# STABILITY OF FROZEN AND THAWING SLOPES IN THE MACKENZIE VALLEY, NORTHWEST TERRITORIES

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ABSTRACT
Slope stability in the Mackenzie valley is currently of interest with the beginning of preliminary design for a pipeline in this corridor. Large slope failures, involving failure of ice-bonded material, do happen but are limited to locations with vigorous toe erosion of high river banks. Extensive slides are also triggered by forest fire if ground surface vegetation is destroyed thoroughly enough to increase the annual depth of thaw. Some slopes at stream crossings along the Norman Wells pipeline should have failed, based on the original slope calculations, measured pore water pressures and increasing pipe and ground temperatures during pipeline operation. However, no failures, except for minor slumping, have occurred. The performance of the pipeline slopes and the requirement of an extreme event, such as a forest fire, to trigger widespread sliding, suggests that conventional slope stability assessment for thawing ground underestimates soil strength.

RÉSUMÉ
Le stabilité des pentes dans la vallée du fleuve Mackenzie est un sujet de grand intérêt lors de la conception initiale d'un pipeline dans ce corridor. Il existe de grands glissements de terrain impliquant la rupture du sol gelé, mais ceux-ci sont limités aux endroits où il y a de l'érosion active au pied des hautes rives des rivières. Les glissements de terrain sont aussi provoqués par un dégel excessif des couches superficielles lors de la destruction de la végétation par un incendie de forêt important. Des pentes à l'intersection des ruisseaux le long de l'oléoduc de Norman Wells auraient dû rupturer selon les calculs de stabilité des pentes, de la pression interstitielle mesurée, et de la température croissante de l'oléoduc et du sol pendant l'opération de l'oléoduc. Cependant aucune rupture n'a eu lieu, a l'exception de subsidences mineures. La performance des pentes le long de l'oléoduc et l'exigence d'un événement extrême, comme un incendie de forêt, pour provoquer les glissements de terrain, indiquent que l'analyse de stabilité conventionelle sous-estime la résistance du sol dégelé.

## 1. INTRODUCTION

Thawing of ice-bonded soil and rock in permafrost regions is a frequently cited trigger for landslides. In the Canadian north, the Mackenzie River valley in the Northwest Territories is particularly susceptible to thaw-induced terrain disturbance. The coincidence of widespread, ice-rich glacial sediments and weak sedimentary rocks with an actively developing transportation and resource corridor points to an ongoing need to accurately evaluate the slope movement hazard. With the possibility of further pipeline construction and other industrial activity in the Mackenzie valley, unstable slopes will continue to be a feature to either avoid or to account for in site selection and design (see Figure 1). Not only recognizing thaw sensitive materials but also understanding how they react mechanically to a variety of landslide-triggering processes will aid the successful development of the Mackenzie region.

Experience with slope stability evaluation in frozen or thawing ground has been accumulating since the early 1970's when analyses of slopes in the Mackenzie valley were first undertaken. Bank failures, where the Mackenzie River and its major tributaries cut into frozen soils, have been analyzed following limiting equilibrium principles (McRoberts and Morgenstern 1974). A time-dependency of cohesive strength for ice-bonded soils was recognized and back calculations of cohesion for frozen sand was compared with laboratory-inferred values. A general correspondence was obtained that continues to compare reasonably with increasing amounts of laboratory data (e.g. Ladanyi 1997). The destabilizing effect of thawing has also been taken into account by including the contribution from thawing ground ice to the pore water pressure predicted by Terzaghi consolidation theory. These developments have supplied an engineering rationale for the design of permafrost slopes. This paper presents additional aspects of materials and conditions in permafrost settings that may warrant eventual inclusion in slope stability assessments.

## 2. SLOPES ALONG THE NORMAN WELLS PIPELINE

No slopes in the Mackenzie valley have received more engineering attention than those crossed by the Norman Wells pipeline (route shown on Figure 1). This 300 mm diameter buried oil pipeline traverses the discontinuous permafrost zone between Norman Wells, Northwest Territories and Zama, Alberta and has been operating since 1985. As part of the pipeline design, about 165 slopes to be traversed by the pipeline were identified as requiring modification to reduce the likelihood of failure or disturbance due to erosion or thaw (Hanna and McRoberts 1988). Most of these slopes are approaches to stream crossings. They typically drop about 30 m over a distance of about 200 m giving an average slope of about 10°. However, slopes locally can reach 20° and are occasionally even steeper. Most slopes are underlain by till or glacial Lake Mackenzie sediments, both typically silty. For frozen slopes, excess ice contents are highly variable but average 20% and commonly reach 35% (Burgess and Lawrence 2000). Carbonate bedrock is within a few meters of the surface for a few of the most northerly slopes.

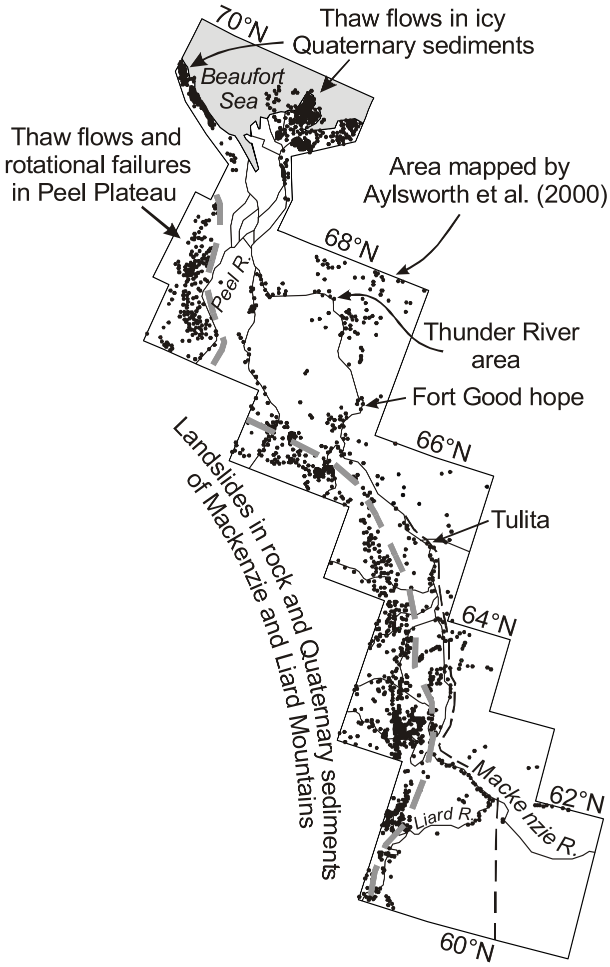


Figure 1. Locations of landslides of all types in the Mackenzie valley as mapped by Aylsworth et al. (2000). Each dot may represent more than one landslide. Dashed black line is the Norman Wells pipeline. Grey dashed lines show approximate boundary between lowland and mountainous areas.

Where permafrost slope stability has been assessed for engineering purposes, limiting equilibrium analyses have been the standard analytical technique. In the case of frozen slopes along the Norman wells pipeline, destabilization was expected due to thawing induced by right-of-way preparation. Ground temperature monitoring at 26 locations, mostly on level portions of the right-of-way, demonstrates that initially frozen sites have generally undergone thaw and subsidence (Smith et al. 2004). To prevent this outcome on slopes, wood chips were spread on all or parts of 54 slopes where stability was judged to be thaw-sensitive (AGRA Earth and Environmental Limited and Nixon Geotech Ltd. 1999) . This measure has met with varying success, in as much as many slopes have remained frozen while thawing has progressed on others. Of 29 slopes which have recently been subject to yearly or more frequent inspections (Figure 2), 9 show deepening of the frost table. Typically, depths to the frost table have increased from 2 or 3 m to 4 to 6 m during the later 1990's (Enbridge, 2001). In an analysis of a typical pipeline slope, Hanna et al. (1994) report that for the steepest portion of this slope (16-19°), factors of safety were below 1 (i.e. as low as 0.8) for certain combinations of slope length and angle. The initial slope design indicated that maximum stable slope angles in the event of thaw ranged between 9 an 18°, depending on the slope material and ice content (McRoberts et al. 1985). Despite the Hanna et al. (1994) indication of unstable slopes and the existence of several other similar slopes along the pipeline which have been undergoing thaw, there have been no slope failures of the circular arc or infinite slope-type anticipated.

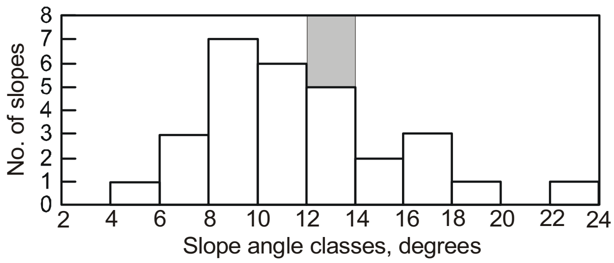


Figure 2. Range of average angles for 29 slopes considered most susceptible to failure along the Norman Wells pipeline. Grey bar indicates the approximate minimum angle of slope that failed as active layer slides after the Thunder River fire.

## 3. ACTIVE LAYER DETACHMENTS

### 3.1 Nature and triggering mechanisms

The most common type of landslide produced by thawing in permafrost regions is the active layer detachment. This feature comprises a sheet of sediment moving on a surface which is customarily assumed to coincide with the frost table. Active layer detachments tend to be overlooked in regional surveys because they are difficult to detect on air photos or quickly evolve into retrogressive flows. They are most likely triggered by an event or condition which permits excessive thickening of the active layer. In addition to the increasing instability resulting from a heavier slide mass to overcome cohesion, deeper than normal thaw will reach the zone of ice enrichment that typically exists just below the active layer (Mackay 1980). This situation also affords a means for generating a higher pore pressure than might otherwise be possible during thaw through less ice-rich material. While unusually warm or wet summers will promote deeper thaw and instability (Lewkowicz 1992), the event most likely to trigger an active layer detachment is a forest or tundra fire. Thus there is a potential for this kind of slide on any forested, ice-bonded slope.

### 3.2 Role of Forest Fire

Fire has probably reached every point in forested areas of the Mackenzie Valley at least once in the last 200 years. This rough estimate is based on records of areas burned between 1965 and 2001 (Sahtu GIS Project 2002). In the Mackenzie Valley, widespread forest occurs between the front of the Mackenzie Mountains and the tree line bordering the tundra to the northeast. Approximately one quarter to one third of this area between latitudes 62°N and 67°N has been burned between 1965 and 2000. In the next 35 year period, assuming that fire initiation and burning occurs in the same way, a similar proportion of the remaining unaffected area should burn. Carrying this trend to a century would leave about one third of the total area unburned. Therefore, for any given location, chances of a forest fire are approximately 65% per century. After 200 years most of the region would have been burned at least once. Of course, on a year to year basis the area affected by burning is very irregular, as suggested by the unusually large area burned in 1994-1995 between Norman Wells and Fort Simpson.

Figure 3. Active layer slide in the Thunder River area. Photograph taken 6 years after the fire.

The Thunder River area (see Figure 1) serves as a convincing example of the effectiveness of fire as a landslide trigger (Figure 3). Thirteen hundred square kilometers of forest adjacent to the Mackenzie River burned in 1986 and within one year extensive active layer slides had developed (Harry and MacInnes, 1988). Several of these slides have evolved into retrogressive thaw flows. These features are primarily in silt-rich tills with head scarps that have visible ice contents of up to 50%. The primary effect of the fire is to reduce or eliminate the insulative quality of ground surface vegetation and the organic layer. This effect was measured for the Thunder River burn. For the burned area, destruction of the organic layer was not complete, with a charred mat of mosses remaining. Adjacent unburned terrain is characterized by a moss, lichen, and dwarf shrub mat. However, the mineral soil surface at the burned site has a thawing degree day index about four times that at the unburned site. The temperatures at the base of the organic layer in adjacent burned and unburned sites in the Thunder River area are shown in Figure 4. Thawing n-factors (ratio of thawing degree days at the ground surface to the thawing degree days in the air), based on a one year record of daily temperatures, are 0.80 and 0.15 for the burned and unburned sites, respectively. These indices amount to a mean thawing period temperature of 8 °C for the burned site and 2 °C for the unburned site. A thawing n-factor for bare mineral soil

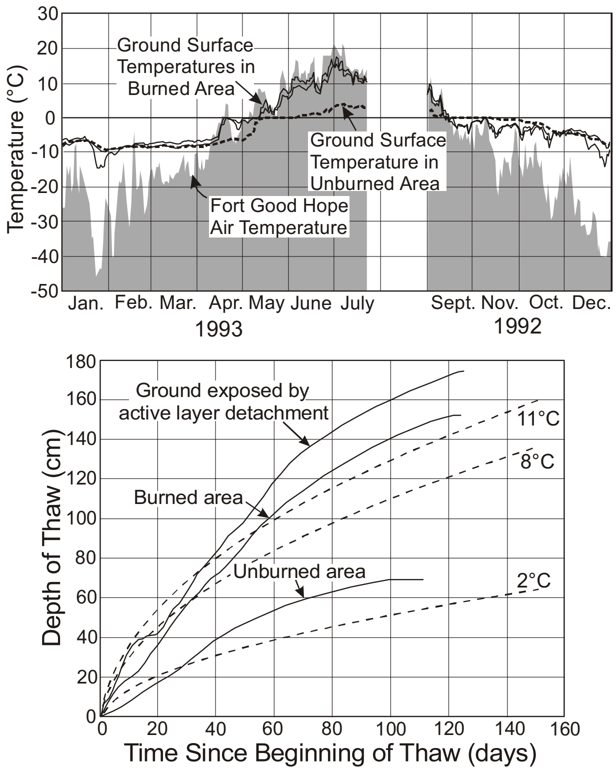


Figure 4. Influence of forest fire on ground surface temperatures and rate of thaw. Solid lines on lower graph show predicted thaw for measured ground surface temperatures shown in upper graph. Dashed lines show predicted thaw for an instantaneous application of the mean thawing temperature.

has not been measured but is assumed to be 1 based on the complete absence of vegetation. The corresponding thawing period temperature for bare ground would be 11 °C. Radiant heating may boost this (i.e. n>1) but by what amount is unknown. Burned sites adjacent to the cleared right-of-way for the Norman Wells pipeline show thawing n-factors ranging between 0.63 and 0.84 for sites with a mix of organic and bare soil exposed (Riseborough 2001).

The tendency for active layer sliding can be assessed with an infinite slope analysis given that most of the failure mass in this kind of slide moves parallel to the ground surface. In terms of a saturated, purely frictional material, an active layer slide should occur on any slope steeper than about 13-15°, assuming $\phi'$ = 25-30°. When excess pore pressure, presumably resulting from thawing ice at the frost table, is included, this range of angles will be reduced. Excess pore pressures due to thaw have been included in the infinite slope analysis by McRoberts (1972) by adding the expression for excess pore pressure derived from Morgenstern and Nixon's (1971) analysis of one-dimensional consolidation of a thawing soil. For the burned area at Thunder River, the range of angles for the maximum stable slope would be reduced to approximately 7-9° under reasonable estimates of the other parameters that govern excess pore pressure (coefficient of consolidation and thermal parameters, including the increased thawing index, that govern thaw) and using shear strength parameters that have been determined for thawed soils typical of Mackenzie valley glacial deposits (Hanna and McRoberts 1988).

Although the extent of active layer sliding associated with the Thunder River fire has not been determined in detail, a topographic survey on one of the largest slides, measuring several hundred meters in length and about 1 m thick, indicates an average slope angle of 13° with slight variability of ±1°. This slope angle is representative of the shallowest failure angle in the area (see Figure 2 for comparison with Norman Wells pipeline slope angles). A visual estimate from oblique aerial photography suggests 30 to 50% of these slopes failed as active layer detachments. The fact that a fire was required to trigger slides on these slopes suggests that they were not on the verge of failure. Cohesion (c') is an obvious contributor to stability but would require a value of only 2.3 kPa to place the factor of safety (FS) for the 13° slope at 1 (c'=10 kPa gives FS=2.5), based on the infinite slope stability calculation . The large increase in stability produced by a small cohesion further suggests that loss of this cohesion could be a slide trigger. The intersection of thawing with an ice-rich horizon at or slightly within the top of permafrost could provide this cohesion loss.

3.3 Role of Active Layer Hydrology

An additional strength loss is the reduction in effective stress due to thaw-consolidation. However, ground ice fabric may produce a departure from the uniform hydraulic conductivity that is implicit in the one-dimensional thaw consolidation calculation. Laboratory and field evidence indicates that increases in hydraulic conductivity in thawing soil parallel to the ground surface can be up to $10^4$ times the value determined from a conventional permeameter test (Dyke and Eggington 1988; Dyke and Egginton 1990). This increase is attributed to a pore fabric generated by thawed ice lenses. Groundwater flow modelling shows that a lateral increase in hydraulic conductivity tends to reduce the pore pressure gradient depending on the degree of anisotropy. Pressure head distributions for a hypothetical thawing slope under increasing hydraulic conductivity parallel to a slope are shown in Figure 5. No consolidation is taking place but the pressures shown are falling from an initial slightly excess pore pressure along the frost table. The modelling results in Figure 5 suggest that these anisotropic hydraulic conditions act to prevent excess pore pressures from developing over much of a thawing slope.

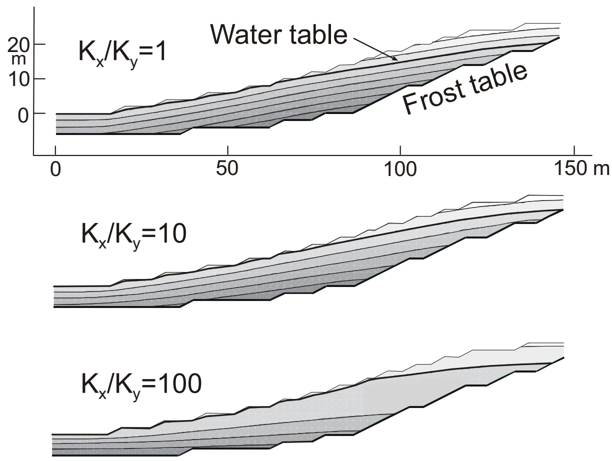


Figure 5. Pore pressure distribution in slopes with the horizontal hydraulic conductivity, $K_x$, varying by factors of 1, 10, and 100 times the vertical hydraulic conductivity, $K_y$. A water flux of 3 cm/mo from the frost table simulates thaw. Pore pressure contour interval = 2 m of pressure head, positive pressure head below water table.

The extreme environmental change that is associated with the triggering of active layer slides by forest fire can be compared with the impact of right-of-way preparation on slopes along the Norman Wells pipeline. The fire at Thunder River essentially doubled the rate of thaw (Figure 4). Thawing has been accelerated on some slopes along the pipeline right-of-way but not to the degree caused by a fire. Although thawing contributes to destabilization according to existing thaw-consolidation theory, the possibility of slope drainage due to lateral high hydraulic conductivity and the sensitivity of slope failure to cohesion suggests that fire-related slides happen when the frost table can reach an ice-rich and hence minimally cohesive horizon. Although the restraining effect of the typical trough-shaped thaw surface beneath the pipeline right-of way has been recognized, additional stability may be conferred by better than expected pore pressure drainage.

## 4. ROTATIONAL FAILURES

### 4.1 Glacial Lake Deposits

Perhaps the most spectacular slope failures in the Mackenzie valley are the rotational landslides located along the Mackenzie River and lower reaches of some tributaries (e.g. Figure 6). These slides occur where these streams have cut into glaciolacustrine sediments laid down in a series of glacial lakes that existed in concert with the retreat of the Laurentide ice sheet (Smith 1992; Duk-Rodkin and Lemmen 2000). Typically, sands and gravels overlie the silts and clays. These slides usually involve the entire height of the bank (as much as 80 m above river level) and can be up to one kilometer in length. These slides may remove as much as 200 m of the bank crest in a single failure, although less than 50 m is typical. In their work near the confluence of Mountain River and Mackenzie River, McRoberts and Morgenstern (1974) demonstrated the these slides involve failure of ice-bonded sediments.

Figure 6. Rotational landslide in the Old Fort Point area along the Mackenzie River. The slide occurred in Spring, 1999, the year photographed. The bank is approximately 60 m high. This slide required re-routing of navigation to the opposite side of the river.

As a general observation, only banks rising at least 50 m above river level appear to be prone to extensive, repeated failure. Banks exposing glaciolacustrine sediments and tills downstream of The Ramparts (Figure 7) are generally lower than this and show little activity of a rotational nature. The most impressive area of rotational landslides is in the vicinity of Old Fort Point (Figure 7), beginning on the right bank of the main channel about 50 km upstream of Tulita and continuing for about 40 km. Figure 7 shows where banks in glacial sediments immediately adjacent to the Mackenzie River exceed a height of 50 m. Also shown are the segments of these high bank intervals which show recent deep rotational failures. Failures become more evident with distance to the south, suggesting that a decreasing thickness of ice-bonded sediments may be responsible for decreasing bank stability.

Permafrost thicknesses predicted by the regional modelling of Wright et al. (2001) are included in Figure 7. Thus along the northern reaches of the Mackenzie River, permafrost is likely to be thicker than the bank height, resulting in slopes which are completely stable against deep-seated failures. At the mouth of Mountain River the modeling indicates permafrost to be approximately 50 m thick, in agreement with borehole measurements in this area. In the Old Fort Point area, the predicted thickness is less than 50 m with scattered areas of less than 20 m thickness. Hence ice bonding in the river banks at Old Fort Point is likely to extend to a depth of only about half the average 60 m bank height in this area. The increasing prominence of bank failures from The Ramparts area southwards may be in part due to increasing instability favored by decreasing thickness of the ice-bonded layer. Although other factors may influence failure frequency, they are probably not as dominant as the extent and thickness of permafrost. The rate of toe erosion is likely to

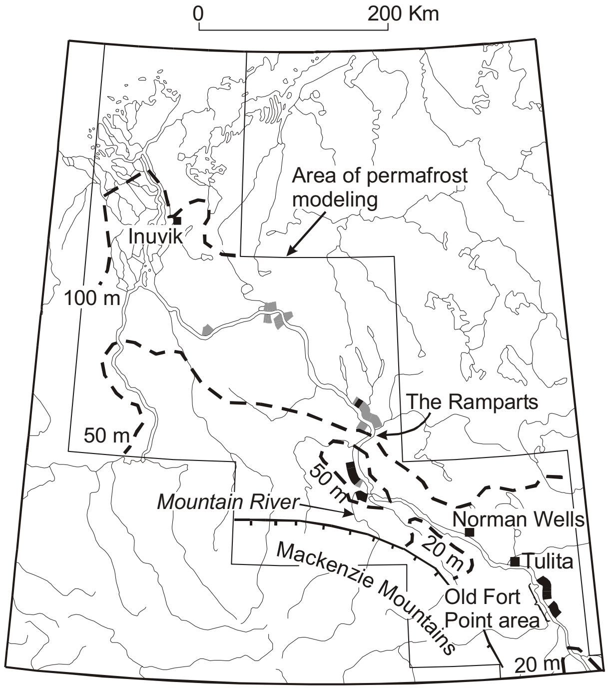


Figure 7. Lower Mackenzie valley showing reaches of the Mackenzie River having banks composed of glacial sediments in excess of 50 m high (grey segments) and portions of these segments which show active slope failure (black segments). Permafrost thickness, generalized from the modelling of Wright et al. (2001), is shown by dashed contours.

be as much a function of permafrost distribution as is failure frequency because failures introduce bank material into the river, hastening erosion. Also, glacial sediments vary in strength, particularly in the case of high strengths associated with compacted tills, but the even larger strength increase that results from ice-bonding is likely the most dominant factor in determining bank stability.

An analysis of slides in the Old Fort Point area demonstrates an association between slide size and toe erosion rate. River bank position for two reaches in the Old Fort Point area are compared in Figure 8 using air photos from 1945 and 1994. Individual slides have been outlined and qualitatively ranked according to freshness of the slide scar. Along these segments, river shorelines have retreated as much as 120 m in the 49 years between the air photos and slide crests have in a few cases retreated even further. There is an obvious association of more recent slides, based on a bare slide surface, with the most rapidly eroding sections of each reach. Furthermore, slides with the longest run-outs and greatest increment of bank retreat tend to coincide with the most rapidly retreating shores.

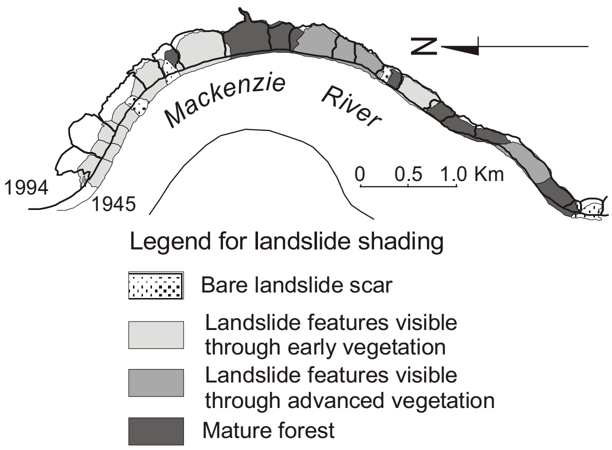


Figure 8. Rotational failures mapped along an actively eroding reach of the Mackenzie River in the Old Fort Point area. Slides appearing on airphoto coverage in 1945 and 1994 are categorized according to stage of re-vegetation.

A limiting equilibrium analysis may not be appropriate for predicting the stability of eroding permafrost slopes in the Mackenzie valley because the stiffness of the ice-bonded portion of the slope may influence the mechanism of failure.Rapid toe erosion and slope loading may result in loss of support for the ice-bonded permafrost horizon as small amounts of deformation in the underlying unfrozen sediments places a bending moment on the permafrost layer. Tensile failure of the permafrost layer will be favoured but at a minimum set back from the bank crest to achieve the required bending moment (see Figure 9). Given a probable tensile strength of frozen sand on the same order as measurements of shear strength (a few 100 kPa), the tensile stress required for failure would not occur closer than at least 100 m from the bank crest for ice-bonded permafrost 30 m thick. Tensile failure in the permafrost would remove a major element of slope strength, perhaps triggering failure of the entire bank.

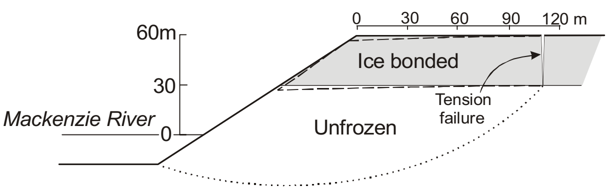


Figure 9. Hypothetical cross-section of an eroding river bank. Bending of ice bonded layer (dashed lines-exaggerated) takes place in response to toe erosion and deformation of the underlying unfrozen material. Eventual tensile failure may trigger rotational failure of the entire bank (dotted line).

4.2 Cretaceaous Shales

One of the greatest concentrations of landslides in the Mackenzie valley occurs between the Peel River and the Richardson Mountains, in the vicinity of the N.W.T. - Yukon boundary. This concentration is prominent on the landslide distribution map of Aylsworth et al. (2000). It stands out as the only major grouping that is not associated with bank instability along the Mackenzie River, rock landslides in the Mackenzie Mountains, or thaw flows along the Beaufort Sea coastlines (Figure 1). The landslides are located at the crest of or on the slopes of a dendritic drainage network that cuts into Cretaceous shales and Quaternary sediments forming the Peel Plateau (Peel Plateau is an upland area flanking the Richardson Mts. to the west and Mackenzie Mts. to the south). These slopes show up to 400 m of relief, typically stand at angles of 30 to 40° and host slides ranging in size from narrow debris flows to failures covering half a square kilometer. Along an 80 km-long zone adjacent to the Peel River from the Yukon border south and extending westward about 30 km to the heads of Peel River tributaries, there are approximately 200 slides readily identified on air photos and dozens more in areas with local concentrations of debris flows. Mapping of this area on airphoto coverage for 1950, 1974, and 1994 indicates that an average of one or two landslides in shale take place each year.

Shallow rotational failures are typical in the shales of the Lower Cretaceous Arctic Red Formation, both along the Peel River and its tributaries. The geometry of these landslides contrasts with the much more elongated shape of failure masses and large near-horizontal translations seen for landslides in Cretaceous shales in non-permafrost areas of western Canada. Although bentonite layers have been recorded in the Arctic Red Fm., failure is largely parallel to a slope, cutting across the typically horizontal bedding. Rotation of bedding is often visible at the base of these slides along the Peel River.

Saline pore water in the shales may contribute to slope destabilization. Seepage zones occur at the base of most slide scars and are often outlined with efflorescences, indicating elevated salinities of shale pore water. Chemical analysis and electrical conductivity surveys indicate total dissolved solids as high as 10 ppt. This salinity may promote long term thawing of slope faces due to freezing point depression of the pore water in the active layer. This condition will promote active layer thickening because successive freezings may further increase solute concentration (and hence freezing point depression). Thus lower temperatures are required for complete freeze-back. Eventually thawing reaches a depth into the slope that triggers a failure. Estimated shear strengths along failure surfaces in the shales, assuming $\phi'=25°$, range from about 30 to 50 kPa. These relatively low strengths suggest that failure is taking place in non-ice-bonded ground and that the failure mass represents a thawed portion of the slope.

## 5. CONCLUSIONS

Examination of slope failures in permafrost settings of the Mackenzie valley suggests that several characteristics of frozen and thawing ground may influence slope stability.

1. Loss of cohesion may be an important trigger for active layer slides where rapid rates of thaw allow the frost table to reach particularly ice-rich ground.

2. Large rotational failures involving ice-bonded ground are restricted to locations of active toe erosion where the loads necessary for triggering these failures can be generated.

3. Where permafrost thickness is in excess of a bank height, failure through ice-bonded ground is unlikely. However, shallower failures can still occur due to thawing into the bank. This mechanism appears to be favoured in the shales of the Peel Plateau area where bank thawing may be promoted by saline pore water.

## 6. ACKNOWLEDGEMENTS

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