastern British Columbia showing trunk and gathering pipelines and the area of terrain feature mapping.

Energy transmission by pipeline is a major transportation mode in Canada. Safe and reliable operation of pipelines is the essential goal of owners and regulators but this goal is compromised by a range of hazards. The National Energy Board (Jeglic, 2004) reports that of 46 pipeline ruptures in Canada during the period 1980 to 2005, only 4 were due to ground movements caused by natural processes. This low proportion underestimates the significance of ground movement as a hazard. Pipeline distress due to slope movement is typically detected well before rupture, resulting in considerable remedial effort that is not included when only rupture is used as a hazard measure. While the major hazards of corrosion or third party damage can theoretically occur anywhere, slope-related damage is restricted to the small portion of the NEB-regulated pipeline network where topographic relief is encountered. Therefore, where slopes are present, ground movement is as likely a hazard as any of the others affecting pipeline integrity.

SCOPE

This report focuses on the magnitude and frequency of slope movements that constitute a hazard to the oil and gas infrastructure in northeast British Columbia. All of northeastern British Columbia east of the Rocky Mountains Thrust Belt is underlain by two landslide-prone units: 1) the late Quaternary dominantly silty sediments of Glacial Lake Mathews and other glacial lakes (Hartman and Clague, 2008; Trommelen and Levson, 2009) and 2) the underlying Cretaceous sandstones and shales (Stott, 1982). Rapid, spectacular landslides occur in both of these units but this report concentrates on the subtle but more common gradual slope movements that seem to be most often implicated in pipeline distress. These slow movements characterize the behaviour of slope deposits that occur in specific locations relative to the Cretaceous stratigraphy. The deposits have been mapped as colluvium or, where there is evidence of movement, as colluvium flows on 23 1:50,000 scale NTS mapsheets (Figure 1 and Terrain Features maps). This mapping covers a 20,000 km^2 area straddling the Alaska Highway from about 150 km north of Fort St. John to about 80 km west of Fort Nelson. The mapping covers the east half of the 94G 1:250,000 NTS mapsheet and almost all of 94J. The study area was selected to include a large part of northeastern British Columbia that is susceptible to slope movements and that coincides with present and possible future oil and gas activities.

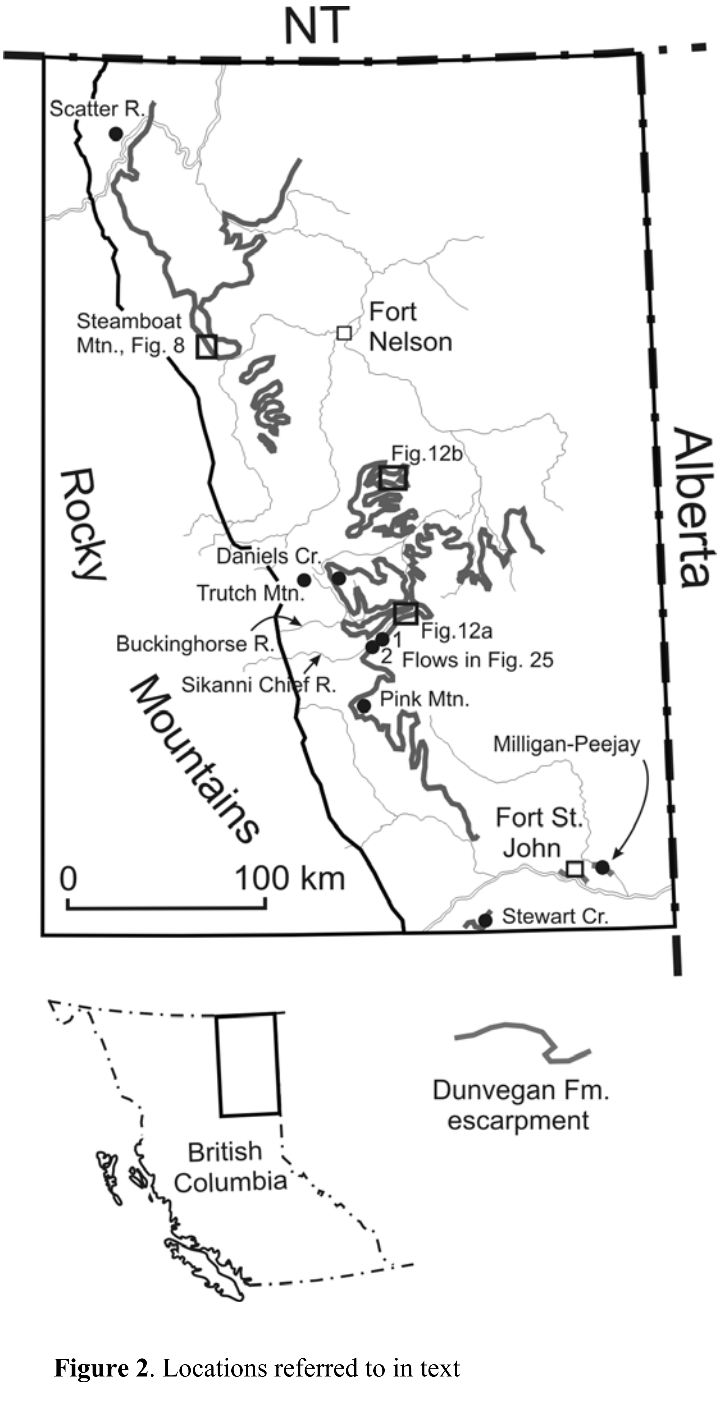

Figure 2. Locations referred to in text

The magnitude and frequency of movements in colluvium and colluvium flows are documented at several locations (Figure 2) by the following methods: quantifying Holocene erosion, radiocarbon dating, comparing successive air photographs, analyzing tree growth reaction to slope movement, measuring borehole deformation, repeating GPS measurements and by radar interferometry. Of these methods, tree growth analysis and borehole measurements provide records of sufficient length and detail to compare with rainfall data so that rainfall amounts that will trigger slope movement can be identified. The expected recurrence of rainfalls based on climate station records can then be used to anticipate future movement. Although a recurrence interval for significant slope movement is determined, the report does not attempt to map where and by how much slopes will move. Instead, three categories of hazard are identified that give a suggested level of vigilance where pipelines cross colluvium flows: assess every several years, assess every few years, and avoid. This classification is based on slope movement characterization, mechanical modeling and geometrical characteristics of the colluvium flow unit and is discussed in the final section of the report. The vigilance categories are intended as a general indication of the likelihood that buried pipelines will be adversely affected by ground movement over time intervals of a decade or more.

PIPELINES ON SLOPES

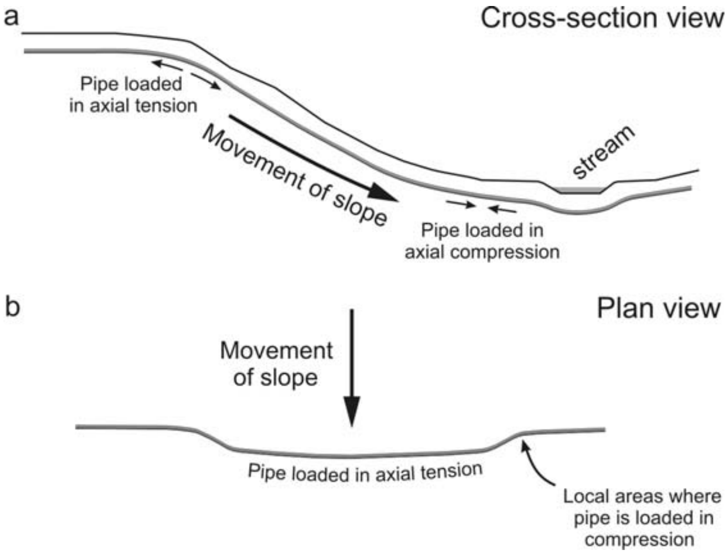

Figure 3. Pipeline loading by slope movement, depending on the orientation of the pipeline to the slope direction.

Slope movements subject buried pipelines to a variety of loadings. Usually slopes are encountered at stream crossings; hence the pipeline tends to be oriented parallel to the slope direction. Assuming the pipe to be fixed at the crest and at the base of the slope, downslope movement will place the pipe in axial tension on the upper parts of the slope and in compression on the lower parts of the slope (Figure 3a). Where slopes are traversed laterally, movement of one part of the slope will laterally load the pipe, placing the entire loaded segment in tension, save for local sharper bends where a compressive fibre stress may develop (Figure 3b). A pipeline is least able to sustain compressive strains because of the localized buckling that develops with small displacements at pre-existing bends. Where the pipe is in tension, localized buckling is not favoured and higher strains can be sustained.

Predicting how much slope movement is required to produce unacceptable deformation in a pipe requires knowing the friction between the pipe and enclosing soil and the restraint offered by the soil to pipe bending. Movements of as little as a few centimetres could produce buckling strains in a pipe if no sliding between the pipe and the soil takes place. This idealization is unrealistic but even with low friction, shearing stress accumulates along the pipe and may eventually produce compression great enough to exceed the elastic limit of the pipe steel. Rotational slope failures, typically characterized by movements in the order of metres over hours or days, will likely produce unacceptable pipe deformations. It is this type of failure that is typically expected in the slope stability assessment phase of pipeline route planning. Gradual but ongoing slope movement, commonly termed creep, is not normally anticipated. Creep may have little or no surface expression and may take several years to decades to result in pipeline distress. Deformation due to creep is usually only detected by instrumentation installed in a slope or by inspection tools run in pipelines.

SLOPE STABILITY IN NORTHEASTERN BRITISH COLUMBIA

Geology

Slope instability in the dissected terrain of northeastern British Columbia east of the Rocky Mountains is directly related to the weak mechanical properties of the Cretaceous stratigraphy and glaciolacustrine silts that dominate the region. The Upper Cretaceous Dunvegan Formation (massive conglomerate and sandstone) forms a distinctive, gently west-dipping to flat, cliff-forming capping to upland areas that extend eastward from the Rocky Mountains (Figure 4). The formation is generally about 150 to 200 m thick in the study area but changes facies with distance from the Rocky Mountain boundary, with siltstone intervals appearing in the eastern part of the project area. Beneath the Dunvegan Formation extend a series of shales and less prominent sandstones. The Sully Formation occurs immediately beneath the Dunvegan Formation and consists of shale and siltstone with a thickness varying between about 100 and 200 m. This unit forms the mid-slopes of the valleys dissecting the uplands and produces the most prominent slope instability in the region. This unit and the overlying Dunvegan Formation have produced the unit named 'colluvium deposits' mapped by Bednarski (2000) in the 94G map sheet and described by him as active and inactive landslides and mass wasting debris. These colluvium deposits occur wherever the Dunvegan Formation caps the topography and have a distinctive undulating, ribbed or hummocky texture on airphotos. They are the main subject of this report because they are widespread and implicated in pipeline disruptions. Similar deposits occur below the Dunvegan Formation in the 94J NTS map sheet and are particularly well developed in the uplands west and southwest of Fort Nelson.

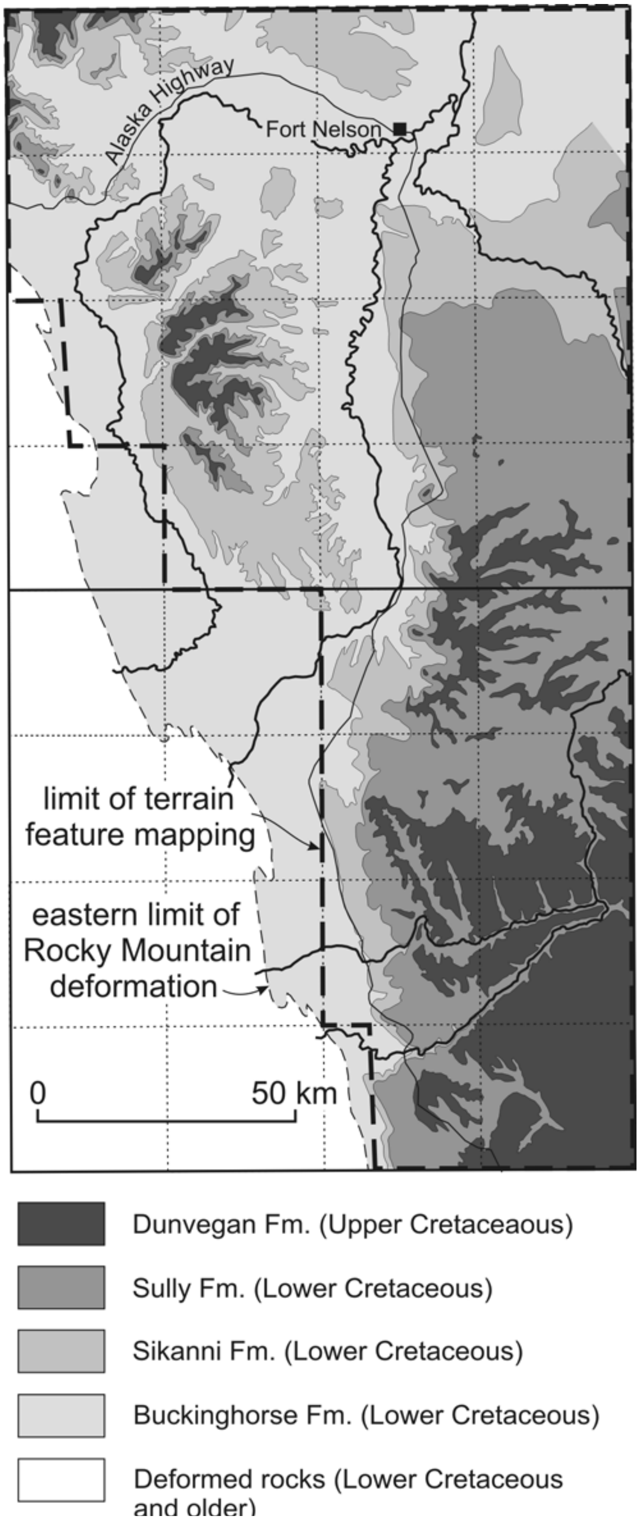

Figure 4. Bedrock geology of the undeformed bedrock in the area of terrain feature mapping (see Figure 1).

The Sikanni Formation (Jowett et al., 2007) occurs below the Sully Formation and is a series of 10 to 30 m-thick sandstone units separated by silty shale intervals for a total thickness of about 300 m, decreasing to about 100 m in the eastern part of the project area. The sandstones in this unit are not as prominent as the Dunvegan Formation but do form subdued cappings as well as buttresses on slopes capped by the Dunvegan Formation. Below the Sikanni Formation is the Buckinghorse Formation (Schröder-Adams and Pedersen, 2003) consisting primarily of shale and siltstone with a thickness of about 1000 m. The Buckinghorse Formation does not promote the same kind of mass wasting forms as the Sully Formation, probably because of where it is exposed relative to the topography. The Buckinghorse Formation underlies all of the lower elevations in the project area and is typically covered by glaciolacustrine deposits. Along streams the Buckinghorse Formation is exposed but downcutting through the formation has not produced enough relief to allow the development of mobile colluvium deposits. Instead, failures in the overlying glacial sediments tend to mask this unit. The Buckinghorse Formation has probably become involved in scattered low gradient flows where initial failures in overlying material subsequently involve the unit.

Landslides

Geertsema et al. (2006) report 20 large, rapid landslides and flows scattered across northeastern British Columbia that have occurred over the last 30 years. Even though these features have runouts of up to a few kilometres, they have not had any direct impact on infrastructure. Three of these events are rock slides in pre-Cretaceous sandstones that are exposed on ridges just within the Rocky Mountains. The rest are flows in tills derived largely from the Cretaceous shales and in glaciolacustrine sediments. The flows in tills are typically located on the sides of major valleys with slopes in the source areas of about 20°. These flows tend to be narrow, following pre-existing drainages and may be triggered by thawing of shallow permafrost. The other type of flow is on a much shallower angle with run-outs of less than 5°. These low gradient flows include transport of intact blocks and are readily identified by scattered ponds impounded in depressions between the blocks. They tend to be about half a kilometre wide. Geertsema and Clague (2006) have studied a concentration of these features in materials mapped as lacustrine along a few kilometres of a drainage from one of the upland areas about 50 km south of Fort Nelson. One slide is modern but several others have been dated over the last thousand years, indicating that locally a potentially damaging landslide of this kind can occur on average about once per century.

Expecting that the flows studied by Geertsema and Clague (2006) are related to mechanical properties of lacustrine sediments, similar events could be anticipated wherever lacustrine deposits have been incised by stream erosion. Bowl-shaped rotational slides are common along all the major streams and tributaries cut into lacustrine sediments in the project area (see slide unit on Terrain Features maps). The size of these slides is dependant on the depth of the stream's incision. Sliding ceases once the depth of the incision decreases to about 10 m. Retrogression and flow-like behaviour does occur but is not common and does not result in a significantly larger retreat of headscarps than is seen for the rotational slides. Involvement of the underlying Buckinghorse Formation may have augmented the flows studied by Geertsema and Clague (2006). These flows extend to the edge of the lacustrine deposits at their study site so involvement of underlying materials is likely.

Rapid landslides are more problematic in the Fort St. John area where failures in Glacial Lake Mathews sediments coincide with a denser transportation infrastructure. Severin (2004) mapped all landslides in Glacial Lake Mathews sediments in the 94A NTS map area (Figure 1). Slope failures are almost continuous along the Peace and Beatton rivers where the valleys are cut into these materials. Since 1995, 10 landslides have taken place within 20 km of Fort St. John (Figure 5), eight of which have had a direct impact on property or infrastructure. The almost complete absence of a flood plain along the Beatton River and the consequent almost continuous juxtaposition of the river edge with the foot of the valley slopes is maintaining active adjustment to toe erosion. Radiocarbon dating of basal organic accumulations from ponds formed on landslide surfaces give ages typically between 100 and 500 years (see Table 1 for dating details), suggesting that the valley sides have been completely renewed by landsliding over the last few centuries. Along the Peace River, landslides are absent where the modern river channel is separated from the foot of the valley side by abandoned terraces.

Although destabilization of slopes by river toe erosion is the overall trigger for this ongoing slope failure, most of the recent landslides in the vicinity of Fort St. John are associated with local alterations to the terrain in the course of infrastructure construction and maintenance (eg. Maber and Stewart, 1974). As an example that movements are easily re-triggered, re-routing of a provincial highway through Beatton River valley resulted in re-activation of an old landslide due to loading by a 3 m-high fill (Polysou et al., 1998). Outwash and lacustrine sediments in the northeastern part of 94J behaved similarly during construction of the British Columbia Railway (Carabetta and Leighton, 1984). Other examples, including the almost continuous maintenance of the Alaska Highway on the south side of the Peace River valley, are reviewed in Sladen and Dyke (2004). Grading of slopes at the Big Bam Ski Hill a few km upstream of the Alaska Highway may have triggered a multiple block failure in 1997 that destroyed the ski hill facilities (location shown in Figure 5).

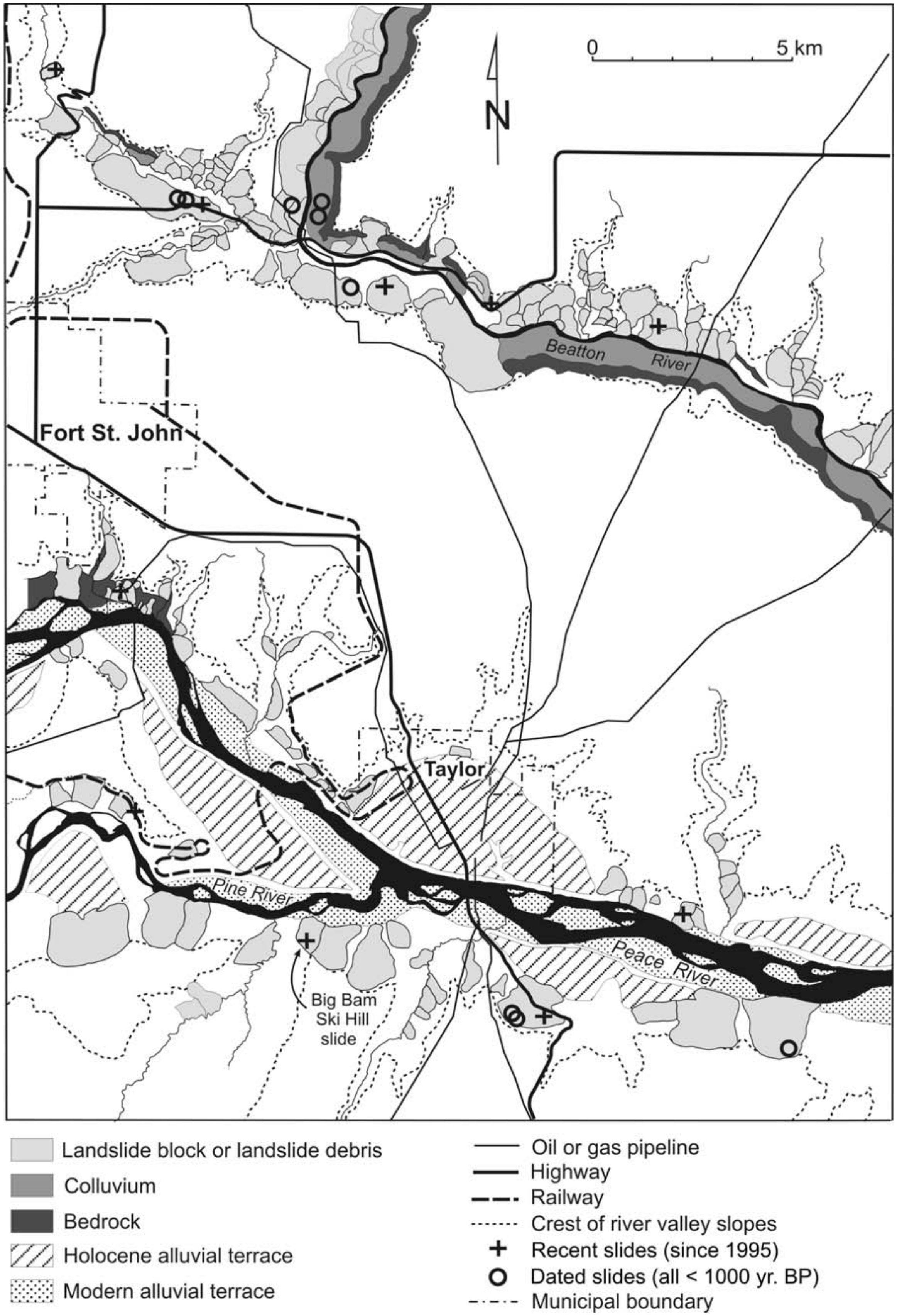

Figure 5. Landslides primarily in lacustrine sediments of Glacial Lake Mathews in the vicinity of Fort St. John. For the location of the area see Figure 1.

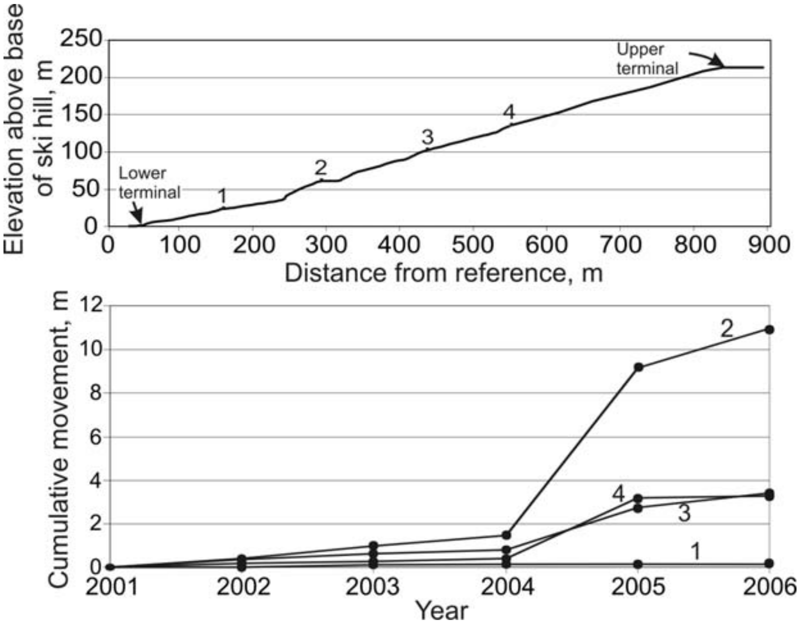

Figure 6. A cross-section of the Big Bam ski hill showing the locations of survey monuments 1 to 4 and the cumulative movement of those monuments from 2001 to 2006.

Four monuments installed in 2001 along the ski-lift route and measured yearly until 2006 show ongoing yearly movements of up to several metres (Figure 6). Slopes eventually restabilize once toe erosion ceases. However slopes appear to require little disturbance to reactivate as suggested by the construction-related slope movements referenced above. These include locations where the bases of slopes have previously been removed from active river erosion.

COLLUVIUM FLOWS

This report focuses on the accumulations of moving erosional debris that form on slopes underlain by the Cretaceous shales and sandstones of the region. These moving deposits, here termed colluvium flows, develop where erosion and weathering of shale destabilizes the overlying massive sandstone. Colluvium flows are most obvious on slopes in the Sully Formation that are capped by the Dunvegan Formation. The eroded shale provides a material of low internal friction that incorporates and transports debris from the disintegrating sandstone. This mixture creeps downhill to form block streams or colluvium flows (see Figure 7, 9 and the colluvium flow unit on Terrain Features maps).

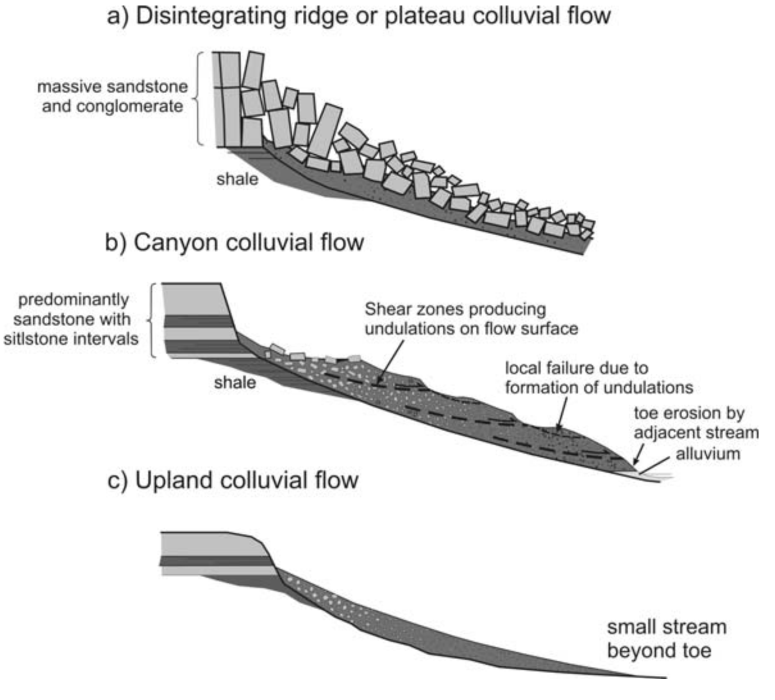

Figure 7. Colluvium flows as identified in the study area. a) Sandstone blocks transported away from disintegrating massive sandstone and conglomerate of the Dunvegan Formation. b) Weathered sandstone, siltstone and shale accumulating at the base of an escarpment in the Dunvegan or Sikanni Formations and flowing downhill. c) Debris accumulating and moving downslope with no significant toe erosion.

The Steamboat Mountain area shows the most extensive development of colluvium flows in the study area (Figures 2, 8, and 9). This upland consists of outliers of a particularly thick, massively-bedded facies of the Dunvegan Formation that gives way to extensive block fields and disintegrating ridges (Figure 7a, 10). The caps formed by the Dunvegan Formation exhibit open fissures suggesting dilation of the caps due to deformation in the underlying shale, similar to a mechanism proposed for the retreat of the Niagara Escarpment (Barlow, 2002). The Dunvegan outliers supply debris streams occupying most of the drainages flowing northward from this upland, some up to 6 km long and descending slightly over 1000 m. Striations on the top of Steamboat Mountain demonstrate that the area was covered by ice. If it can be assumed that the present debris has

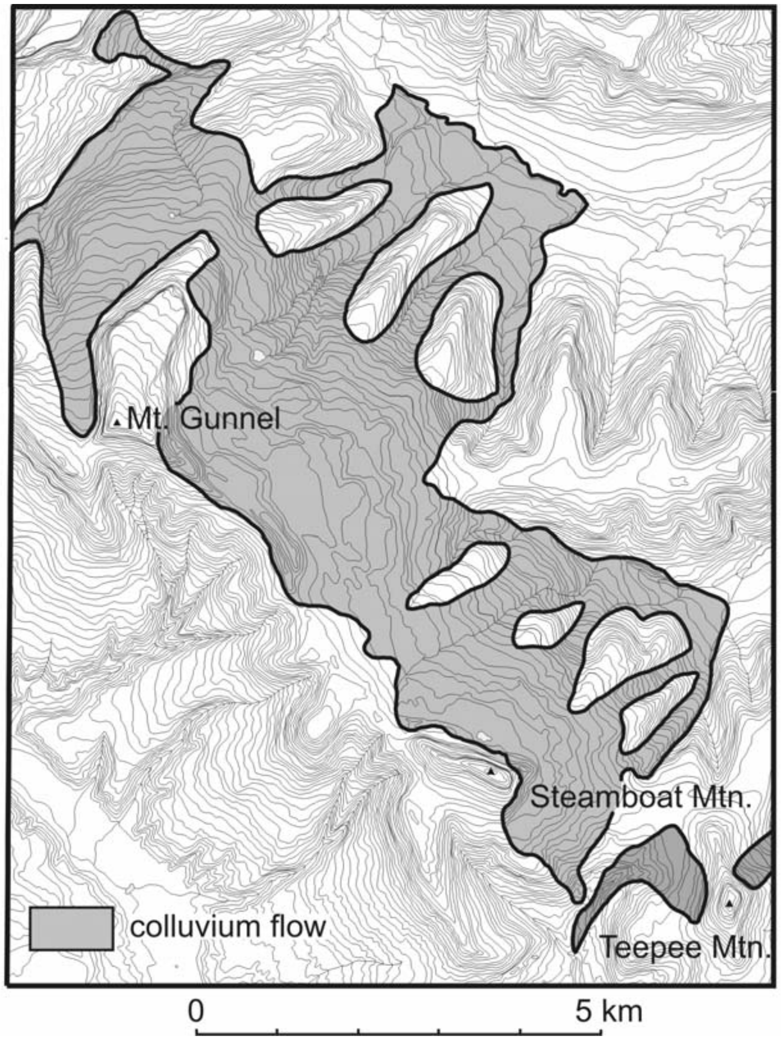

Figure 8. Colluvium flows in the vicinity of Steamboat Mountain. For location see Figure 2. The contour interval is 20 m.

accumulated since the last glaciation, then the apparent thickness and distribution of the debris suggest that a continuous ridge of Dunvegan Formation existed incorporating the present Dunvegan outliers represented by Mount Gunnel, Steamboat Mountain and Teepee Mountain. Thus debris has probably traveled most of the distance from the present ridge to the present termini of the debris streams.

Colluvium flows are most common bordering eroding streams (Figure 7b, 11) or flanking upland plateaus formed by other outliers of the Dunvegan Formation (Figure 7c). They are identified on airphotos by a stippled texture imparted by the sandstone debris. Deformation in the colluvium also results in a ribbed or hummocky surface, often with scattered, elongate ponds (Figure 11a). Where these surface characteristics are not visible, slopes are mapped as colluvium. Considerable evidence indicates that colluvium other than that mapped as flows is also in motion.

The colluvium deposits mapped by Bednarski (2000) in the 94G mapsheet are colluvium flows that have formed by the Holocene downcutting of the valleys of the Buckinghorse and Sikanni Chief rivers (for location see Figure 2). These valleys have probably been completely cut during the Holocene, based on the existance of abandoned fluvial channels beside the rim of the present Sikanni Chief canyon a few kilometres upstream of the Alaska Highway. The Dunvegan Formation caps these valley slopes but the facies is not as massive as at Steamboat Mountain and contains siltstone intervals. Steamboat Mountain lies less than 10 km east of the beginning of the Rocky Mountain Thrust Belt and the Dunvegan Formation provenance whereas the colluvium flows bordering the Buckinghorse and Sikanni Chief rivers are 20 to 60 km east of this boundary. As a consequence, these colluvium flows, although still littered with blocks on the uppermost parts, lack the block coverings that characterize the Steamboat Mountain area.

The Buckinghorse and Sikanni Chief flows deliver angular sandstone boulders in a clayey silt matrix to the river banks. Colluvium flows occupy most of the sides of these valleys between the Alaska Highway and the confluence of the two rivers (Figure 12a). The flows extend upslope from either river for about 1 km. From the base of the Dunvegan escarpment to river level, the flows descend about 200 m, making them comparable in gradient to the flows in the Steamboat Mountain area. Erosion at the river banks keeps these flows active. Colluvium flows are also present along most upland ridges capped by the Dunvegan Formation (Figure 12b). These ridges generally lack an adjacent major stream and so the flows have developed without significant removal of material from the toe. Although the mechanism of development is similar

Figure 9. Steamboat Mountain from approximately 3 km northeast. Note rock debris immediately in front of and to the left of the mountain as well as the flow streamlines (block streams) in the foreground.

Figure 10. The disintegrating edge of the east side of Mount Gunnel.

to the Steamboat Mountain features, the lower relief has limited the length of these features to about 1 km. These flows tend to be concave in profile and likely decrease in thickness with distance down-slope.

Features that can be described as coarse colluvium flows are also reported by Hungr et al. (1984) along the lower reaches of Scatter River, a tributary to the Liard River about 100 km northwest of Steamboat Mountain (for location see Figure 2). Here, sandstones also overlie shales but at a level stratigraphically lower than the Dunvegan-Sully association. The lower Scatter River valley has developed by the transport and disintegration of sandstone blocks to form sloping, ribbed or stepped flows up to 2 km wide.

The only thickness measurements for colluvium flows come from features in the vicinity of Fort St. John (McClarty, 2003). A 12-inch gathering pipeline crosses a colluvium flow on the south side of Beatton River, approximately 15 km east of Fort St. John. A 30-inch trunk pipeline also laterally traverses a flow above Stewart Creek about 40 km southwest of Fort St. John. The former flow is approximately 20 m thick while the latter thins from about 60 m to 20 m downslope. Along the Sikanni Chief and Buckinghorse rivers, flow materials overlying intact shale are occasionally exposed, indicating a flow thickness of about 20-30 m at the downslope end (Figure 11b). The thickness of a flow probably depends on the rate at which rock debris is supplied at the upper end and the rate of debris movement.

MOVEMENT RATES OF COLLUVIUM FLOWS

Much of the Sikanni Chief and Buckinghorse rivers (see Figure 2) between the Alaska Highway and their confluence consist only of the river channel confined between colluvium flow margins with no alluvial plain. Comparison of 1948 and 1997 airphotos shows that the river channel along these confined reaches has been laterally displaced up to 100 m, suggesting that flow fronts can move up to 2 m/yr. If creep was the mechanism transporting erosional debris from the valley sides to a river channel, movement would have to average about 1 m/yr, assuming a flow 20 m thick and valley incision commencing with deglaciation about 10,000 years ago (Bednarski, 2000). The dating of basal organic sediments from 10 ponds located on flows gives ages ranging from modern (probably less than 50 years) to 1060 radiocarbon years (see Table 2 for dating details). This range of ages is consistent with a 1 km-long flow surface that would presumably be completely renewed in 1000 years by movement of 1 m/yr.

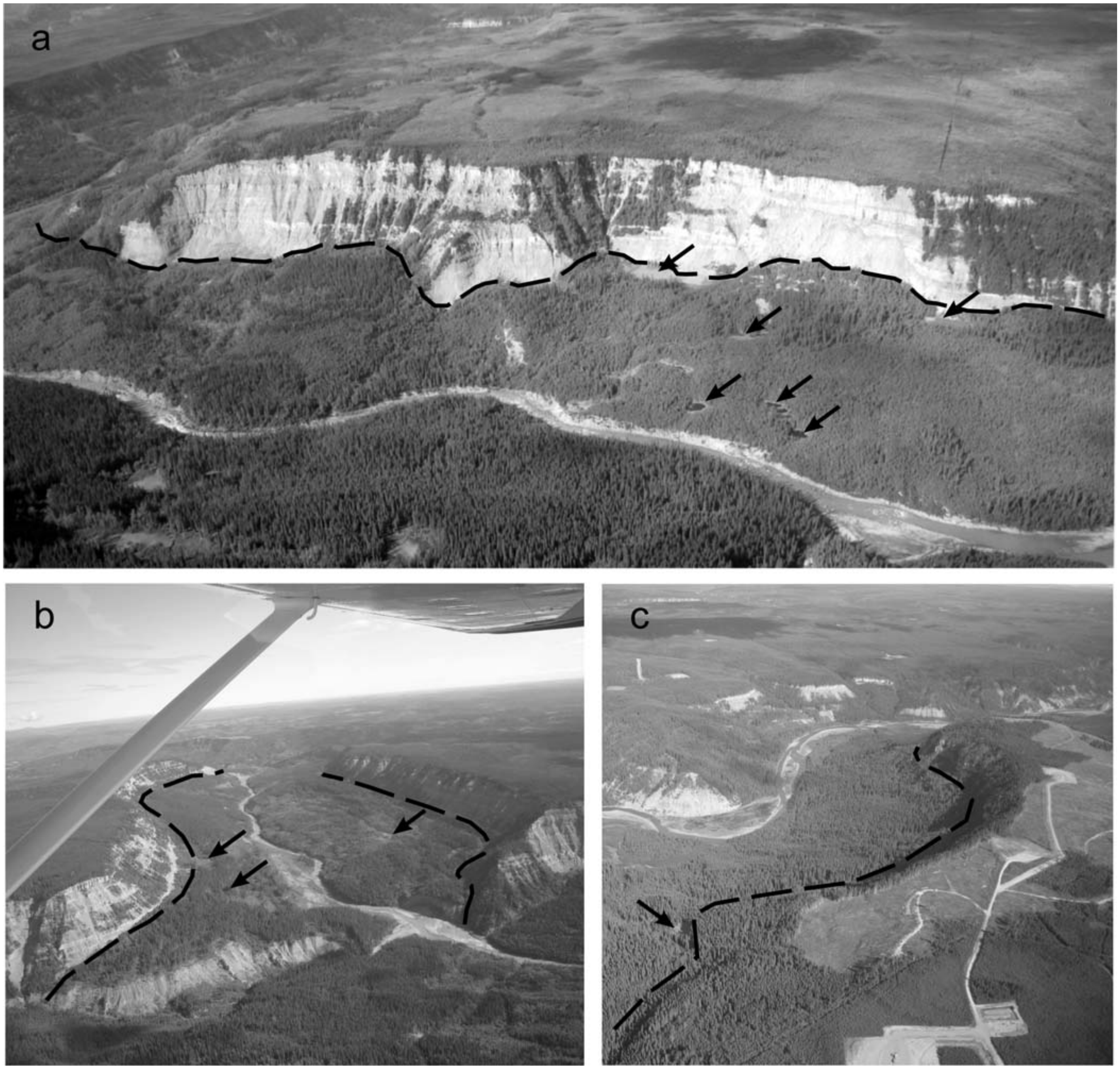

Figure 11. Colluvium flows bordering the Sikanni Chief River. a) Immediately downstream of the confluence with Buckinghorse River. b) 10 km downstream of confluence with Buckinghorse River, showing flow cross-section exposed by tributary erosion. c) 25 km downstream from the Alaska Highway crossing. The arrows point to ponds formed by uneven extension and compression within flows. The dashed lines show the upper boundary of flows.

Debris reaching the valley bottom immediately north of Steamboat Mountain (approximately 5 km) would require an average movement rate of about 0.5 m/yr assuming the same 10,000 yr time interval for flow development.

The estimates of movement based on radiocarbon dating and valley incision rates show that colluvium flows have probably been active throughout the Holocene at rates undoubtedly harmful to infrastructure. To understand the behaviour of flows in more detail, we measured colluvium flow using dendrochronology and in situ instrumentation. The increased precision of these techniques allows slope movement to be related to rainfall or variations in effective stress indicated by pore pressure changes. Records from climate stations can then be used to characterize rainfall variability to give a probabilistic

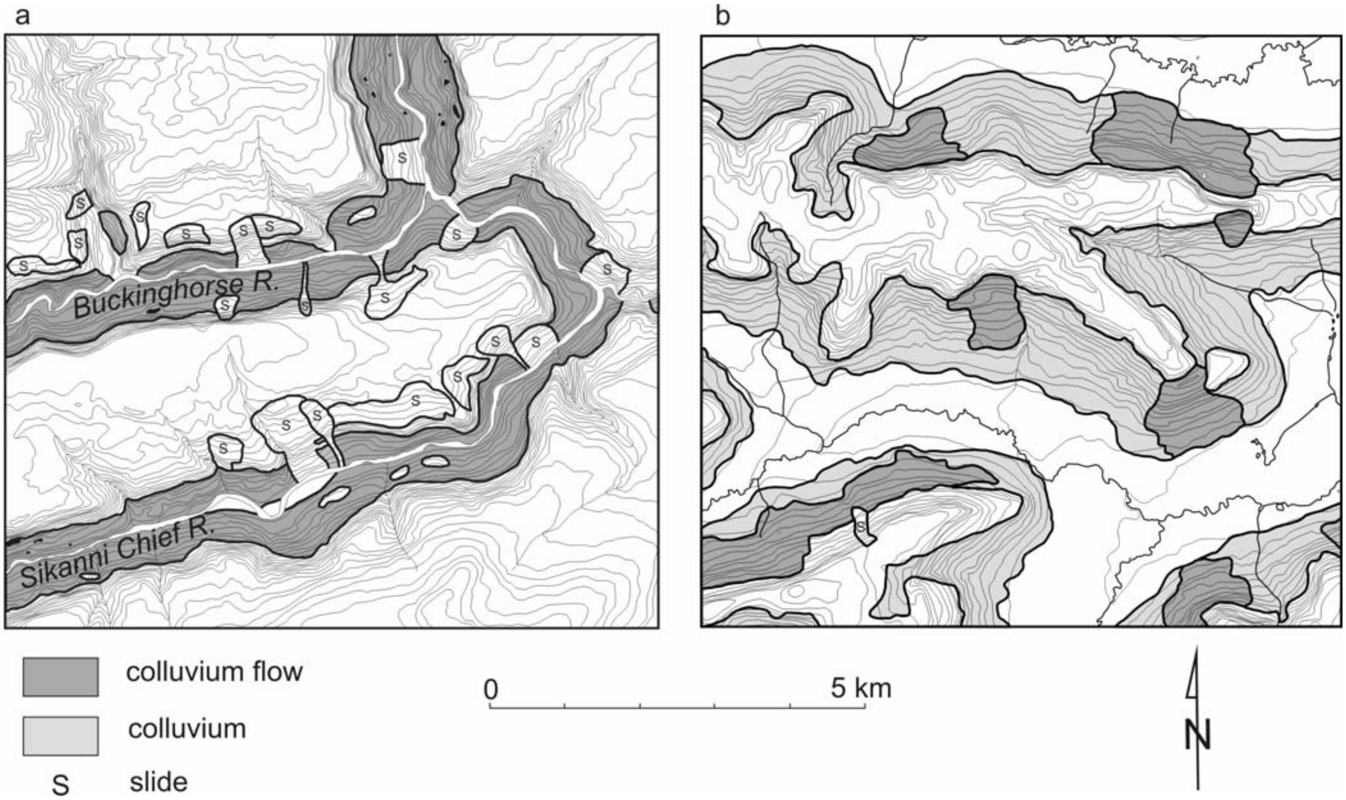

Figure 12. Examples of colluvium flows from a) NTS map area 94G8 (canyon-type colluvial flow) and b) NTS map area 94G16 (upland-type colluvial flow). Contour interval is 20 m. For the location of these sites, see Figure 2.

estimate of future movement based on the past frequency and duration of rainfall. Rather than following this procedure only for the sites instrumented during this study, we use all of the different types of measurement to give a general characterization of the frequency and magnitude of movement for colluvium flows throughout the study area.

INSTRUMENTATION

In-place inclinometers have been installed in existing inclinometer casings on two pipeline rights-of-way where the pipelines cross colluvium flows. The in-place probes allow an essentially continuous measurement of deformation. Piezometers nests instrumented with pressure transducer loggers were also installed within a few metres of each inclinometer instrumented. These installations allow continuous measurement of pore pressure at specific depths. The two measurements give an indication of the sensitivity with which slope movements respond to changes in effective stress. At one other colluvium flow, radar corner reflectors for carrying out interferometric measurements using signals from the RADARSAT 2 radar satellite have been installed.

Manual surveys of the inclinometer casings installed in the colluvium flows show the deformation to be typically concentrated at shear zones. The precision with which manual inclinometer surveys can measure a shear zone thickness is limited by the gauge length of the inclinometer probe. Thus, with a gauge length for manual readings of 0.61 m, manual surveys based on raising the probe in increments of its own length can resolve a shear zone thickness to no less than this length (Figure 13). The displacement across the shear zone is the sum of the displacements for adjacent manual readings that show a change in inclination (Figure 13b). For a shear zone thinner than the gauge length, at most two adjacent probe positions will show displacements. Shear zones are assumed to be parallel to the surface of the colluvium flow, hence displacements recorded across a shear zone also occur at the ground surface.

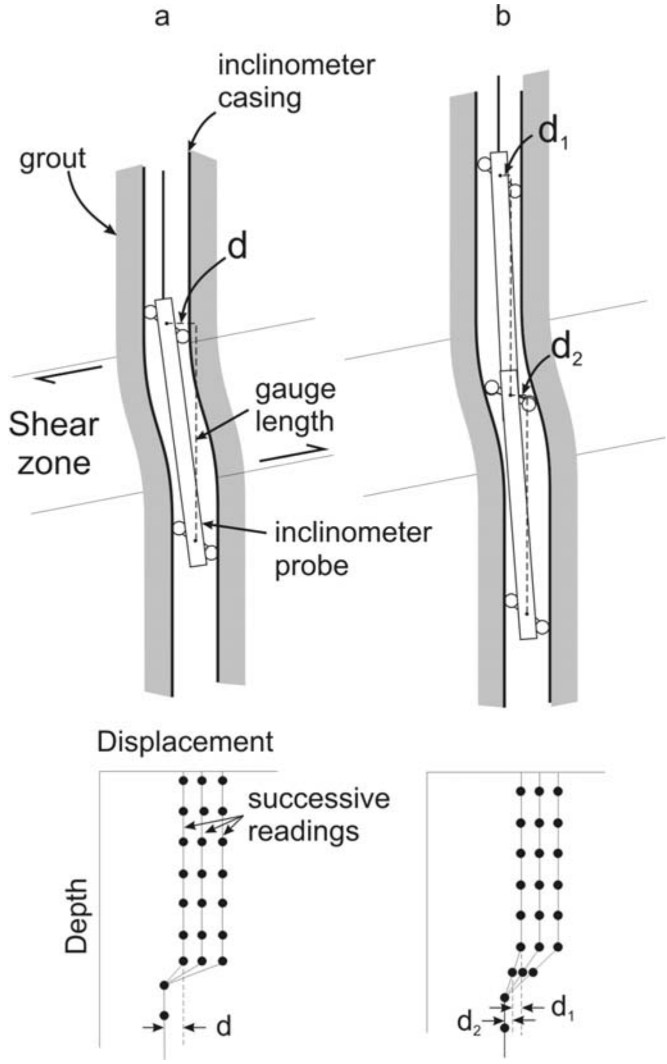

Figure 13. Measuring shear zone displacement with an inclinometer probe. The inferred thickness of the shear zone in a) and b) depends on the locations of the probe relative to the shear zone during a manual survey. In a) the shear zone thickness may be as great as the gauge-length of the probe. In b) the shear zone thickness may be as thick as two gauge lengths. The depth profiles below show how the plot of each survey would look.

Ground surface displacements are also derived from changes in position of radar corner reflectors anchored at the ground surface (Figure 14). The actual measurement is the change in position of the reflector along the line-of-sight to the satellite, measured every 24 days. The precision of this measurement can be of the order of 1 cm. The measured change in distance is assumed to be caused by movement of the reflector parallel to the ground surface. Therefore the measured movement toward or away from the satellite must be resolved along the expected movement direction of the reflector to determine the ground surface movement. The radar reflector positions have also been determined with GPS measurements for two successive years as an independent check on the interferometric measurements.

Inclinometers

Milligan-Peejay site

The Milligan Peejay pipeline is a raw gas transmission line constructed in 1969 that runs from a gathering area 50 km north of Fort St. John to the Taylor gas processing plant southeast of Fort St. John. The monitoring site is located on the south approach slope to the Beatton River, 15 km east of Fort St. John (Figure 15, see Figure 2 for location). The slope is characterized by a steep, 30 to 35°, bedrock slope formed mainly by the Dunvegan Formation, shallowing at the bottom to a gentle (2 to 12°) slope descending to the Beatton River for a total relief of about 220 m. The gentle slope segment is underlain by the Sully Formation. The colluvium flow comprises the gentle part of the slope and is described from drill cuttings as clayey silt, silty till, and weathered shale, in total up to 40 m thick. Several small landslides in glacial sediments and weathered bedrock along the pipeline right-of-way prompted instrumentation beginning in 1998. An in-line inertial survey of the pipeline in 2002 revealed an outward pipeline

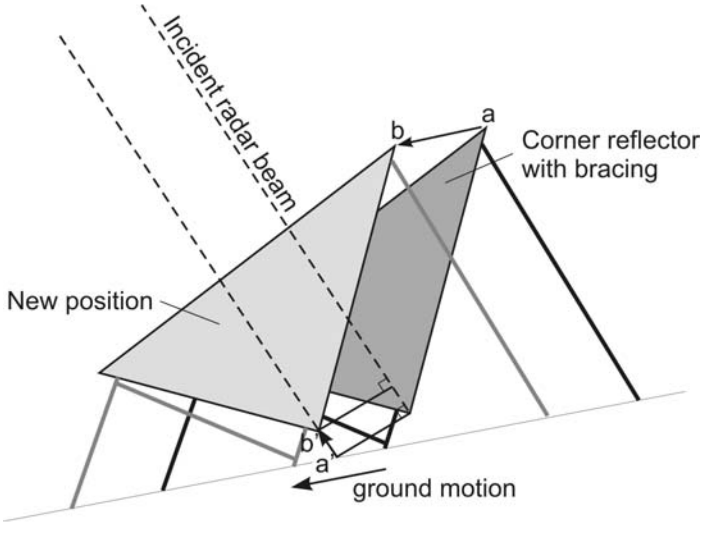

Figure 14. Radar corner reflector showing the relationship between the movement of the reflector parallel to the ground surface (ab) and the change in distance from the satellite (a'b').

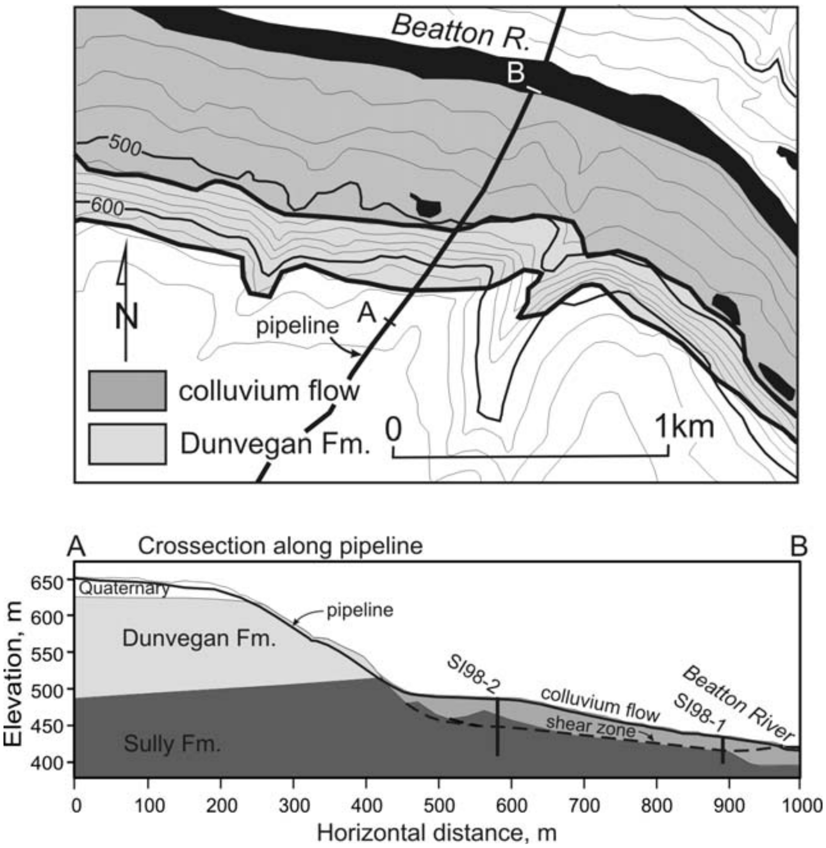

Figure 15. Milligan-Peejay pipeline crossing of the Beatton River. The cross-section shows the Cretaceous stratigraphy and location of the colluvium flow along the segment AB of the pipeline. Contours show elevation above mean sea level with a 20 m contour interval. For the location of the site, see Figure 2.

wrinkle near the bottom of the colluvium flow (McClarty, E., 2003).

Inclinometers installed within the colluvium flow each show shearing along a single zone near the base of the colluvium flow (Figure 16). Pairs of in-place inclinometers were installed to coincide with the zone of shearing indicated by manual surveys. For the upper inclinometer (SI98-2), displacement is exhibited for two adjacent manual readings, indicating that the shear zone thickness is less then 1.2 m. For the lower inclinometer (SI98-1), only one manual reading shows displacement, indicating that the thickness is probably less than 0.6 m.

Stewart Creek site

The 30” McMahon gas pipeline was constructed between 1955 and 1957 from the gas processing plant at Taylor to Vancouver. The Stewart Creek crossing is located 47 km southwest of Fort St. John and has been subject to ground deformation since 1963 (AGRA, 1996). The right-of-way originally contained an oil pipeline which was rerouted in 1977 following two failures at each of the creek approach slopes and a gas pipeline which failed in 1979 near the toe of the south approach slope. The original gas pipeline route across Stewart Creek has been abandoned in favour of a loop line which crosses Stewart Creek a few kilometres upstream.

The original pipeline approached Stewart Creek by first paralleling the creek valley before descending about 120 m on a 20° slope to the crossing (Figure 17). Bedrock at the Stewart Creek crossing is entirely within the Dunvegan Formation and is well exposed for several tens of metres above the creek bottom. Overlying the bedrock is up to 53 m of silt and clay with scattered sandstone clasts. The site was first instrumented with inclinometers and piezometers in 1977. However, that instrumentation has since sheared off or been damaged and a second suite of instrumentation was installed in 2000. Several slow-moving

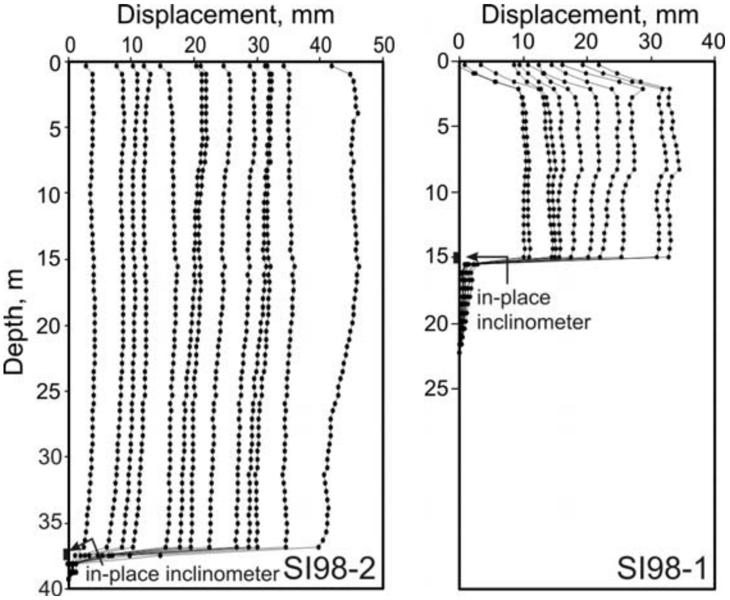

Figure 16. Manual readings for the inclinometer casings at the Milligan-Peejay site, taken between 1998 and 2003. The black bars on the depth axes show the location of the in-place inclinometers coinciding with shear zone

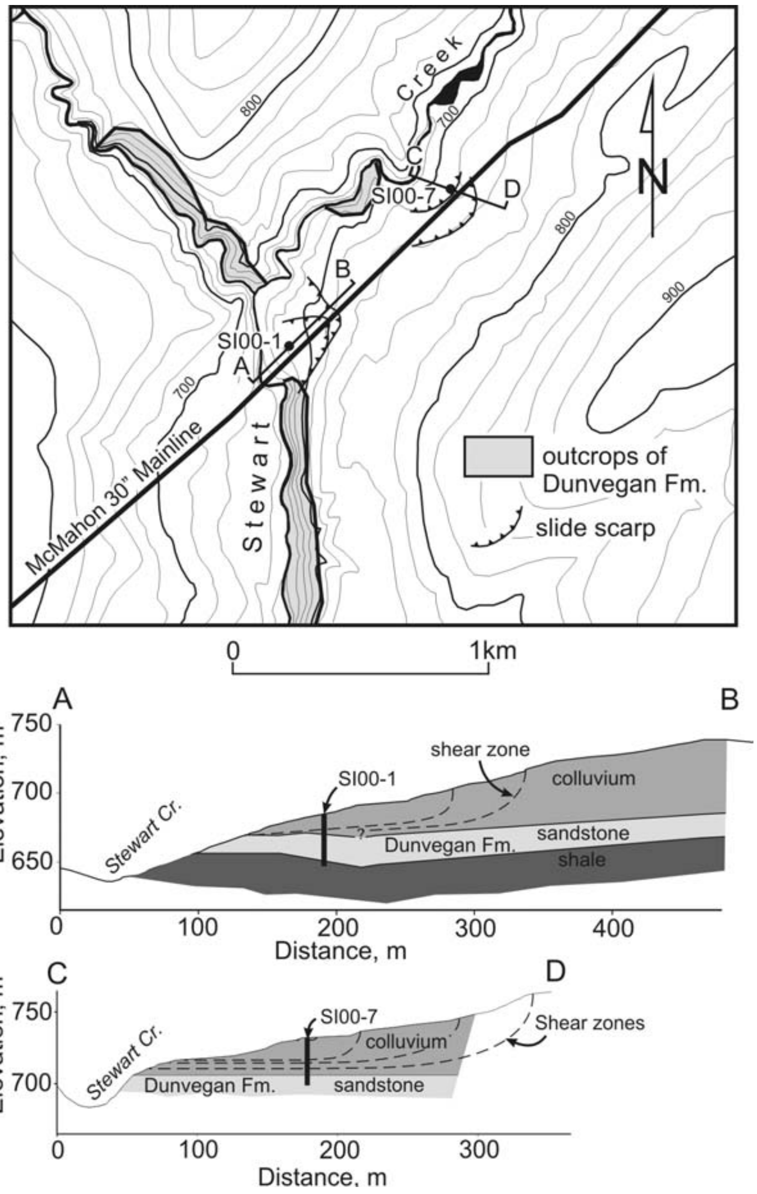

Figure 17. Stewart Creek pipeline crossing site. The cross-sections show the stratigraphy and locations of inclinometer casings SI00-1 and 7 along lines AB and CD shown on the map. The contours show elevation above mean sea level with a 20 m contour interval. For the location of the site, see Figure 2.

slides have been detected, both as translational movement of bedrock masses on the slope down to Stewart Creek and as shear distributed over about 12 m of the silt and clay cover. Two inclinometer casings were chosen for use in this study. One of the inclinometers is located on the translational slides (SI00-1, Figure 18) and the second in the distributed shear zone (SI00-7, Figure 18). This latter installation is considered to be a colluvium flow although the geology differs from the typical setting where the Dunvegan Formation is exposed above the feature.

Daniels Creek site

The 30" Fort Nelson gas pipeline was constructed in 1964 connecting the gas processing plant at Fort Nelson with Chetwynd. Inertial in-line surveys were undertaken in 1994, 1995 and 2002 revealing the downslope translation of a 450 m section of the pipeline where it parallels the headwaters of Daniels Creek (Czyz and McClarty, 2005; Figure 19). Between 1964 and 2002 this section was transported 4 m downhill with 1.5 m of this displacement occurring since 1995. Bending had taken place over a 40 m distance at each end of the displaced segment but with no wrinkling. A segment of the pipeline including the displaced part was excavated and replaced on the ground surface to reduce the traction in the event of further ground movement.

There is no surface evidence of ground movement at the pipeline right-of-way. Although the slope across which the affected pipeline segment runs shows no obvious features of a colluvium flow, the stratigraphic setting is the same as for colluvium flows regionally. The Dunvegan

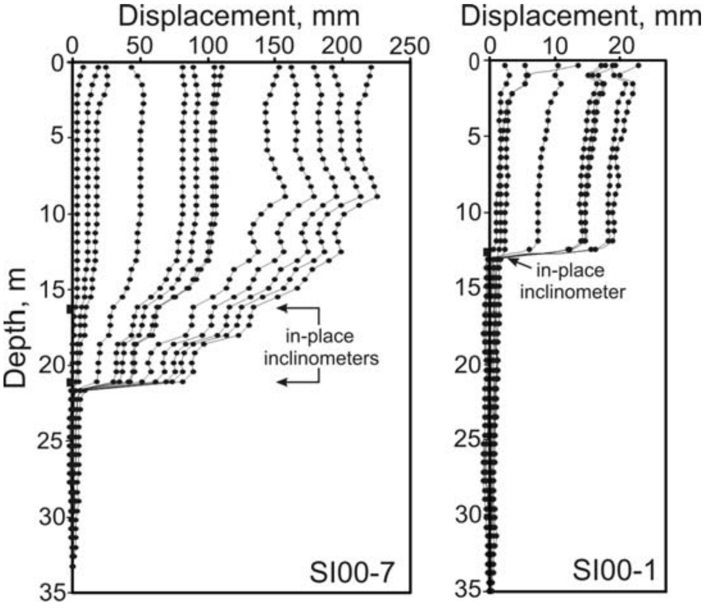

Figure 18. Manual readings for the inclinometer casings at the Stewart Creek site, taken between 2000 and 2003. The black bars on the depth axes show the location of the in-place inclinometers.

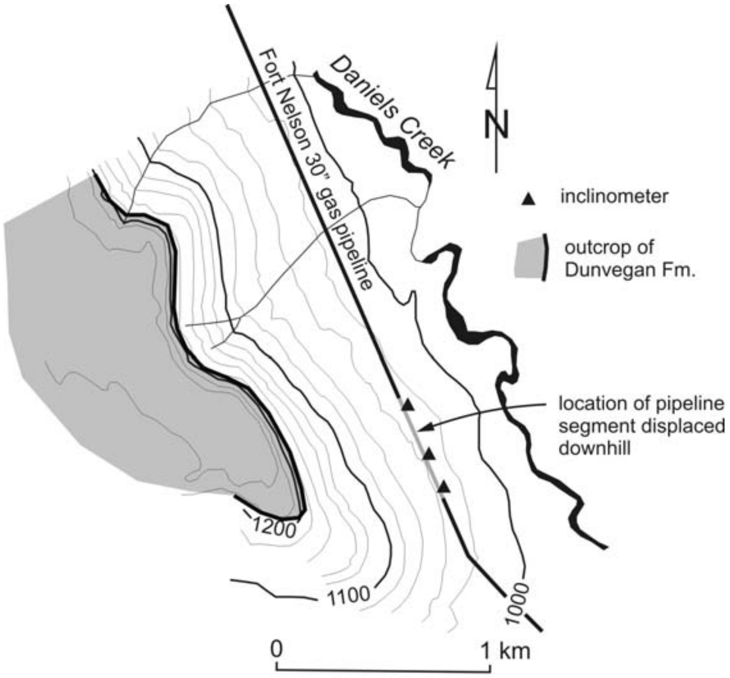

Figure 19. Daniels Creek pipeline instrumentation site. Contours show elevation above mean sea level with a 20 m contour interval. For the location of the site, see Figure 2.

Formation forms 10 to 20 m cliffs at the slope crest, about 250 m above Daniels Creek. No bedrock is exposed below the cliffs but rotational failures a few tens of meters across and uphill-facing scarps occur. Downslope of the right-of-way, outward movement of the slope has produced a steepening which in turn has induced slumping and tilting of trees. Ponds are found in depressions formed by the small rotational failures and groundwater seeps from the soil cut along the uphill side of the right-of-way. The right-of-way along the excavated segment exposes a silty diamict containing abundant sandstone clasts. Three inclinometers have been installed along the exposed pipeline segment. Only one of these shows movement since installation in 2003 on a shear zone at a depth of about 12 m. The shearing rate is slow at about 1 mm per year. Because no significant movement has been recorded by these inclinometers, the movement that has affected the pipeline is presumably occurring below the 50 m depth to which the inclinometer casings extend.

Radar interferometry and GPS

Trutch Mountain

This site comprises a west-facing colluvium flow on a segment of a north-south trending ridge that extends for 30 km parallel to the present Alaska Highway between Buckinghorse River and Trutch Creek (see Figure 2 for location). The site was chosen to help verify that colluvium slopes, in addition to the most well developed colluvium flows, exhibit downhill movement. The angle of the colluvium slope gradually increases with elevation, beginning at about 10° and increasing to approximately 30° at the top. The overall relief is about 300 m. Fine grained sandstones of the Sikanni Formation cap the slope and are intermittently exposed at the slope crest. The exposures show the sandstones grading downwards into interbedded silts and shales. Silts and shales of the Sikanni Formation presumably underlie most of the slope at depth, based on limited exposure in creek incisions and road cuts along the present Alaska Highway.

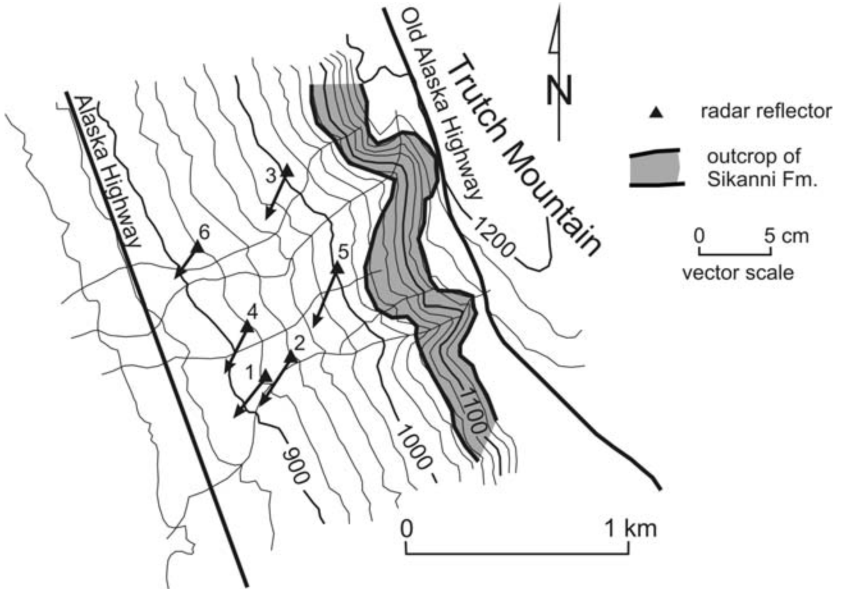

Figure 20. The location of the radar corner reflectors at the Trutch Mountain site. The arrows are vectors indicating the horizontal component of reflector movement between August 2007 and September 2008 based on GPS measurements. Contours show elevation above mean sea level with a 20 m contour interval. For the location of the site, see Figure 2.

Materials overlying bedrock consist of colluvium of differing composition, including cobbly silts, clayey silts, and weathered shale detritus. There is no information on the thickness of these materials other than the creek incisions suggesting that in places these materials are at least 10 m thick. Although the slope generally steepens upward, local steepenings having a lobate form are present on the central portion of the site. On the lower half of the slope seepage zones and a shallow piezometer indicate that the watertable is within 1 m of the ground surface.

Six radar corner reflectors have been installed on the central portion of the slope where slope angles range from 10 to 20°. The reflectors are rigidly anchored and were used as monuments for GPS positioning and re-surveying one year later. This re-survey serves to verify the assumed movement direction of the reflectors and gives an independent check on the accuracy of the interferometry. Figure 20 shows the location of the reflectors and the horizontal component of movement between the GPS surveys in August 2007 and September 2008. Movements of 3 to 4 cm took place over this one year interval.

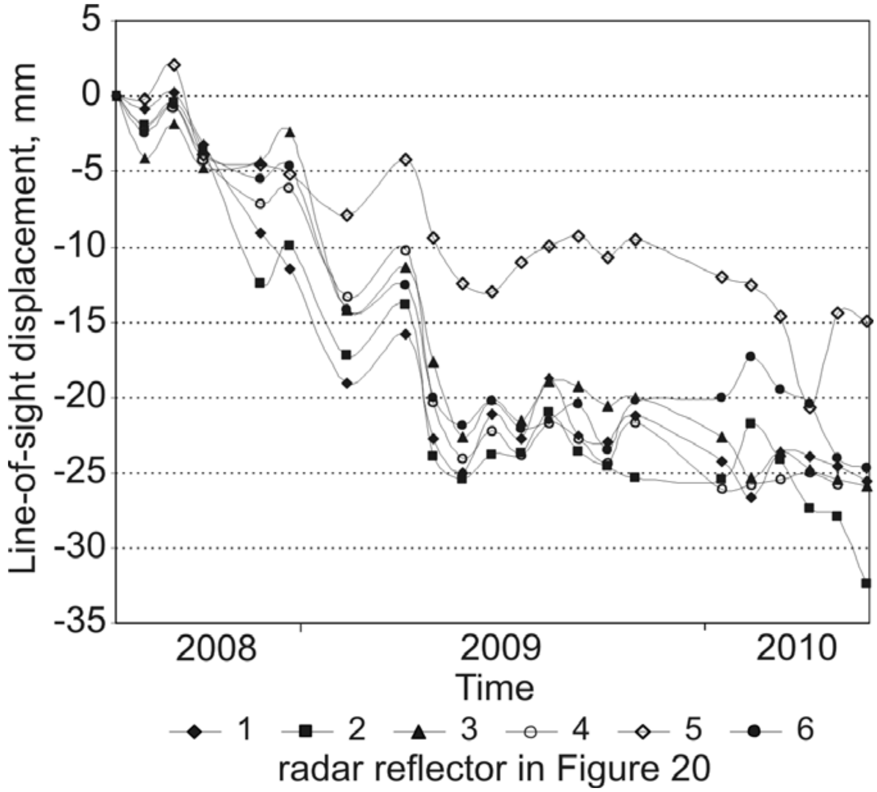

Figure 21. Movement of the Trutch Mountain radar reflectors in the direction that the reflectors are facing (approximately parallel to the slope direction) from August 2008 to May 2010.

Figure 21 shows the interferometry results for the same reflectors for September 2008 to May 2010. Movements are plotted as changes in the line-of-site distance from a reflector to the RADARSAT 2 satellite and show that all reflectors have moved about 2.5 cm during the recording interval. Because the line-of-site is inclined at 50° to the horizontal, the reflector has actually moved further if the line-of-site change has been caused by movement parallel to the slope direction (see Figure 14). Noting that the GPS re-survey indicates that the reflectors have moved in a direction approximating their pointing azimuth as well as approximately parallel to the slope direction, the line-of-site changes can be converted to true downslope movements by determining the downslope movement required to achieve the line-of-site changes. This conversion approximately doubles the movement to about 5 cm. Most of the movement takes place during the first year of observations, giving a rate similar to the previous year's GPS measurement.

Dendrochronology

Ground movement can be dated using the growth reaction of white spruce to disturbance by slope movement. After being rotated out of the vertical, this tree species will grow denser, darker wood on the downward side of the trunk in an attempt to straighten (Shroder, 1980). Curved trunks and an oblong trunk cross-section are exterior indications that the tree has grown reaction wood. The onset of reaction wood can be dated to the year of disturbance so that the method offers the best precision of any proxy measurement for dating movements.

We carried out two dendrochronology surveys. The first survey in 2004 assessed the periodicity of slope movements over the entire project area. Several rotational slides in colluvium derived from weathered shale and sandstone or slides in lacustrine deposits were sampled as well as three small colluvium flows. Three to nine trees were selected on each of nine features. Samples from individual slides consisted of no more than three groups of trees, each group located on a rotated block or steepening toe of a lobe (Figure 22). The second survey in 2006 characterized the periodicity of movement on colluvium flows. Two features bordering the Sikanni Chief River were visited for detailed sampling. Again, groups of trees on local flows or rotational failures within each colluvium flow were selected.

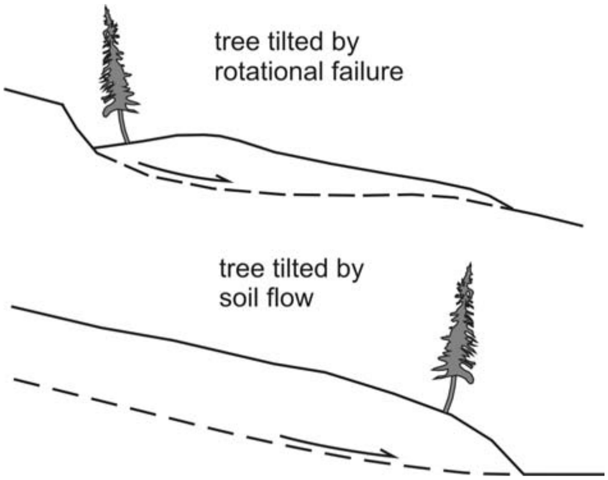

Figure 22. Ways in which a slope movement can disturb a tree.

Care was taken that disturbed trees were associated with clear evidence of ground movement, thus ensuring that trees are responding to ground movement with a rotational component of motion and not disturbance from other tilting factors such as undermining, wind, or the impact from another fallen tree. A slice approximately 2 cm thick was taken at the location on the trunk exhibiting the greatest curvature. One side of each slice was sanded enough to allow the finest growth rings to be counted. Each slice was digitally scanned at 600 dpi and the initial ring of reaction wood episodes marked on the digital image. Tilting dates are determined by counting inwards from the most recent growth ring to the initial reaction ring. Reaction wood typically grows for the remainder of the tree's life or until the stem at the sampling location returns to vertical. Often a tree exhibits two or more intervals of reaction wood growth suggesting multiple tiltings. Where more than one reaction wood episode is present, groupings of rings from different episodes tend to wrap around the tree circumference, distinctly beyond the previous group.

2004 survey

Reaction wood events for each tree sampled are plotted in Figure 23, grouped according to rotational landslide or colluvium flow. The most striking feature of this compilation is the event in 1977

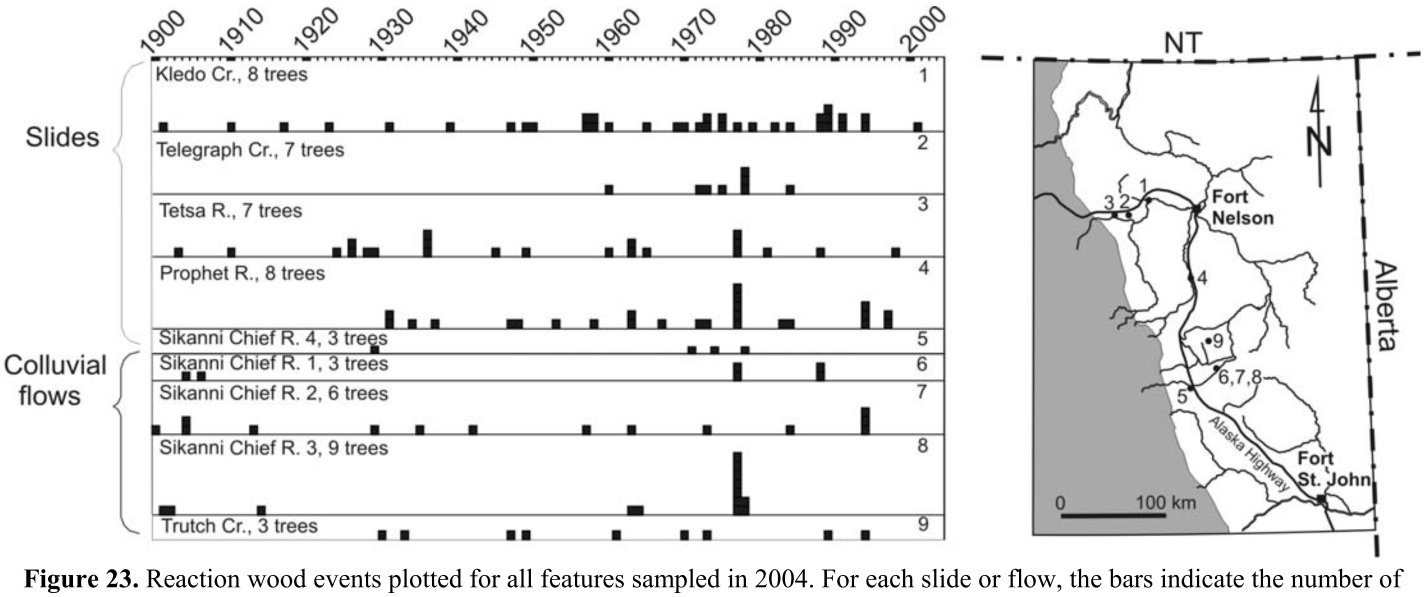

Figure 23. Reaction wood events plotted for all features sampled in 2004. For each slide or flow, the bars indicate the number of trees showing reaction wood initiation for each year. The number of trees sampled is listed by the name of each site and is represented by the height of each row. The numbers on the map correspond to the site numbers shown at the right end of each row.

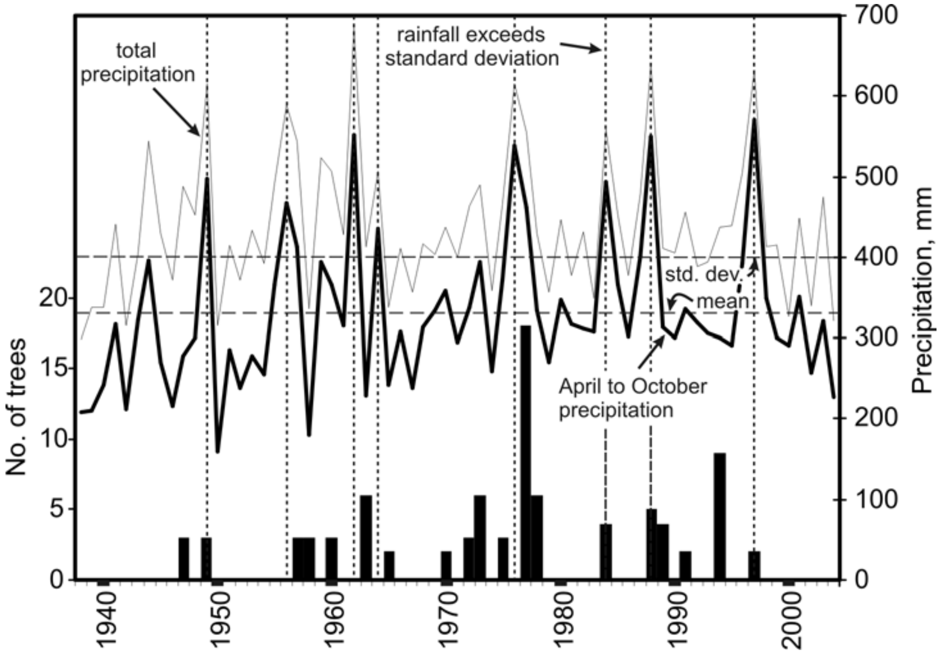

Figure 24. A comparison of precipitation recorded at Fort Nelson and tree reaction for the 2004 dendrochronology survey. The heavy line shows the precipitation occurring mainly as rain and the bars show the total number of trees showing reaction wood initiation for each year. The dashed lines show the mean rainfall and upper standard deviation for the period of record.

which is prominent in three of the slides and two of the colluvium flows. This event coincides with a year having 27% above the average precipitation for the period of record at Fort Nelson. The previous year had 40% above average as well as the highest monthly rainfall ever recorded (198 mm). Although Pink Mountain (see Figure 2 for location) is more removed from the landslide study sites, 1977 is the wettest year for the period of record there and includes the second highest monthly rainfall for that period of record. These coincidences suggest that these wet conditions triggered rotational movements in three out of the five rotational slides studied. If tree reactions are grouped for all study sites and matched with yearly precipitation, other less prominent events appear, but only two of these events coincide with well-above average yearly precipitation (Figure 24).

Although excessive rainfalls are not closely matched by all the tree reactions, the coincidence is close enough to suggest that the long-term precipitation pattern gives an indication of the frequency of rotational movements. The 1977 event coincides with two consecutive years (1976, 1977) with above-average precipitation at Fort Nelson, making this precipitation peak in Figure 24 the most prominent for the period of record. This coincidence suggests that two consecutive years with excessive precipitation constitutes a threshold for slope movement. Although the overall correlation is too weak to support this notion, an average recurrence of above-average (25% or more) precipitation every 8 years (standard deviation = 3 years) suggests a maximum frequency with which rotational movements will take place. Colluvium flows show little evidence of episodic movement with the exception of Sikanni Chief R. 3 (Figure 23). This feature clearly exhibits an event in 1977. The entire colluvium flow appears to have moved laterally, resulting in much of the forest cover being toppled or rotated. A pond close to the top of the flow, visible on 1948 air photography, is missing on 1999 coverage. This colluvium flow may in fact be a rotational block, especially as it lacks the prominent escarpment that usually borders the top of a colluvium flow. A displaced seismic line visible on the 1999 airphoto coverage indicates several tens of meters of displacement that is probably part of the 1977 event.

2006 survey

The colluvium flows studied in 2004 are small and not subject to the vigorous toe erosion affecting the large features bordering Sikanni Chief and Buckinghorse rivers. To more thoroughly document the behaviour of colluvium flows, two features along the Sikanni Chief River were studied in detail (Figure 25). Colluvium flows typically exhibit a terrace, often containing ponds, immediately below the adjacent sandstone escarpment. On the two features examined, the slope from the terrace down to river level is broken by local rotational failures and flows. These subsidiary features are presumed to form as parts of the colluvium flow surface oversteepen in the course of movement. Their

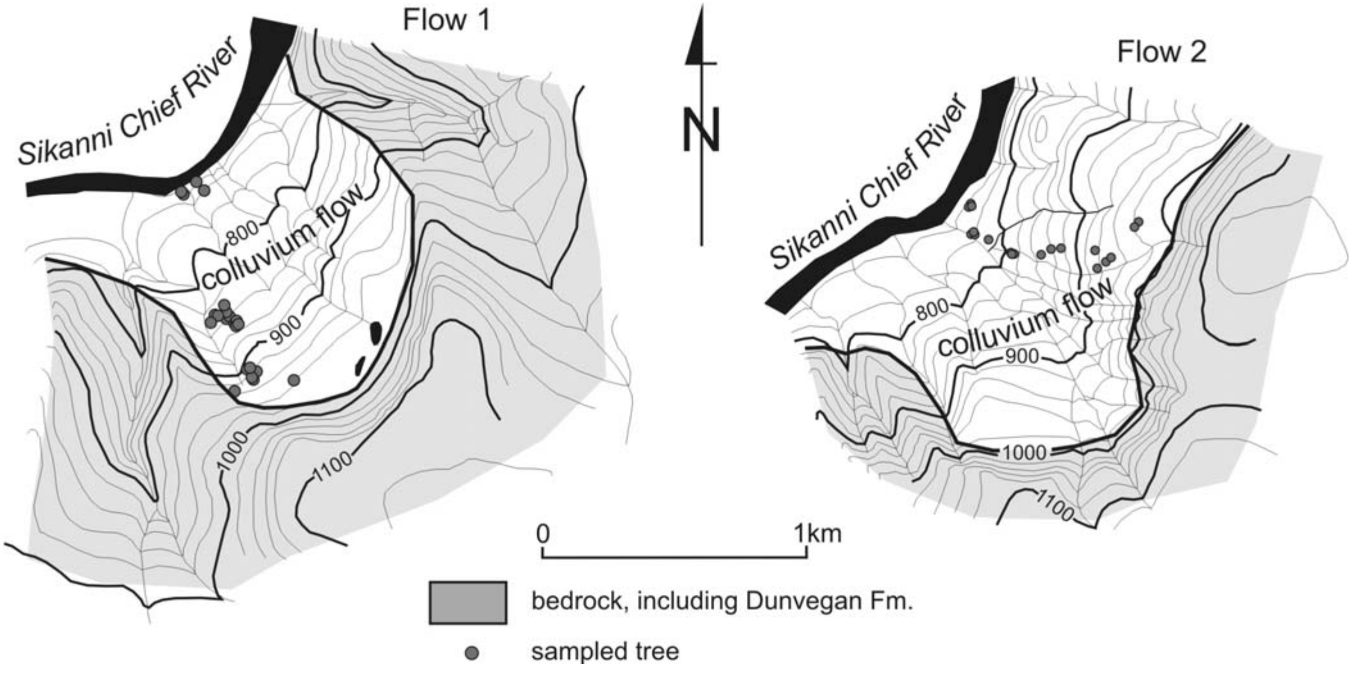

Figure 25. The colluvial flows sampled for the 2006 dendrochronology study. The locations of the flows are shown in Figure 2

formation can be used as an indication of activity for the entire colluvium flow. Therefore, tree sampling focussed on dating the movements of these subsidiary features.

Reaction wood initiation for all trees on each of the two selected colluvium flows is shown in Figure 26. The most apparent attribute of these plots is the general increase in tree reaction over time. Although this trend might be expected as more trees become available, the trend is most apparent after 1900 when 75% or more of the trees sampled are alive. Reaction wood initiation is also composed of several peaks in activity associated with excessive rainfall. Because only a small number of tree groups were sampled on each of the two flows, bias toward a particular event may have resulted. Tree reaction in 1997 forms the most prominent peak. If this event is removed, the general increase in reaction becomes less apparent but the recurrence of reaction wood episodes remains. These recurrences indicate that local slope movement has taken place somewhere on either of the two sites eight times over an interval of approximately 70 years (Figure 26). The location of slope movements on each flow has been plotted on cross-sections in Figure 27. The dates for the primary tree reaction at each local movement site are also shown in Figure 27. This representation of movement data demonstrates that, because local movement features are distributed across each flow, local ground movement is almost certain somewhere on each flow approximately every 10 years.

The results from the 2004 and 2006 surveys support the role of rainfall as a trigger for slope movements, based on the correlation of prominent reaction wood events with excessively wet years (typically having excessively wet months). All reaction wood episodes do not correlate with excessive

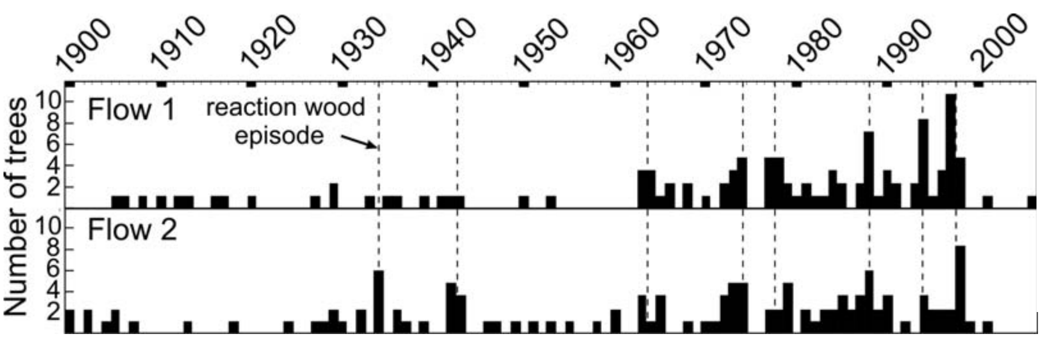

Figure 26. Reaction wood initiation for the two colluvium flows examined in 2006. Individual tree locations on each flow are shown in Figure 25.

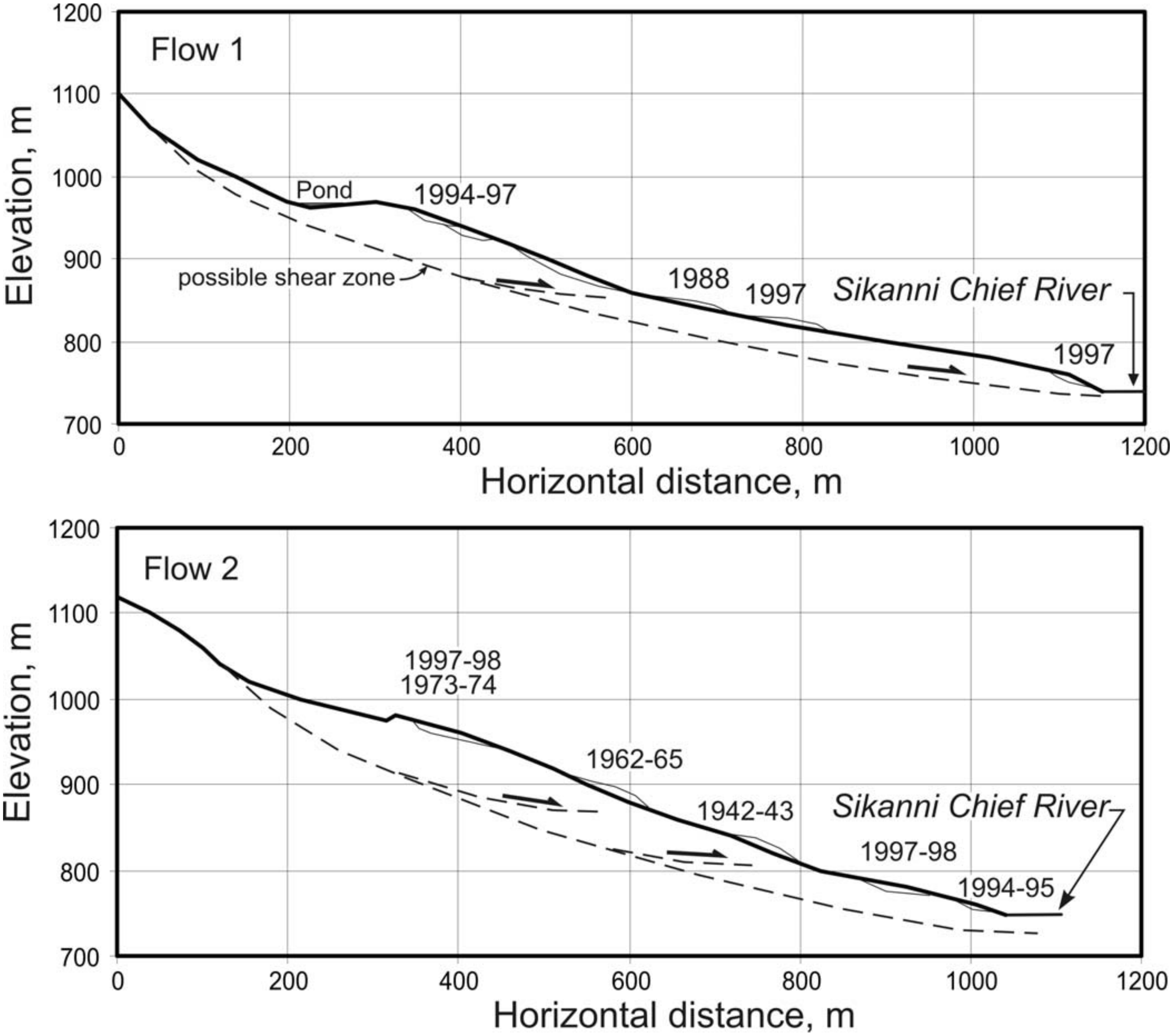

Figure 27. Cross-sections of colluvial flows 1 and 2 in the vicinity of the sampled trees. The dates shown beside individual small slope movement features are the dates for the initiation of the most prominent reaction wood in the trees sampled on each feature.

moisture, possibly because movement within a flow is continuous, triggering local movements irrespective of excessive rainfalls. Although a rainfall threshold for slope movement cannot be reliably identified, the documented association between rain and tree reaction and records of excessive rain suggest a minimum slope movement recurrence of about 10 years.

THE MECHANICS OF COLLUVIUM FLOWS

All of the measurements of movement and of event frequency confirm that colluvium flows are continuously in motion with variable velocity. The features are termed flows because they are being continuously supplied by erosional debris at their heads and transporting this material to the toe in a glacier-like manner. A rock glacier provides a useful analogy. The fines content of the colluvium flow plays the role of rock glacier ice and the incorporated sandstone blocks are equivalent to rock glacier blocks. In both cases, block to block friction acts to resist movement and requires a threshold shear stress before movement can begin. Accelerating the flow requires a shear stress in excess of that required to overcome frictional resistance. The viscous component of resistance, determined by the flow matrix, then determines the velocity that the excess shear stress will produce. Canyon-type colluvium flows are typically thicker and move more rapidly than upland-type flows because of the increased shear stress provided by a more rapid supply of erosional debris.

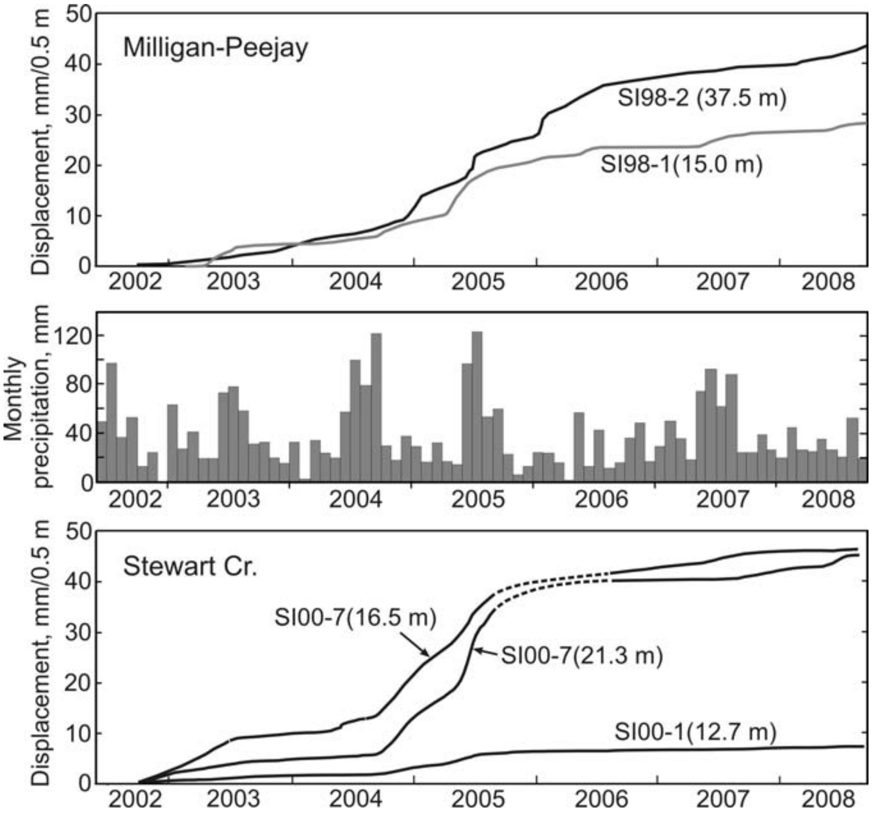

Figure 28. Displacement records for in-place inclinometers at the Milligan-Peejay and Stewart Creek sites. Numbers in brackets are the depths of the in-place inclinometers. The center graph shows the monthly precipitation during the period of record for the inclinometers.

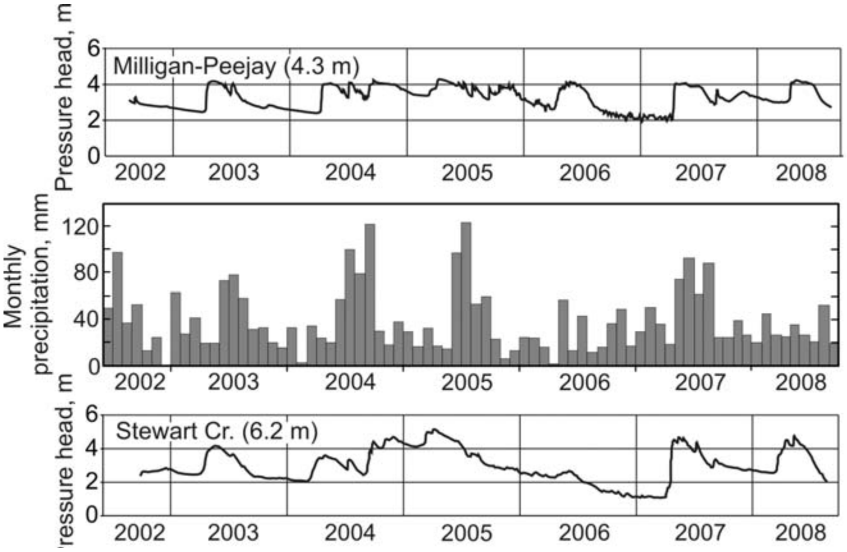

Figure 29. Continuous records for the shallowest piezometer at the Milligan-Peejay and Stewart Creek sites (screen depth shown in brackets). The central bar graph shows monthly precipitation measured at the Fort St. John airport.

In the model outlined above, movement may or may not take place, depending on the amount of frictional resistance. Pore water pressure will modify the frictional resistance and is assumed to be the primary variable controlling colluvium flow velocity. Increases in velocity associated with rainfall confirm the importance of pore pressure, especially when the correlation between piezometer records, movement records and rainfall for the Milligan-Peejay and Stewart Creek sites is considered (Figure 28, 29). To assess the sensitivity of movement rate to pore pressure, we adapt a mechanical model of rock glacier behaviour to include pore pressure. We also employ groundwater flow simulation to estimate the possible variability of pore pressure under the rainfall regime of the study region.

Colluvium flow model

The velocity, $V_{x(z)}$, of an infinite slope composed of ice containing blocks in frictional contact has been modeled by Ladanyi (2006). The equation derived is essentially the one-dimensional Glen flow law integrated over the depth of the infinite slope (Eq. 1). The Coulomb friction term ($\sigma \tan\phi$)

$$V_{x(z)} = \frac{\gamma}{n+1}\left[\frac{g\rho\sin\beta}{\tau+(\sigma-u)\tan\phi}\right]^{n}(D^{n+1}-z^{n+1})$$ Eq. 1

where σ is the normal stress and ϕ is the angle of internal friction, is added to the shear stress (τ) that produces the reference shear strain rate ($\dot{\gamma}$) of the interstitial material. The Coulomb term accounts for the frictional contact of blocks. The exponential term n from the Glen flow law, if greater than 1, produces a non-linear dependence of velocity on shear stress, a characteristic of ice. This rheology is also referred to as pseudoplastic, whereby increasing shear stress promotes increasingly plastic behaviour (β, D, and z are defined in Figure 30, g and ρ are the gravitational acceleration and material density, respectively).

The in-place inclinometer measurements for the Milligan-Peejay and Stewart Creek sites show that movement rates accelerate when the pore pressures in adjacent piezometers rise (Figure 28 and 29). Ladanyi's equation for an ice-rock block mixture is adapted for a colluvium flow by including pore pressure (u) in the Coulomb friction term. The value for n is typically 3 or 4 in the case of ice. Ice responds to increasing shear stress with increased mobilization of dislocations in the ice crystal structure. Adsorbed water on clay particles assumed to be included in the colluvium flow matrix offers a far more restricted volume for dislocation-mediated deformation so the value for n will be less. Purely viscous behaviour is described when n = 1 while pseudoplastic behaviour begins when n>1. A shear stress that overcomes the block-to-block frictional component of the colluvium flow strength may produce a strain rate increase described by n >1 but probably <3. However, the low value of ϕ probably exhibited by the flow matrix material will tend to raise n toward 3.

Eq. 1 describes the motion throughout the entire thickness for a colluvium flow. However, inclinometer records show that shearing is typically concentrated in narrow zones. Therefore the equation is restricted to describing the total displacement across the shear zone. The rest of the feature above is

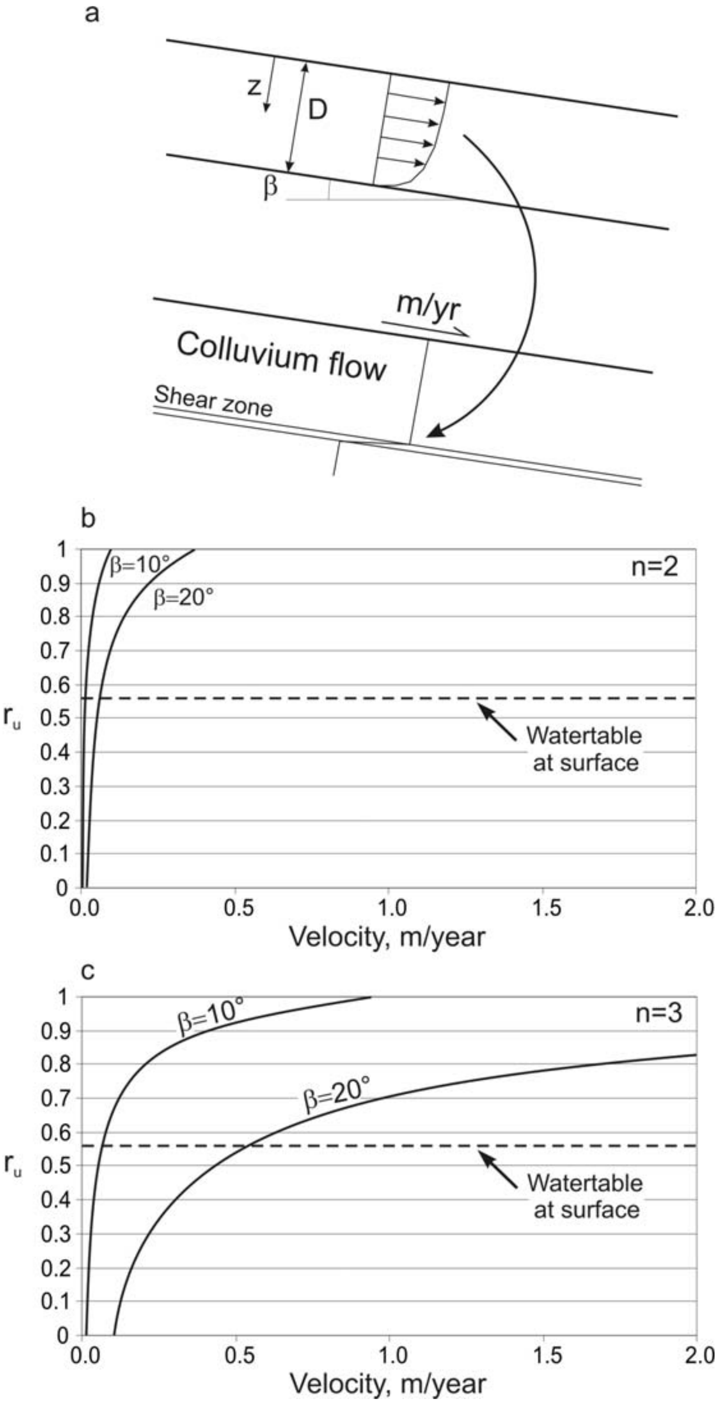

Figure 30. a) Deformation in the shear zone which is described by Eq. 1 and the location of the shear zone in a colluvium flow. b) and c) Plots of Eq. 1 showing the velocities at the top of the colluvium flow depending on pore water pressure (in terms of r_u), the slope of the flow (β) and the value of n.

carried along rigidly. Two in-place inclinometers attached in tandem and placed at the shear zone locations in each of two inclinometer boreholes on the Milligan-Peejay colluvium flow provide displacement rates for determining a reference shear strain rate for the shear zone. The average shear strain rate determined from the in-place inclinometer record can be used as the shear strain rate required in the equation and then the sensitivity of movement rate to other factors, in particular pore pressure, can be studied.

The in-place inclinometers indicate an average of about 1 cm per year of movement of the upper end of the inclinometer instrument relative to the lower end. The instrument is 0.50 m long, giving a shear strain rate of 0.02/yr. The shear stress that produces this strain is the shear stress at the shear zone, determined by the slope angle and depth of the shear zone. The angle of internal friction (ϕ) for sandstone fragments and blocks in contact that are in the colluvium flow is set at 30°. In Figure 30 the velocity at the top of the shear zone and hence the top of the colluvium flow is analyzed with respect to pore pressure (pore pressure ratio, r_u) at the shear zone and for values of n =2 and 3. The analysis shows that velocity is sensitive to pore pressure ratio, particularly above $r_u = 0.5$ (watertable within 2 m of the ground surface). Velocity is also very sensitive to the value of n and especially so at steeper slope angles. These results indicate that the colluvium flow velocity will respond to pore pressure increases during abnormally wet times and that this effect will be pronounced for steeper features.

Field observations show that colluvium flows exhibit a range of velocities similar to the range shown in Figure 28. The Milligan-Peejay feature provides the reference mechanical behaviour for calibrating Eq.1, with the measured movement averaging about 2 cm/yr for this 10° slope. Colluvium flows with slopes of 20° and river removal of support at the toe move as rapidly as 2 m/yr. The broad agreement of these velocities with the velocities predicted by Eq. 1 suggests that colluvium flows do exhibit pseudoplastic behaviour. The correspondence is too general to be used for anticipating colluvium flow activity but the sensitivity of velocity to pore pressure supports the anticipation of movement based on the likelihood of excessive rainfall.

Pore pressure variability

Piezometer nests at the Milligan-Peejay and Stewart Creek sites provide an indication of pore pressure variability in colluvium flows. Each nest consists of three Casagrande standpipes. Within each nest, at least one piezometer screen is located at the depth of measured shear. The piezometer screens are located at the depths of the instrumentation used to measure the casing deformation at shear zones. This positioning presumes that the piezometer readings reflect pore pressures within the shear zones. Of the total of 12 piezometer records, only four show pressure changes that clearly correlate with rainfall records (two piezometer records shown in Figure 29). These four piezometers have the shallowest screens, all being within 10 m of the ground surface. The other piezometers are either dry, show very gradual changes or show changes that bear no obvious relationship to rainfall. Dry piezometers are located in settings favouring either deep watertables (i.e. close to an escarpment) or perched watertables (Figure 31). Ground electrical conductivity measurements along the cross-section at the Milligan-Peejay site (Figure 31) record localized zones of high conductivity interpreted as seepage from perched watertables. This watertable pattern is consistent with the interbedding of sandstone and siltstone that characterize the stratigraphy of the escarpment-forming rocks at the inclinometer sites. Slowly changing piezometers or piezometers showing changes independent of rainfall may be measuring responses to rainfall that have been muted or delayed by intervening aquitards.

The response of piezometers that appear to be sensitive to rainfall and the response of those that show only gradual change can be simulated with transient groundwater flow modeling. Modeling is performed with the GEO-SLOPE software product SEEP/W, version 5. This is a finite element formulation that includes unsaturated flow. The simulated pore pressure changes provide an estimate of the rainfall amount that is required to produce a significant increase in groundwater pressure. A

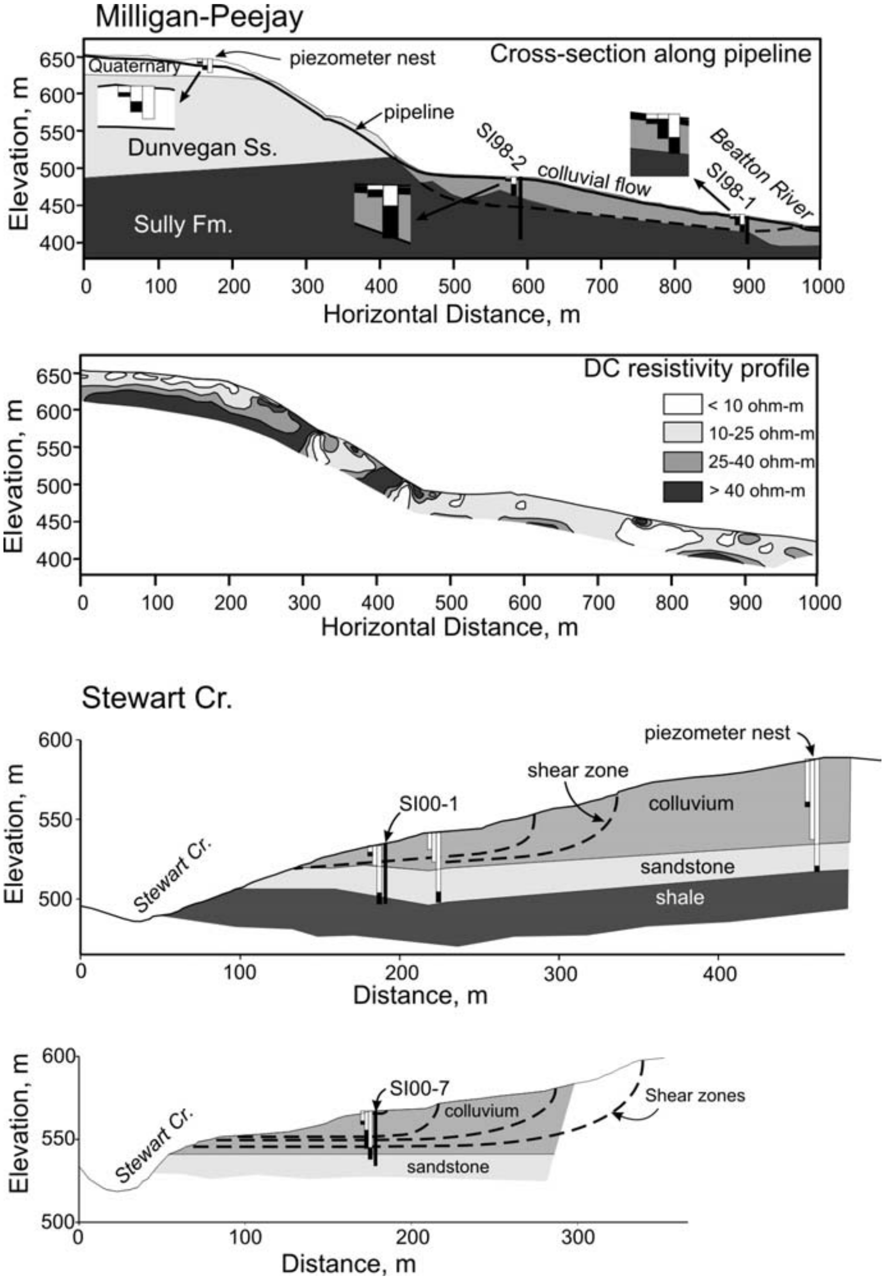

Figure 31. The crossections of the Milligan-Peejay and Stewart Cr. sites showing the location of and general water level in the piezometer nests (black fill). The DC resistivity profile shows the electrical resistivity along the Milligan-Peejay crossection to a depth of about 30 m. Low resistivity areas are interpreted to be seepage zones.

cross-section of a colluvium flow, adjacent escarpment, and upland taken from the Daniels Creek site is used for groundwater flow modeling (Figure 33, 34).

The cross-section typifies the colluvium flow setting. The colluvium flow overlies a simplified stratigraphy of sandstone overlying shale, overlaping the lowest level of the sandstone and therefore providing a potential for elevated pressure within the flow. The modeling explores the potential for excess pore pressures in the flow due to confined seepage in the sandstone. The modeling also examines the pore pressure variability within the colluvium flow due to infiltration directly into to flow. Pore pressure increases due to either mechanism will accelerate the movement of a colluvium flow.

To carry out the modeling, hydraulic conductivities and the volumetric water content under unsaturated conditions were assigned for each statigraphic unit from a selection of hydraulically characterized geologic materials supplied with the SEEP/W software. The saturated hydraulic conductivities assigned to the model materials are as follows: sandstone, $1*10^{-4}$ m/sec; shale, $6*10^{-8}$ m/sec; colluvium flow, $1*10^{-6}$ m/sec. The transient analysis was initiated using the hydraulic head distribution produced by a steady yearly infiltration of 150 mm. This infiltration is approximately one quarter of the 1971-2000 climate normal mean precipitation for Fort Nelson, the closest Environment Canada climate station to the Daniels Creek site. This amount of infiltration produces a watertable close to the surface over the lower part of the Daniels Creek valley, matching the position observed in the field. To simulate a wet spell, infiltration is imposed over the upland surface at a higher rate. For the three climate stations in the region, the maximum monthly rainfall for the period of each record is 183, 219, and 199 mm respectively for Fort St. John, Pink Mountain and Fort Nelson. These amounts actually occur over time intervals of about 3 days, giving a mean daily rainfall of approximately 70 mm. This daily amount is applied over 3 days and one-tenth of this amount (7 mm) over 10 days. No pressure increase is produced anywhere at or below the watertable by either of these events. Considering the approximate 100 m thickness of unsaturated sandstone above the steady state watertable, infiltration evenly distributed over the upland surface would only begin to saturate this thickness. It is unlikely, therefore, that uniform infiltration on an upland surface is responsible for pore pressure changes in colluvium flows.

Figure 32. Ponding on the plateau surface at the Daniels Creek site.

As an alternative to an even distribution, infiltration may be concentrated at locations favourable for water entry. Although low permeability Quaternary sediments are widespread on the plateaus bordering sandstone escarpments, the bedrock can be exposed, as it is at escarpments. Surface runoff from large areas of upland may pond on bedrock depressions within upland surfaces (Figure 32) or this water may reach escarpments and infiltrate there. Pressure head responses were determined for infiltration over a portion of an upland surface.

To simulate ponding, a constant total hydraulic head is applied to one third of the upland surface of the model cross-section. The head is set to be the elevation of the plateau surface and is applied for 3 days and 10 days (Figure 33). The 3-day ponding produces a watertable response directly beneath the ponding location about 2.5 months after the ponding initiation. The watertable response is much more rapid for the 10-day ponding, beginning by the end of the ponding interval. However, within the colluvium flow, pressure responses are slow, and completely attenuated by about 100 m downhill from the end of the sandstone unit.

Infiltration directly into the colluvium flow is the only way to achieve pressure changes that correspond to the magnitude and timing of pressure changes observed with the piezometers. Infiltrations of 70 mm per day for 3 days and 7 mm for 10 days were applied to the colluvium flow with the same initial watertable position used for examining infiltration from the plateau. These simulations produce immediate responses with increases of 0.2 to 1.0 m in pressure head, depending on the infiltration rate and the duration (Figure 34). Pressures return to the pre-infiltration level about one month after the end of the infiltrations.

DISCUSSION

The piezometer and inclinometer measurements made on colluvium flows in northeastern British Columbia verify that movement of the flows is either initiated or accelerated by pressure head increases resulting from rainfall infiltration. However, even if the relationship between pressure and movement were accurately known, an accurately predicted rainfall would also be necessary to forecast slope movement. The correlation between tree reaction wood events and excessively wet years does give an indication of the rainfall amount that is necessary to cause significant movement. Therefore, based on the statistical recurrence of excessive rainfalls, a likelihood of significant movement can be stated. A significant movement is one large enough to initiate reaction wood growth in disturbed trees. Such a movement is probably larger than the mean annual movement for a particular colluvium flow. For the

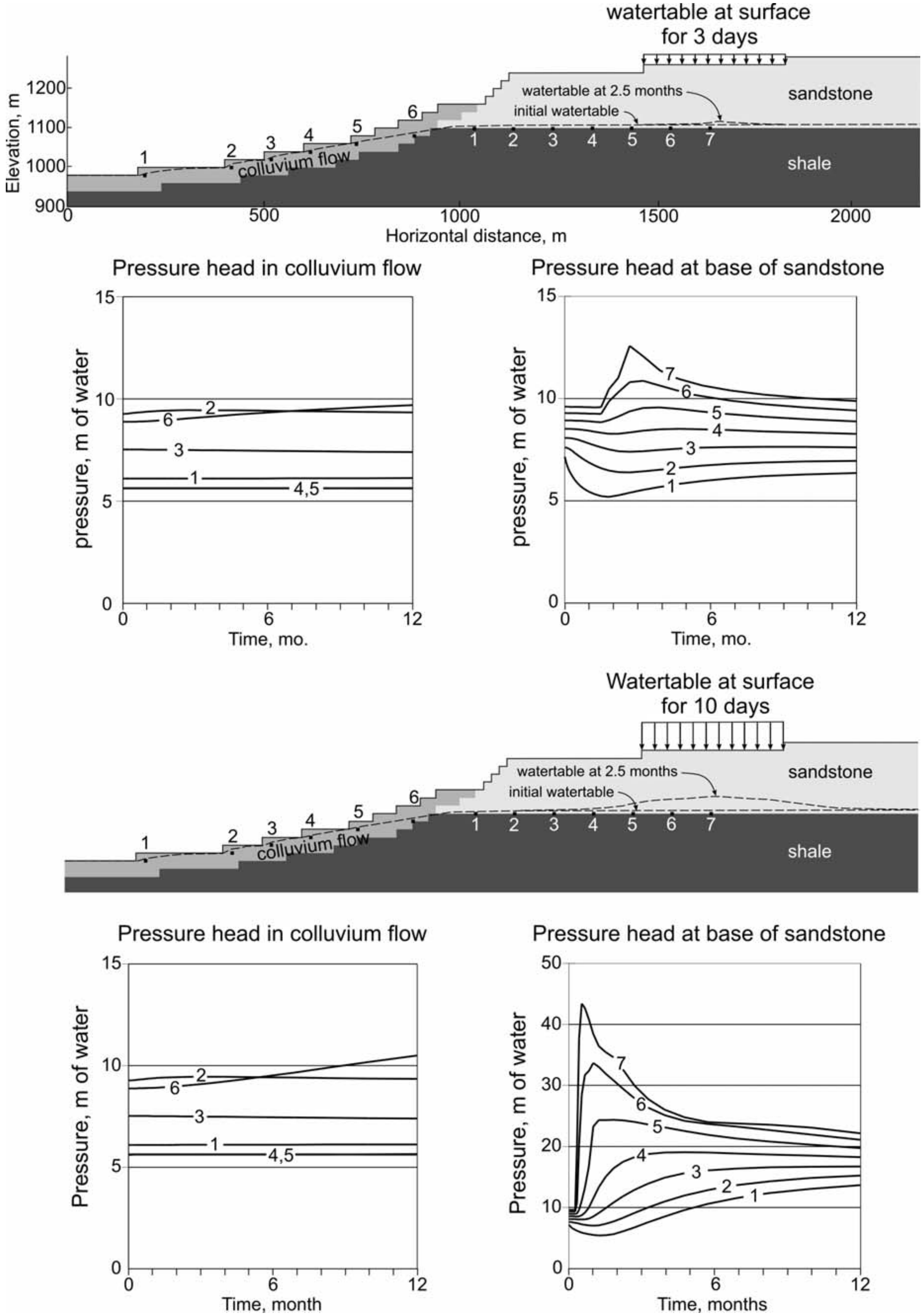

Figure 33. Groundwater modeling results for the Daniels Cr. site. The graphs show pressure head responses for 1 year after the beginning of 3 and 10 day pondings on the upland surface. The number labels on the graph lines refer to the numbered nodes on the cross-section.

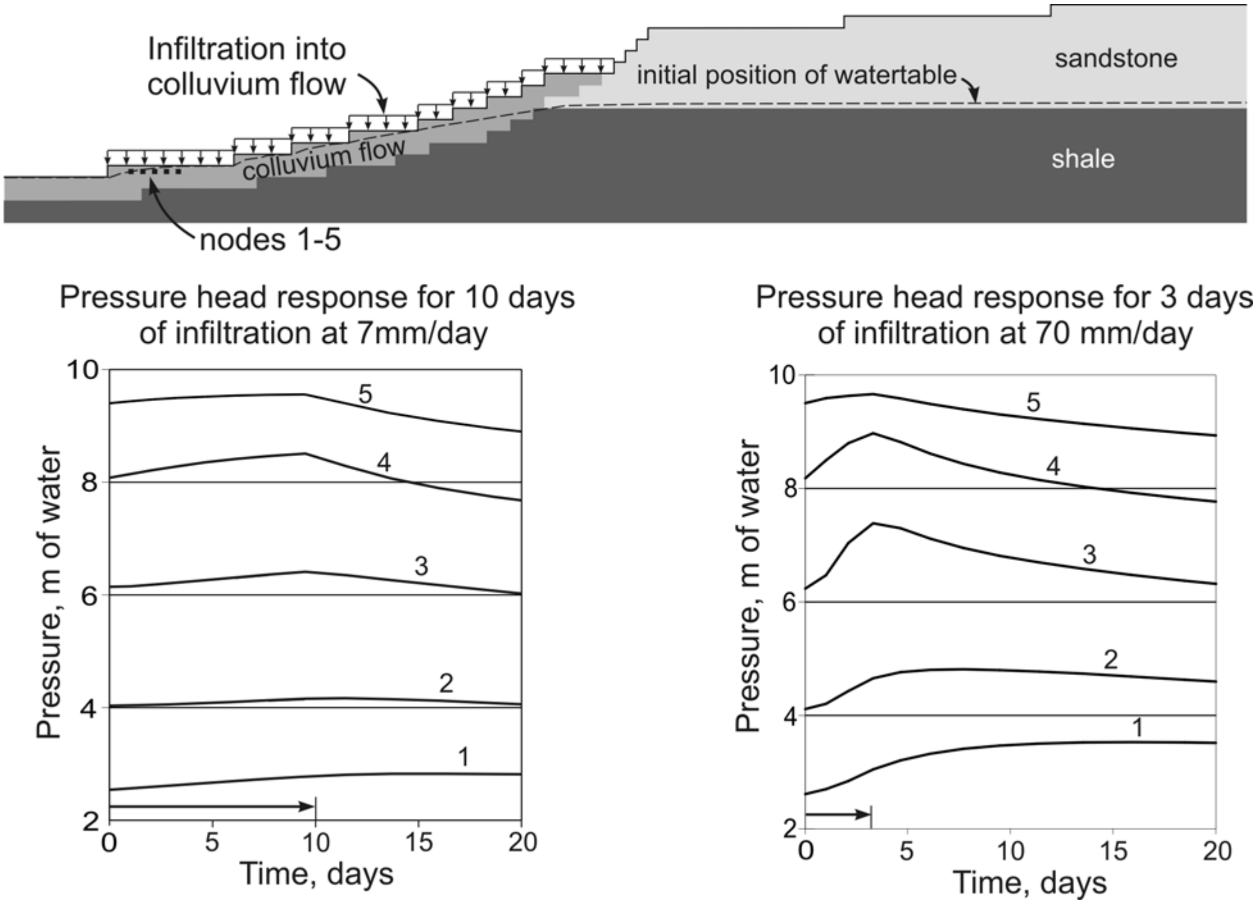

Figure 34. Groundwater modeling results for the Daniels Cr. site. The graphs show pressure head responses for 20 days after the beginning of 10 and 3 day infiltrations (arrows at bottom of graphs) of light and heavy rainfalls on the colluvium flow surface. The number labels on the graph lines refer to the numbered nodes on the cross-section.

rapidly moving colluvium flows along the Buckinghorse and Sikanni Chief rivers, a reaction wood episode likely exceeds the 2 m/yr average annual movement indicated by air photo comparisons. Colluvium flows that are not undergoing vigorous toe erosion move much more slowly. The instrumental observations from the Milligan-Peejay, Stewart Creek and Daniels Creek sites and the radar reflectors on Trutch Mountain all show annual movement of a few centimetres. The Milligan-Peejay and Stewart Creek inclinometer records extend for 6 years (2002-2008), long enough to give an indication of the variability in movement rate and the relationship to pore pressure and the Fort St. John rainfall. The highest inclinometer movement for both Milligan-Peejay and Strewart Creek, recorded in 2005, corresponds with the highest annual precipitation and pore pressure during this 6 year interval. The 2005 precipitation amount is excessive and it is tentatively concluded that similar wet years will produce similar movement. Movement is probably continuous but with pronounced accelerations at the 8 to 10 year average recurrence interval for excessive precipitation indicated by the Fort St. John and Fort Nelson climate records.

The modeling of the pressure head response to infiltration is difficult to assess for accuracy. Assumptions are necessary for the hydraulic properties of the geologic materials and infiltration amounts are specified rather than measured. However, confidence in the results is given by the realistic position of the water table close to the ground surface on the lower part of the colluvium flow. All three instrumented sites exhibit this characteristic. The modeling results verify that a rainfall similar to the excessive events in the climate records is necessary to cause the pressure change that the piezometer measurements indicate is associated with a movement acceleration.

The measurements of colluvium movement made in this study suggest that the most rapidly moving flows occur where the slope equilibrium is continually disturbed by toe erosion. These slopes tend to be planar or convex upward in profile with slopes greater than 10°. This geometry suggests that debris supply is great enough to overcome any tendency for stabilization at the toe of the colluvium flow. Colluvium flows that are not subject to toe erosion tend to have a concave upward profile because the debris is not being actively removed and has had the time to move onto the low angle flanking slopes, typically inclined at 10° or less.

The two kinds of slope, concave upward and convex upward, suggest end-members for classifying colluvium flows according to anticipated movement rate. Colluvium flows for which instrumental measurements are available all fall into an intermediate category where the features are either concave upward with a minimum slope >10° or are planar with a slope of 10° or less. Measured movement rates fall between 1-10 cm/yr. For concave slopes diminishing to 10° or less, the anticipated movement rate is set at <1 cm/yr. For planar or convex slopes >10°, it follows that the anticipated movement rate is >10 cm/yr. Because of the difficulty of digitally describing the curvature, the colluvium flow unit delineated on the terrain feature maps accompanying this report has been isolated on a separate set of maps showing slope, and subdivided as follows: less then 10°, 10-20°, and greater than 20° (see Slope Maps). The curvature of the slope can be assessed visually by noting if the slope of a particular colluvium flow steepens or shallows downhill. Slopes greater than 20° are not associated with a further increased motion but are shown to help identify the curvature of a colluvium flow. Thus colluvium flows can be assigned a movement rate (<1cm/yr, 1-10 cm/yr, and >10 cm/yr) based on the minimum slope of the feature and the overall curvature. Significant accelerations can be anticipated for excessively wet years. For pipeline route planning, the maps will be useful for identifying locations to avoid (i.e. planar or convex slopes > 10°). For the purposes of pipeline route planning and maintenance, the movement rate categories can be interpreted in terms of the qualitative categories introduced under the Scope section: assess every several years, assess every few years, and avoid.

ACKNOWLEDGEMENTS

Natural Resources Canada through the Program on Energy Research and Development (PERD) provided the funds for this research. The authors thank Edward McClarty of Spectra Energy for his support of this research through data sharing and the logistics for the installation of piezometers and in-place inclinometers. Ibrahim Konuk of the Geological Survey of Canada is thanked for his introduction of the authors to pipeline operators, discussions and sharing his incisive knowledge of soil mechanics. The radar interferometry reported is a cooperative effort with the B.C. Ministry of Energy, Mines and Petroleum Resources (Travis Ferbey) and the Canada Center for Remote Sensing (Vern Singhroy, Robert Hawkins, Kevin Murnaghan, Valetin Poncos, François Charbonneau). Réjean Couture is thanked for his clarifications offered as critical reviewer and also for his help with the selection of terminology.

Table 1. Radiocarbon sample locations and dates on landslides in the vicinity of Fort St. John.

GSC Lab. No.	Latitude (N)	Longitude (W)	Description of location	Radiocarbon date
GSC-6657	56°06'	120°39'	Basal organic sediment from pond in landslide on the south side of the Peace River at the Alaska Highway crossing.	400 ± 80 years
GSC-6691	"	"	As above	330 ± 60
GSC-6788	56°12'	121°08'	Basal organic sediment from pond in landslide on the south side of Moberly River	modern
GSC-6790	56°18'	120°48'	Basal organic sediment from pond in landslide on south side of St. John Cr.	270 ± 60
GSC-6793	56°18'	120°48'	Basal organic sediment from pond in landslide on south side of St. John Cr., immediately below GSC-6790	170 ± 60
GSC-6795	56°18'	120°44'	Basal organic sediment from pond in colluvial flow on east side of Beatton R.	modern
GSC-6796	56°17'	120°44'	Basal organic sediment from pond in colluvial flow on east side of Beatton R.	490 ± 60
GSC-6798	56°18'	120°45'	Basal organic sediment from pond in landslide on west side of Beatton R.	900 ± 70
GSC-6799	56°16'	120°43'	Basal organic sediment from pond in landslide on west side of Beatton R.	170 ± 60

Table 2. Radiocarbon sample locations and dates for landslides in the 94G and 94J NTS map areas.

GSC Lab. No.	Latitude (N)	Longitude (W)	Description of location	Radiocarbon date
GSC-6845	58°09'	122°48'	Basal organic sediment from pond in landslide on east side of Prophet R.	modern
GSC-6846	58°31'	122°47'	Basal organic sediment from pond in landslide on east side of Prophet R.	modern
GSC-6847	58°09'	122°47'	Basal organic sediment from pond in same landslide as GSC-6845.	1060 ± 60
GSC-6848	58°28'	122°50'	Basal organic sediment from pond in landslide on east side of Prophet R.	990 ± 50
GSC-6849	58°40'	123°53'	Basal organic sediment from pond in landslide on west side of Gardiner Cr.	730 ± 60
GSC-6851	57°22'	122°21'	Basal organic sediment from pond in colluvial flow on north side of Sikanni Chief R.	530 ± 60
GSC-6852	57°13'	122°45'	Basal organic sediment from pond in landslide on south side of Sikanni Chief R.	610 ± 50
GSC-6853	57°13'	122°44'	Basal organic sediment from pond in same landslide as GSC-6852.	410 ± 50
GSC-6854	57°23'	122°22'	Basal organic sediment from pond in colluvial flow on north side of Sikanni Chief R.	modern
GSC-6855	57°37'	122°43'	Basal organic sediment from pond in colluvial flow on north side of Trutch Cr.	70 ± 50

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