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Landslides of the Mackenzie valley and adjacent mountainous and coastal regions

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Abstract: Approximately 3400 landslides, distinguished by failure class (flow, slide, complex, unclassified) and parent material (bedrock or unconsolidated Quaternary sediment) have been mapped in the Mackenzie valley. Many landslides are related to the degradation of permafrost and ground ice; others are influenced by the control permafrost maintains on ground water movement. Given the prevalence of permafrost and icy sediments in this region, any climate change leading to a rise in ground temperatures and degradation of permafrost will increase the frequency of landslides. The most vulnerable sites include ice-rich, fine-grained sediments on slopes near water bodies or in fire scars, and frozen, coarse-grained sediments overlying clay or clayey till in steep riverbanks where permafrost does not extend to the base of the section.

Résumé : Dans la vallée du Mackenzie, on a répertorié et cartographié quelque 3 400 glissements de terrain que l'on a classés selon le type de rupture (coulée, glissement, complexe, non déterminé) et la nature des matériaux touchés (substratum rocheux ou sédiments quaternaires non consolidés). De nombreux glissements de terrain sont causés par la dégénérescence du pergélisol et de la glace de sol; d'autres dépendent du contrôle qu'exerce le pergélisol sur la circulation des eaux souterraines. Étant donné que le pergélisol et les sédiments gelés dominent dans cette région, tout changement climatique provoquant une hausse des températures du sol et la dégénérescence du pergélisol multiplierait les glissements de terrain. Parmi les sites les plus vulnérables, mentionnons les versants près d'étendues d'eau ou dans les brûlis qui sont découpés dans des sédiments à grain fin riches en glace, ainsi que les berges abruptes formées dans des sédiments à grain grossier gelés reposant sur des argiles ou des tills argileux, où le pergélisol ne descend pas jusqu'à la base de la coupe.

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INTRODUCTION

An inventory of 3400 landslides has been compiled for the Mackenzie valley and adjacent mountainous regions and the Mackenzie Delta and Tuktoyaktuk Peninsula (Aylsworth, 1992; Duk-Rodkin, 1993; Aylsworth and Traynor, in press; Duk-Rodkin and Robertson, in press; Aylsworth et al., in press). This area covers approximately 250 000 km^2 and extends in a 1200 km strip from the Northwest Territories border at 60°N to the Beaufort Sea, encompassing the Mackenzie River and at least the lower reaches of all its tributaries. This corridor also includes the communities of the Mackenzie valley, the Fort Liard, Mackenzie, and Dempster highways and the Norman Wells to Zama oil pipeline (Fig. 1).

Within an area of this size, a tremendous variety of topographical, geological, and thermal conditions are found. Topography ranges from flat or rolling plains to dissected plateaus and rugged mountains. The region is underlain by Cambrian to Tertiary sedimentary bedrock, and, with the exception of steep mountain slopes, most of the valley is covered by Quaternary deposits characterized by till, lacustrine clay, silt and sand, and glaciofluvial and alluvial silt, sand, and gravel (*see* Aylsworth et al., 2000). Permafrost underlies much of the region. Permafrost varies from continuous and thick (>100 m) in the north to sporadic and thin (<5 m) in the extreme south of the valley. Segregated ground ice is common in all fine-grained sediments. Because of the variety of physical conditions in the region, the types of landslides and

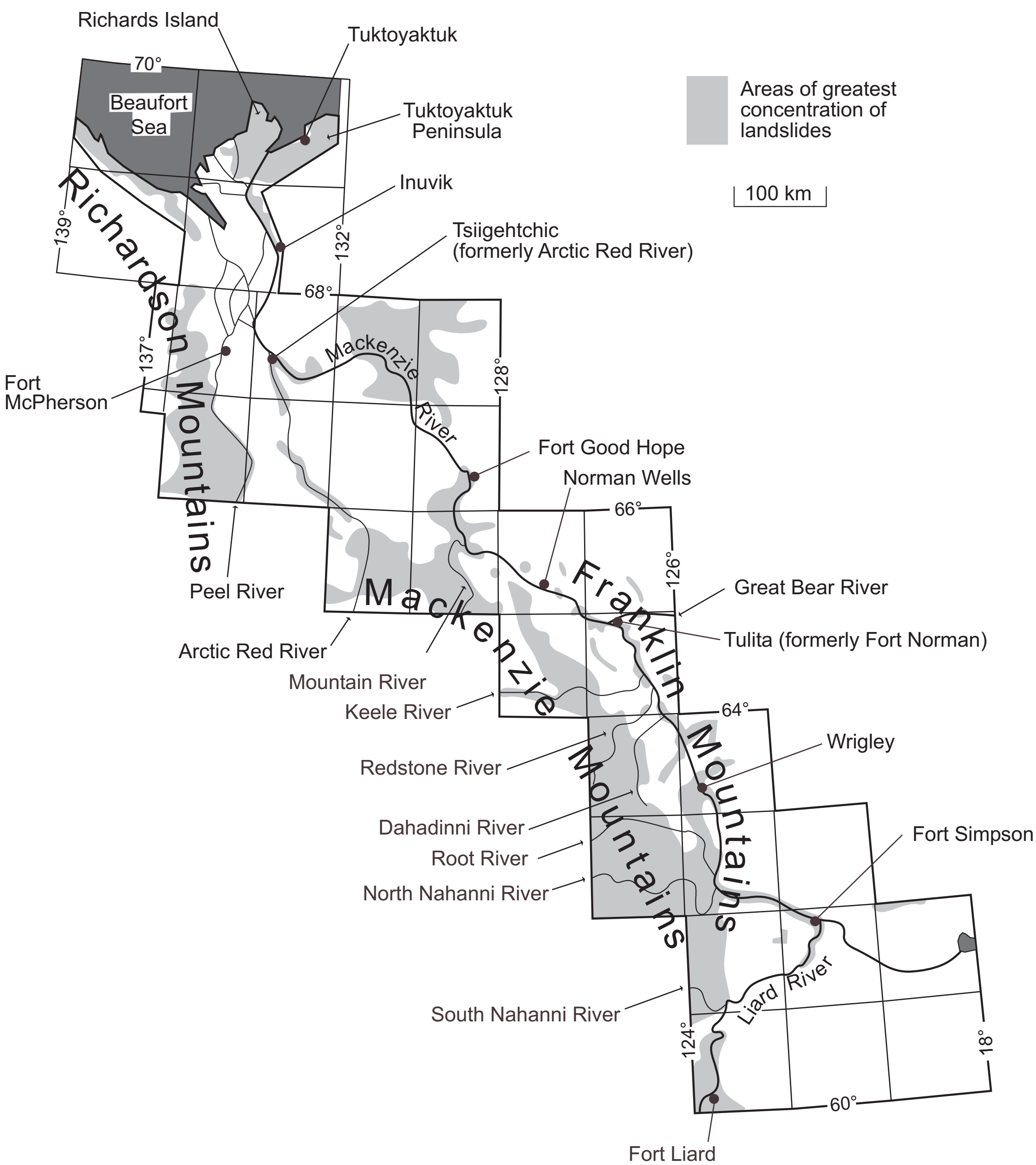

Figure 1. *Location map of study area depicting where landslides are most common.*

their mechanisms of failure vary depending on local relief, geology, permafrost and groundwater conditions. Many slope failures are closely related to the thawing of ice-rich permafrost or the pressure exerted by groundwater confined by permafrost. It is areas containing ice-rich unconsolidated sediments that would be most susceptible to landsliding resulting from the degradation of permafrost in the event of global warming.

In the Mackenzie valley and adjacent regions, the major impact of landslides will most likely be the disruption or destruction of pipelines, roads, and bridges. River navigation might be temporarily affected in the event of a landslide dam on a river. As well, landslide dams could cause further thermal instability upstream, possibly promoting additional landslides. Increased landsliding could also affect fisheries through possible increased siltation in streams and rivers, and possible destruction of spawning beds.

COMPILATION METHODOLOGY

Compilation of the landslide inventory is based primarily on the interpretation of airphotos or compilation from existing surficial geology maps (*see* listing of maps in Aylsworth et al., 2000). For the most part, the latter maps were also produced mainly from airphoto interpretation. North of 68° latitude, the interpretation is based on 1985 images, and 1948 to 1972 airphotos were used between 68° and 64°N. Between 64° and 60°N, most of the landslides in the area were compiled from existing surficial geology maps based on 1947 to 1971 airphotos; however, within a corridor extending approximately 3 km on either side of the Mackenzie and Liard rivers, all available airphoto images (1947 to 1990) were re-examined during this project. Throughout the entire study area, landslides that occurred subsequent to the years of airphoto coverage are only included in the inventory if reported either in field observations made by GSC staff, mainly during regional surficial geology mapping projects or permafrost studies, or from publications describing individual failures. Many of the slope failures along the banks of the Mackenzie River have been previously noted by Code (1973) and McRoberts and Morgenstern (1973), and, in the vicinity of the Beaufort Sea coast, landslides have been mapped and discussed by Mackay (1966, 1986) and Rampton (1988).

The inventory consists of 1:1 000 000 scale maps showing landslide distribution, differentiated by landslide type, and is accompanied by a digital database consisting of information on individual landslides or groups of landslides. Location, class and type of failure, dimensions, description of bedrock lithology or unconsolidated sediments, age if known, additional comments if any, and airphoto numbers are all given, and references if available. The database contains 2014 entries, of which 55% represent individual landslides and a further 10% represent a pair of closely spaced landslides. The remaining 35% of entries represent clusters of closely spaced landslides with numbers ranging from more than 2 to more than 30 landslides per cluster, with most clusters consisting of fewer than 10. For the most part, these clusters represent groups of small retrogressive thaw flows in the northern third of the study area.

CLASS AND TYPE OF LANDSLIDE

In the database, landslides were divided into those in which the failure plane occurred in bedrock and those in which the failure plane occurred in unconsolidated Quaternary sediments of glacial, glaciofluvial, lacustrine, marine, alluvial, or colluvial origin. In many cases it was the cementing presence of ice-bonded permafrost that gave strength to the unconsolidated sediments. Of the 2014 landslides or landslide clusters in the database, 31% occurred in bedrock and 69% occurred in unconsolidated sediments. The landslides have been categorized by 'class' (Fig. 2a, in pocket), which describes the basic style of failure: flow, slide, or complex, which incorporates elements of both (based on Varnes, 1978). Many of the landslides in the southern region, particularly those in the Mackenzie Mountains, remain unclassified. 'Class" is further subdivided into 'type' (Fig. 2b, in pocket), which refers to the specific kinds of landslide and implies not only style of failure, but also the specific physical attributes of the landslide. The names of failures associated with melting of frozen ground or ground ice, and therefore unique to permafrost regions, follow common permafrost terminology.

Landslides in permafrost terrain are characterized by two distinct classes: 'flows' and 'slides'. These classes are based on mechanism of failure, although the differences are also reflected in morphology. Flows have a fluid character, showing evidence of mobility throughout the failure. Slides, on the other hand, show evidence of rigid movement in that components of the slide move downslope as more or less intact blocks. Two other classes of failure mechanism, 'falls' and 'topples' (the names are self-evident), have a minor role, particularly as a contributing factor to the development of a larger failure, but are generally too small to distinguish on an airphoto and are not included in the inventory. 'Complex' is assigned when not only is there more than one type of movement, but also each type of movement accounts for a significant volume of the landslide. Two mechanisms of failure may be active at the same time in an individual landslide, or, as a landslide develops, one type of failure may evolve into another type. Slope movement in permafrost regions may continue either continually or cyclically for weeks, years, or even decades.

Several different types of landslides make up each of the two major classes, flows and slides. Flows can be subdivided into shallow, active-layer detachments (or skin flows), deeper retrogressive thaw flows (also commonly known as bimodal flows or ground-ice slumps), and rapid debris flows. Slides are divided into rotational slides and translational (or planar) slides.

Active-layer detachments

Shallow slope failures involving detachment and downslope movement of only the active layer and vegetation mat are known collectively as active-layer detachments (Fig. 3, 4, 5). Movement may involve either sliding of a relatively intact, thawed piece of ground on the underlying frozen sediment (sometimes known as an active-layer glide) or flow of water-saturated sediment (also known as a skin flow). They are generally triggered by unusually warm temperatures or some disturbance of the vegetation mat (*see* Dyke, 2000). Either instance will result in overdeepening of the annual active layer, which, if icy sediment is thawed, may detach and move downslope. The landslide tends to expand laterally as adjacent icy sediment also thaws. This type of failure is common in ice-rich terrain following a forest fire if the insulating organic mat is damaged or destroyed. Numerous active-layer detachments were reported in the fall and spring near the Mackenzie River following the summer 1994 and 1995 forest fires southeast of Tulita (formerly Fort Norman) (M.M. Burgess, K.L. MacInnis, pers. com., 1994, 1995). If the removal of the water-saturated sediment continually exposes massive ice or icy sediments at greater depth, an active-layer detachment may develop into a retrogressive thaw flow. Such is occurring in several of the above mentioned examples (M.M. Burgess, pers. com., 1995, 1996). On steep slopes, the active-layer detachment may develop into a debris flow.

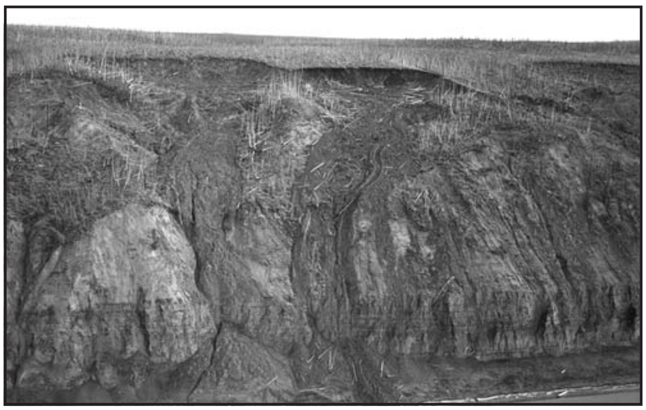

Figure 3. *Landslides along the Mackenzie riverbank near the mouth of Thunder River. These still-active flows, triggered following the 1986 fire, have evolved from shallow skin flows into flow complexes. The upper portion of the landslide has developed into a retrogressive thaw flow as continued retrogression in the newly exposed, ice-rich sediment has resulted in deepening and steepening of the headscarp. The rapid movement on the steeper part of the bank may more properly be called a debris flow. Photograph by J.M. Aylsworth in 1994. GSC 2000-034A*

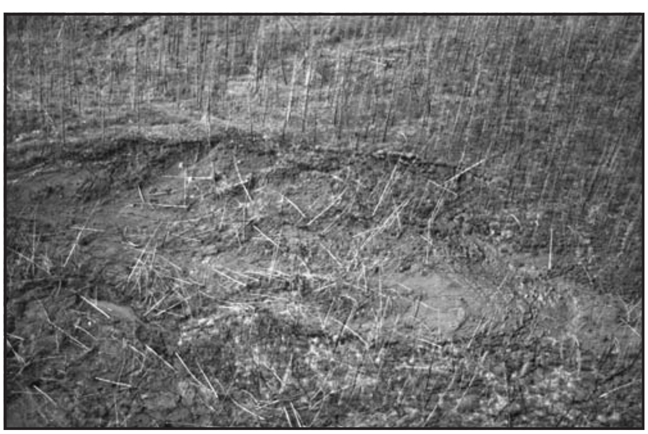

Figure 4. *Head of active-layer detachment (skin flow) in the 1986 Thunder River fire scar. Photograph by J.M. Aylsworth in 1994. GSC 2000-034B*

Figure 5. *Active-layer detachments (skin flows) line the banks of the Mackenzie River south of Tulita (formerly Fort Norman). Flows were triggered following a large forest fire in 1995. Photograph by M.M. Burgess in 1997. GSC 2000-034C*

Retrogressive thaw flows

The most common type of flow is the retrogressive thaw flow (Fig. 6, 7, 8). Retrogressive thaw flows occur only in ice-rich terrain. They have a characteristic bowl shape and a bimodal profile with a steep headwall and a low-angle tongue. The headwall gradually erodes upslope as massive ground ice or icy sediment thaws in the scarp, and the resulting water-saturated sediment flows downslope away from the scarp.

Retrogressive thaw flows may be initiated by any process or event that results in the exposure to melting of massive ice or icy sediment. For example, active-layer detachments may develop into a retrogressive thaw flow if ground ice is exposed. In the northern part of the study area, massive ice may become exposed in dilation cracks resulting from growth of ground ice, or in tension cracks formed as icy sediment deforms and creeps under its own weight. Exposure of the ice-rich scarp, which is essential to the development of thaw flows, may also be initiated at coastal sites or along scarps by block falls or topples.

Once the massive ice or icy sediment is exposed in the headwall, a seasonal cycle becomes established, beginning in summer when snow melts away from the scarp face. Water derived from snow melt and melting of ground ice helps to clean the scarp face of debris that may have accumulated the

Figure 6. Retrogressive thaw flow demonstrating the classic bowl shape, with a steep, ice-rich headscarp and a very low-angle tongue, Tuktoyaktuk Peninsula. Photograph by J.M. Aylsworth in 1992. GSC 2000-034D

Figure 7. Two recent retrogressive thaw flows in an older retrogressive thaw-flow scar, Tuktoyaktuk Peninsula. Massive ground ice is visible in the headscarp. Photograph by J.M. Aylsworth in 1992.GSC 2000-034E

previous season. As sediment is released from the melting ice, it falls, slides or flows down the scarp face. Melting of the ice undercuts the active layer at the top of the scarp, and the undercut peat and sediments detach and fall down to the base. These become incorporated into the water and debris at the base of the scarp face and flow downslope. Eventually the slide stabilizes as the face becomes buried by debris, the ice content of the sediment at the scarp decreases, or the slope of the scarp decreases (Mackay, 1966).

Retrogressive thaw flows tend to be cyclic in nature. The scarp face may become buried if debris is not removed at a rate faster than it is supplied. If the flow is not reactivated immediately, it can become quickly revegetated because any fallen blocks that remain intact carry vegetation into the bowl of the slide (Mackay, 1966). If the flow does reactivate, a new scarp face may develop within the old scar, and the old flow deposits are recycled in the new failure. In icy sediment, a retrogressive thaw flow will remain active wherever the slope is sufficiently steep to continually evacuate the scar, or where fluvial erosion transports debris away from the toe of the landslide, or in the case of a lake or coastal shoreline, if wave energy is sufficient to erode the flow debris and keep the scarp face exposed. Rising water levels and wave activity during a storm may reactivate a stagnated slide by eroding the toe of the slide and triggering more movement of debris away from the face (Carter et al., 1987). During major storm surges the debris may be overtopped or quickly eroded back to expose the ice face to direct wave attack.

Debris flows

Debris flows, rapid flows of water-saturated sediment, occur in areas of higher relief (Fig. 9, 10). These flows are typically long and narrow, and widen into debris fans at their base. They may be triggered by extreme precipitation or unusually deep seasonal thaw in an abnormally warm summer. For example, the abnormally warm summer temperatures of

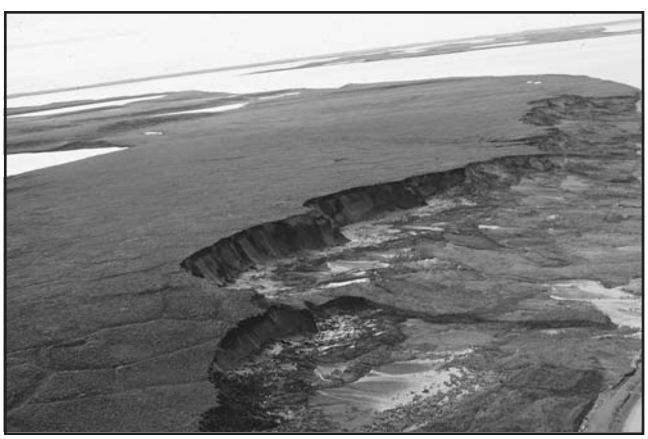

Figure 8. Large retrogressive thaw flows, northern Richards Island. Extensive areas of the Beaufort Sea coast are subject to similar slope failure. Flows remain active as long as ice is exposed in the headscarp and debris is removed from the toe of the landslide by erosion. Photograph by J.M. Aylsworth in 1992. GSC 2000-034F

Figure 9. Debris flow of 1990, Peel River. Flow, which occurred in till on the slopes in the distant background, extends for approximately 2 km to river level. Photograph by L.D. Dyke in 1992. GSC 2000-034G

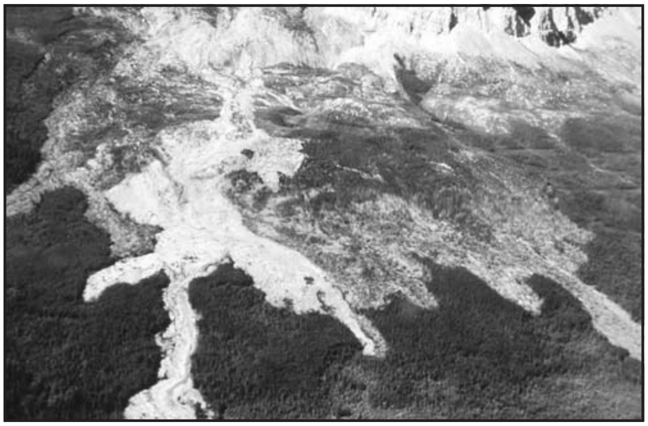

Figure 10. Debris flow in colluvium at Nahanni Butte triggered by the 1988 extreme rainstorms in the Liard Basin Photograph by J.J. Clague in 1988. GSC 2000-034H

Figure 11. Shallow rotational slide in lacustrine silts failed as a single block sliding along a circular failure surface. West bank of the Mackenzie River south of Old Fort Point. Photograph by J.M. Aylsworth in 1994. GSC 2000-034I

Figure 12. Deep-seated rotational slide in frozen lacustrine sands and silts, Mountain River, occurred as a series of rotational block movements. Unfrozen clay occurs at river level. Photograph by J.M Aylsworth in 1992.GSC 2000-034J

1989 triggered a debris flow in the Caribou Hills east of the Mackenzie Delta that ran 1.5 km downslope in a few minutes (Aylsworth et al., 1992). Exceptionally heavy precipitation induced a debris flow at Nahanni Butte on the Liard River that narrowly missed a ranger station (Clague, 1988) and a large translational slide in bedrock along a tributary of Mountain River was reactivated after a heavy rain in the summer of 1971. In mountainous areas, active-layer detachments formed in burn scars may develop into debris flows if large amounts of meltwater are produced by the thawing of newly exposed ground ice.

Rotational slides

Rotational slides involve the downslope movement of a rigid block of sediment along a curving failure surface, such that the toe of the block extends well beyond the original slope and the original upper surface of the block is generally back-tilted towards the scarp of the landslide (Fig. 11, 12, 13, 14, 15, 16). Such failures may occur as an individual block or as a stepped series of blocks. Many multiple failures have occurred.

Rotational slides are commonly induced by undercutting of a riverbank by erosion. Pressure of ground water, confined beneath the permafrost layer, is probably an important contributor in these failures (*see* Dyke, 2000).

Rotational slumps may subsequently deform and move as flows, probably as ice within the slump melts. The flow may drastically modify the shape of the original feature. In this case the landslide would be classified as a slide-flow complex. Numerous examples of this type of landslide can be found along the banks of the Mackenzie River downstream of Fort Simpson and upstream of Tulita at Old Fort Point (Fig. 17; McRoberts and Morgenstern, 1973).

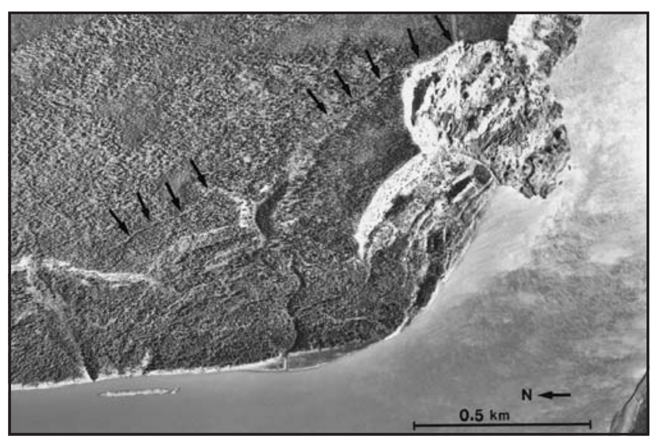

Figure 13. Several rotational slides line the Mackenzie riverbank south of Old Fort Point in this airphoto. Arrows indicate block cracks behind the landslides. The fresh landslide occurred in July, 1984, as a series of block failures. Prior to 1984, the block cracks extended to the right along the present headscarp. Another large rotational slide occurred upstream (right) of the 1984 slide in the winter of 1997. NAPL A26839-125 in 1984

__Figure 14.__ Large rotational slide occurred in February or March, 1997, immediately upstream of the 1984 landslide shown in Figure 13. Part of the 1984 landslide is visible in the extreme left of the photo. Photograph by M.M. Burgess in 1997. GSC 2000-034034K

__Figure 15.__ Close-up of headscarp of the 1997 rotational slide. Landslide occurred in frozen lacustrine silt over clay. The shape of the feature has evolved since this photo was taken, as frozen blocks thawed. Photograph by M.M. Burgess in 1997. GSC 2000-034L

__Figure 16.__ Large cracks, indicated by arrows, are visible on the flat surface behind the headscarp of the 1997 landslide. Photograph by M.M. Burgess in 1997. GSC 2000-034M

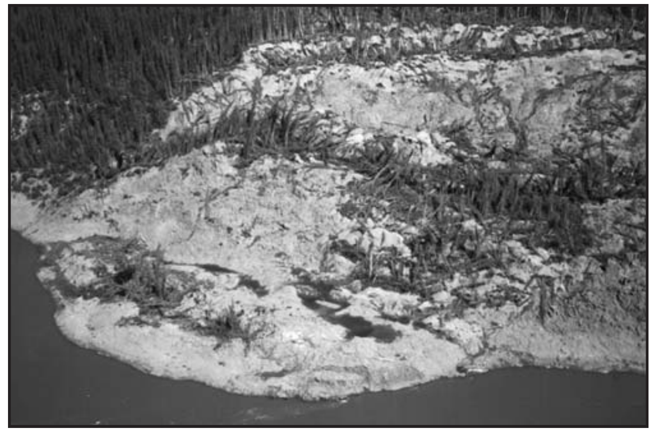

__Figure 17.__ This landslide, in lacustrine silts overlain by sands, occurred as a series of rotational blocks during the winter, 1992. Subsequent flow occurred as the sediment thawed. Photograph by J.M. Aylsworth in 1992. GSC 2000-034N

Translational slides

Translational slides involve rigid movement along a planar failure surface, commonly a bedrock bedding plane. They may be induced by fluvial erosion of the base of an inclined bedding plane. These slides are restricted to mountainous areas.

LANDSLIDE DISTRIBUTION

Landslides occur the length of the Mackenzie valley; however, they tend to be concentrated in specific zones within the study area (Fig. 1, 2a, c, d, e). These zones include the banks of the Mackenzie and its tributaries where the rivers have eroded deep channels into the underlying unconsolidated Quaternary sediments, or, in places, bedrock; the slopes rising towards the Mackenzie and Richardson mountain fronts; the steep slopes of the ranges in the Mackenzie and Franklin mountains to the west of the Mackenzie River, and to a lesser extent the slopes of the ranges east of the Mackenzie River; the shores of the hundreds of small lakes of the Tuktoyaktuk Peninsula and Richards Island; and the cliffs of the Beaufort Sea coast.

Landslides range in area from 225 m^2 to 20 km^2. The mean area of a landslide in the inventory is approximately 0.5 km^2 and median value is 0.25 km^2. Area of a landslide is considered to include the area of the scar and of the debris tongue. In most cases it was roughly calculated from the mean width and length of the feature. Volume was not calculated. In general, size of landslide increases towards the south. The northern part of the study area is characterized by hundreds of small retrogressive thaw flows. Rotational slides, which generally are larger, are more frequent in the southern part of the study area. Many of the massive landslide areas are composed of several large coalescing and overlapping landslides which may represent years of landslide activity rather than one event.

Elevations of the scars range from a few metres above sea level along the Beaufort Sea coast to 1980 m in the Mackenzie Mountains. A general trend of increasing elevation of landslide scar to the west reflects the general rise to the Mackenzie and Richardson mountains. Although there is a range of elevations represented, generally landslides are restricted to lower elevations (500 m or lower). These are the areas with the greatest accumulation of unconsolidated Quaternary sediments, in particular glaciolacustrine sediments, and also the areas most affected by river erosion. Landslides at higher elevations are almost exclusively bedrock failures on steep slopes.

Although no strong relationship exists between landslide frequency and aspect (direction of movement), there are somewhat fewer landslides with a northerly aspect. When only landslides in unconsolidated Quaternary sediments are considered, a westerly aspect is slightly more dominant than the other directions. For the most part, the role of aspect unrelated to site control is insignificant. Site considerations, i.e. position with respect to erosion along a river or inclination of a bedrock formation, are more important.

Within the above-mentioned zones of dense landsliding, distinct types of slope failures are associated with specific geological units.

GEOLOGICAL ASSOCIATION

Certain geological materials are particularly prone to slope failure. In his survey of the Mackenzie riverbanks, Code (1973) noted that landslides involving bedrock occurred most commonly in weak, soft shale and weakly cemented Cretaceous sandstone and siltstone, where any steep bank exceeding 30 m height was potentially unstable. He noticed for fewer landslides in the mainly well cemented, resistant Devonian rocks along the river. However, further west, in the ranges of the Mackenzie and Franklin mountains, numerous landslides have occurred in rock that is Devonian or older.

Regardless of geological age, most landslides in rock occur in shale or in shale-mudstone-siltstone formations — soft, thinly bedded and generally friable and fissile sedimentary rock. For example, numerous landslides scar slopes in the shales of the Fort Simpson Formation, which is widespread in the southwestern part of the study area, as well as in other formations such as the Clausen and Mattsen. Where landslides occur in harder, more competent rock such as limestone, dolomite, sandstone, and quartzite, sliding usually occurs along the bedding plane. For example, large landslides are found in the limestones and dolomites of the Nahanni, Funeral, and Whittaker formations, and the Arnica and Sombre formations, respectively. Yet in most cases involving more competent bedrock, the failure plane is actually in a shale bed within the formation such as the Trout River and Redknife formations (sandstone and siltstone with shale beds) or the Flett formation (limestone with shale), or the failure plane lies in an underlying shale formation. Shale may move as a flow (active-layer detachment or debris flow) if very moist and disintegrated or as a slide; limestone and dolomite fail as a slide, either a translational failure along a bedding plane, or a rotational failure on underlying weak shale. Bentonite layers have been identified as crucial to some failures (K.W. Savigny, pers. com.,1992).

For unconsolidated Quaternary deposits (Fig. 2e), the greatest number of landslides (65%) occurred within till, a glacial sediment having a wide range of particle sizes. This number of failures is probably a reflection of both the potentially icy nature of the fine-grained matrix and the widespread distribution of till as compared to other Quaternary sediments within the region. In some cases, the failure plane is at the till/bedrock interface. Lacustrine clays and silts are involved in 17% of the landslides, and glaciofluvial sands, silts, and gravels (10% of the landslides), deltaic sands and silts (5% of the landslides) and other deposits (3% of the landslides). In the case of glaciofluvial and deltaic sediments, the deposit commonly overlies lacustrine fine-grained sediments and in many instances the failure includes these underlying sediments.

Fine-grained sediments (silts and clays or fine-matrix tills) are commonly ice rich, with ice content varying from ice crystals to massive lenses of pure ice. These silts and clays are found in parts of the Mackenzie and adjacent valleys that were temporarily flooded by glacial lakes during retreat of the Laurentide Ice Sheet (*see* Duk-Rodkin and Lemmen, 2000; Aylsworth et al., 2000). High ice contents may also occur in fine-matrix till and fine-grained colluvium. Thaw in ice-rich, fine-grained sediments causes flow-type landslides, due to the low strength of the resulting water-saturated sediments. In these icy sediments, even low-angle slopes in areas of relatively little relief are susceptible to active-layer detachments and retrogressive thaw flows. If relief is sufficient, these flows can move very rapidly as debris flows. Although much less common, sands, if well saturated, also may flow rapidly downslope as debris flows.

Coarse-grained sediments (sands and gravels) are less likely to contain ice in excess of the pore volume. Landsliding is most likely along steep riverbanks eroded in sands and gravels deposited along the margins of the above-mentioned glacial lakes. These sands and gravels tend to fail in blocks as rotational slides. These failures also involve the underlying lacustrine sediments, and, in fact, are promoted by the presence of weak, unfrozen clays beneath the typically frozen sands. In many locations south of about 65°N latitude, the height of the riverbank and the thickness of the coarse-grained sediments is greater than the depth of permafrost, so that groundwater is free to move toward the bank through the sand and gravel between the overlying permafrost and underlying clay layer. If the cliff face is stable, a frozen seal of ice-cemented sediments may develop on the slope and artesian pressures build up, triggering a failure. Conditions such as rapid erosion by the river of the base of the bank or insulation by deep snow cover at the base of the bank can remove that permafrost plug. The resulting rapid drawdown of water in saturated sediments may induce a landslide by initiating erosion of loose sediment.

IMPLICATIONS OF CLIMATE CHANGE

In permafrost regions, climate warming is likely to reduce the stability of slopes by causing a reduction in the thickness and the strength of frozen ground. However, it is presently not possible to predict the precise impact of climate warming because of the lack of data on the failure strength of frozen and thawing sediments and bedrock. In Dyke (2000) the sensitivity of slope stability to decreasing permafrost thickness or increasing active-layer thickness is discussed. This analysis suggests that thawing of icy permafrost sediments would significantly reduce slope stability.

Rockslides are less likely to be affected by climate change. They are more commonly induced by random physical processes such as earthquakes or river erosion, or by weathering and loss of strength along existing planes of weakness. Many may have occurred following glacial retreat as a result of oversteepening of valley walls by glacial erosion.

Although climate warming will reduce slope stability, it will most likely act only to accelerate an already active process. Many rotational slides are triggered by removal of the slope toe and undercutting of the bank by river erosion, which not only causes failures, but can maintain movement of an active slope by continually removing the supporting debris that accumulates at the base of the slope. Wave action in lakes and along coasts plays a similar role. On the other hand, anything that deepens the active layer, whether it be abnormally warm air temperature, removal of the insulating organic mat by fire or other means, or thermal instability resulting from proximity to warm water bodies, can cause slope failure. In icy sediment, the first two conditions would result in an active-layer detachment which may then develop into a larger failure (retrogressive thaw flow). The third condition, which would cause loss of support at the base of a slope, may induce a larger, deep-seated failure. Also, pore-water pressure from groundwater confined by permafrost may become more effective as permafrost thins (*see* Dyke, 2000).

If climate change should occur in the Mackenzie valley as suggested, then there should be warmer air temperatures, particularly in winter and spring, drier conditions due in part to increased temperatures, decreased snow and an earlier melt, and more extreme storms (consensus of opinion at the Mackenzie Basin Impact Study Final Workshop, Yellowknife, 1996). The ground temperatures would respond to these changing climate conditions; permafrost would degrade, possibly disappearing altogether in the south and active layers would deepen, melting interstitial ice, elsewhere. Given the prevalence of permafrost and icy sediments in this area, any regional ground-temperature warming that might occur would increase the frequency of landslides in the area, at least in the short term. Active-layer detachments and retrogressive thaw-flow slides are the most likely failure types under those conditions. Likewise, any increase in extreme storms will result in an increase in landslides. Heavy rainfall may saturate the ground, favouring debris flows, or increase the pore-water pressure in slopes, leading to deep-seated rotational slides. Riverbanks may be undercut by higher discharges in rivers following these storms, inducing rotational slides or smaller topples. The latter, by exposing icy sediment, may develop into retrogressive thaw-flow slides. Drier conditions, making forests more susceptible to lightning strikes, will result in fire-induced, active-layer detachments. In the north, rising sea level will inundate coastal and estuarine areas, creating thermal instability at the base of frozen slopes.

At a regional scale, those areas most susceptible to landslides in the event of climatic warming are likely to be areas that presently are experiencing significant numbers of landslides. At a more localized scale, terrain sensitivity will be dependent on local geology, topography, permafrost, and ground-ice conditions. Sites most susceptible to climatically induced landslides include ice-rich, fine-grained sediments on slopes in close proximity to bodies of water or rivers, or frozen coarse-grained sediments overlying clay or clayey till in steep sections along riverbanks where permafrost does not extend to the base of the section. In addition, fire scars on ice-rich slopes are susceptible to landsliding.

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