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Landslide inventory of the south-central Mackenzie River valley region, Northwest Territories

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Abstract: As part of the Northern Energy Development Mackenzie Valley Project, an inventory of terrain and geomorphic processes is currently being compiled for the Camsell Bend (NTS 95 J), Root River (NTS 95 K), Dahadinni River (NTS 95 N), and Wrigley (NTS 95-O) 1:250 000 NTS map sheets. The interaction between high relief, steep slopes, heavy precipitation, complex tectonic and glacial history, and the range of surficial deposits and bedrock along the Mackenzie River valley transportation corridor has resulted in a variety of landslide types. Earth materials most susceptible to failure are colluvial, glaciolacustrine, alluvial, and organic deposits containing discontinuous permafrost. Till and glaciofluvial outwash are the most stable earth materials. Channel migration has triggered numerous complex landslides along the Mackenzie River. Removal of stream-side vegetation and soil also leads to retrogressive-thaw flows and slides in ice-rich terrain.

Résumé : Dans le cadre du projet de la vallée du Mackenzie visant le développement de l'énergie dans le Nord, nous procédons actuellement à la compilation d'un inventaire des processus de terrain et des processus géomorphologiques dans les régions visées par les cartes suivantes à l'échelle du 1/250 000 : Camsell Bend (SNRC 95 J), Root River (SNRC 95 K), Dahadinni River (SNRC 95 N) et Wrigley (SNRC 95-O). L'interaction entre le terrain accidenté, les pentes abruptes, les fortes précipitations, l'histoire tectonique et glaciaire complexe et la variété des dépôts de surface et des roches du substratum dans la voie de communication de la vallée du Mackenzie a engendré une gamme de types de glissements de terrain. Les matériaux du sol qui sont les plus susceptibles de glisser sont les colluvions, les dépôts glaciolacustres, les alluvions et les dépôts organiques qui sont affectés par un pergélisol discontinu. Les matériaux les plus stables sont le till et les dépôts d'épandage fluvioglaciaire. La migration de chenaux a provoqué de nombreux glissements complexes le long du fleuve Mackenzie. La disparition du sol et de la végétation en bordure de ce cours d'eau donne lieu également à des coulées rétrogrades du sol et à des glissements provoqués par le dégel dans des sols riches en glace.

INTRODUCTION

As part of the Northern Energy Development Mackenzie Valley Project, the Geological Survey of Canada (GSC) is currently working to improve knowledge of the geology and geomorphology in the southern Mackenzie River valley region (DiLabio, 2005). Information on bedrock, surficial deposits, permafrost, and landslides is essential for environmental-impact assessments; construction of pipelines, highways, and settlements; extraction of fossil fuels, minerals, and aggregate; and sensitivity studies of groundwater and ecology. To better understand the range of landslide processes and their impacts on the region (Fig. 1), important terrain-mapping objectives include the identification and classification of individual and groups of landslides (Huntley and Duk-Rodkin, 2006). Together with surficial-geology and applied-terrain maps produced as part of this study, this inventory will contribute to an objective quantitative inventory of landslide hazards, showing the range, distribution, and magnitude of landslide events by the number and size of mass movements.

LANDSLIDE-PROCESS INVENTORY

The aim of this paper is to present an inventory of landslide and other geomorphic processes in the south-central Mackenzie River valley, a study area encompassing parts of the following physiographic regions (Duk-Rodkin and Lemmen, 2000):

A) Mackenzie Mountains and Franklin Mountains: montane terrain with exposed folded and thrust-faulted carbonate and clastic sedimentary rocks, characterized by high relief and steep slopes.

B) Mackenzie Lowland: drift-covered foothills and intermontane plateaus underlain by folded and faulted weak shale, limestone, and sandstone, and deeply incised by tributaries draining to the Mackenzie River.

C) Great Slave Plain: till and glaciolacustrine plains blanketed by extensive organic deposits, and overlying relatively undeformed shale, sandstone, and limestone.

Rock falls and debris avalanches

Rock falls are common in mountainous watersheds, and involve the toppling and detachment of bedrock masses from slopes (greater than 70%), and their subsequent free-fall,

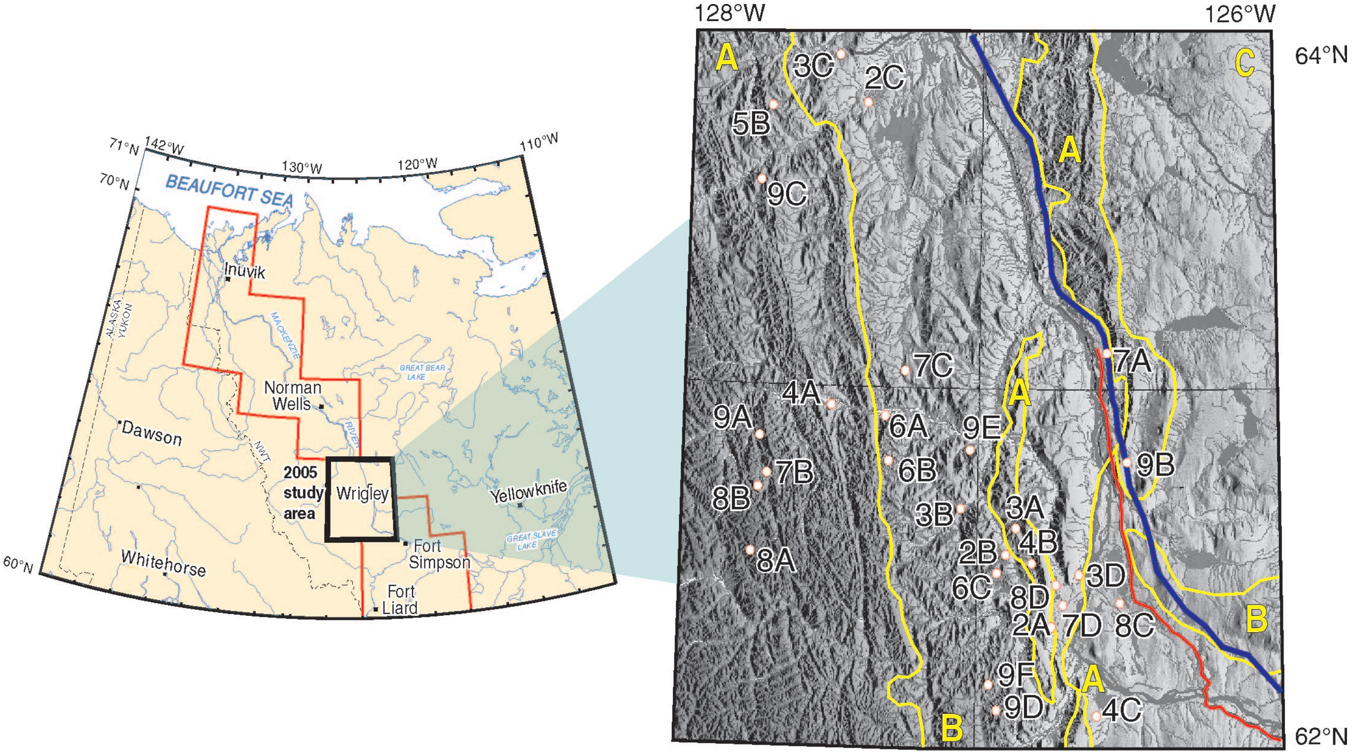

Figure 1. (Left) Limits of the Mackenzie Valley Project, location of the 2005 study area and locations of photographs in Figures 2 to 9. (Right) Detail of study area, with generalized physiography modified from Duk-Rodkin and Lemmen (2000): **A**) montane terrain; **B**) foothills and intermontane plateaus; **C**) plains. Symbols: red line, Mackenzie Highway; blue line, proposed pipeline route (AMEC Americas Limited, 2005).

bouncing, rolling, sliding, and eventual stopping (Evans and Savigny, 1994; Cruden and Varnes, 1996). In mountainous terrain, rock falls are gradational into debris avalanches as fragments become pulverized during the rapid downslope movement in steep gullies or bedrock exposures (Fig. 2A). Toppling of coherent blocks of carbonate, sandstone, and quartzite is observed where vertically jointed bedrock dips in the direction of slope (Fig. 2B). Gravitational spreading (*see* below), mechanical weathering, and earthquakes along active fault zones are important triggers of modern rock falls. In lowland areas and over the plains, debris avalanches are observed were channel erosion has exposed thick sequences of unconsolidated and frozen valley fill (Fig. 2C).

Figure 2. A) Camsell Range, Mackenzie Mountains: rock falls and debris avalanches, triggered by gravitational spreading, earthquakes, and frost-shatter, modify steep rock faces; colluvial cones at base of slope overlie glaciolacustrine deposits modified by permafrost processes. **B)** Carlson Creek, Mackenzie Lowland: escarpments formed in gently dipping limestone; toppling triggered by glacial incision, karst processes, gravitational spreading, and earthquakes. **C)** Dahadinni River, Mackenzie Lowland: advance-phase glaciofluvial outwash overlain by lodgment till and retreat-phase glaciolacustrine deposits exposed in river cutbank; stream incision at base of slope triggers debris avalanches.

Planar, rotational, and translational slides

Bedrock slides involve movement of coherent rock masses, most of which remain in contact with defined shear surfaces (Cruden and Varnes, 1996; Aylsworth et al., 2000). Translational slides involving the rigid movement of debris and rock along a planar failure surface (Fig. 3A) are restricted to mountainous terrain and the lowland, where they are typically triggered by glacial and fluvial erosion at the base of an inclined planar bedrock structure (e.g. bedding and fracture surfaces). Rotational slides involve the downslope movement of rigid blocks of bedrock and sediment along a curved failure surface forming the toe of a slide that extends well beyond the original slope. The upper surface of the block is back-tilted toward the scarp of the landslide. Slumped material can deform and flow as a result of melting ice within the slide material, modifying the shape of the original feature (Fig. 3B). Debris slides occur in thick deposits of unconsolidated glacial, glaciofluvial, and glaciolacustrine sediments (Fig. 3C, D). As a result, they exhibit considerable geological, hydrogeological, and geotechnical complexity. Another important contributor to failure is the undercutting of riverbanks by stream erosion and pressurized groundwater confined beneath the permafrost layer (Aylsworth et al., 2000; Dyke, 2000).

Debris flows

Rapid, open-slope, and channellized debris flows in steep mountain valleys and lowland watersheds are typically long and narrow, but widen into debris fans or cones at their base. Active flows comprise coarse-grained debris and organic material rapidly moving down steep open slopes or confined to pre-existing gullies and channels (Fig. 4A). Debris flows

Figure 3. A) Camsell Range, Mackenzie Mountains: translational slide in shale, sandstone, and carbonate triggered by postglacial uplift, gravitational spreading, and valley incision. **B)** English Chief River, Mackenzie Lowland: rotational slide in weak shale and carbonate triggered by rapid postglacial incision by river; note that colluvial shale and glacial debris are remobilized as secondary debris flows. **C)** Redstone River, Mackenzie Lowland: rapid planar debris slide triggered by melting of discontinuous permafrost in glaciolacustrine deposits and till exposed by cutbank erosion (evolving into debris flow). **D)** Mackenzie River, Great Slave Plain: rotational debris slide involving till, glaciolacustrine deposits, and glaciofluvial outwash triggered by cutbank erosion.

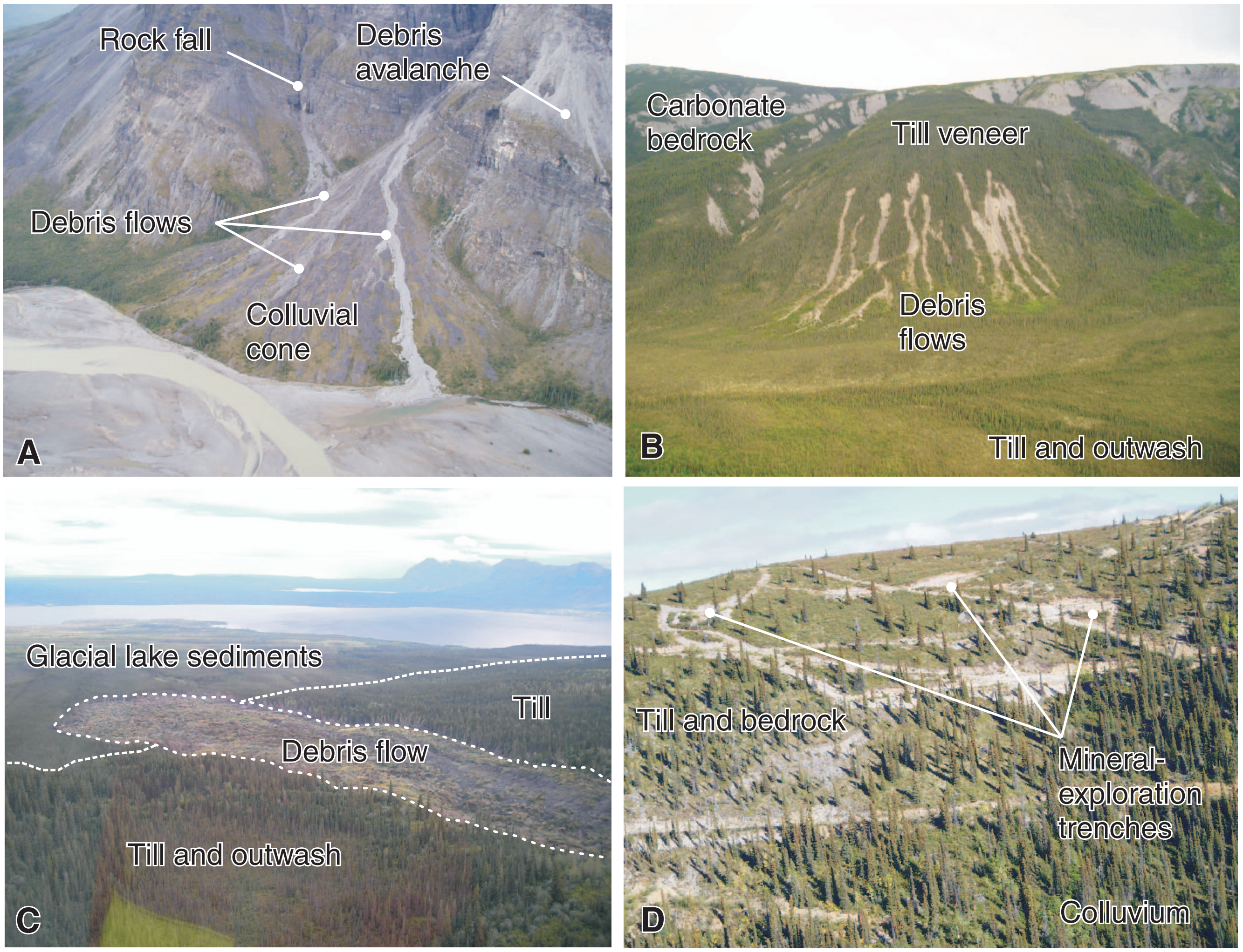

Figure 4. A) Root River, Mackenzie Mountains: channellized debris flows on a colluvial cone produced by remobilization of rock- and debris-fall material and snowmelt. **B)** Camsell Range, Mackenzie Mountains: debris flows on an open slope with a 40% gradient, disturbed by taiga fire; colluvial deposits failed after becoming saturated with snowmelt and summer precipitation. **C)** Cli Lake, Great Slave Plain: lobate debris flow involving discontinuously frozen glaciolacustrine and morainal deposits on open slope with a 6% gradient. **D)** Prairie Creek, Mackenzie Mountains (NTS 95 L): mineral-exploration trenches and access roads exposing potentially unstable morainal and colluvial deposits; failure of surficial materials at this location could lead to open-slope and channellized debris flows.

may be initiated by rock falls and shallow debris slides in gullies and channels, and on slopes mantled by a veneer of colluvium, till, or glaciofluvial deposits that has been mixed, transported, and deposited by storm runoff and snowmelt. Shallow failures on unconfined steep slopes may also develop into open-slope debris flows (Fig. 4B). Slow-moving debris flows are observed in the Mackenzie River valley along the eastern flank of the Camsell Range (Fig. 4C). These lobate, open-slope flows appear to be triggered by heavy rainfall; snowmelt; deep, seasonal thaw during warm summers; taiga fires; and loading disturbance through rock and debris fall along the mountain front. Land-use practices (e.g. seismic survey lines, pipeline and road construction, mining, and recreational activities) may also provide favourable conditions for the initiation of debris flows by disturbing soil and surficial deposits in ephemeral gullies and stream courses and on sensitive slopes (Fig. 4D).

Gravitational spreading

The slow deformation of steep slopes under the influence of gravity in mountainous terrain manifests itself as uphill-facing cracks, fissures, trenches, and scarps at middle and upper slope locations (Fig. 5A, B). Planar structural elements (e.g. joints, bedding planes, foliation) and slope are important controls on the rate and nature of gravitational spreading along detachment surfaces. In neighbouring Yukon and British Columbia, gravitational spreading is associated with

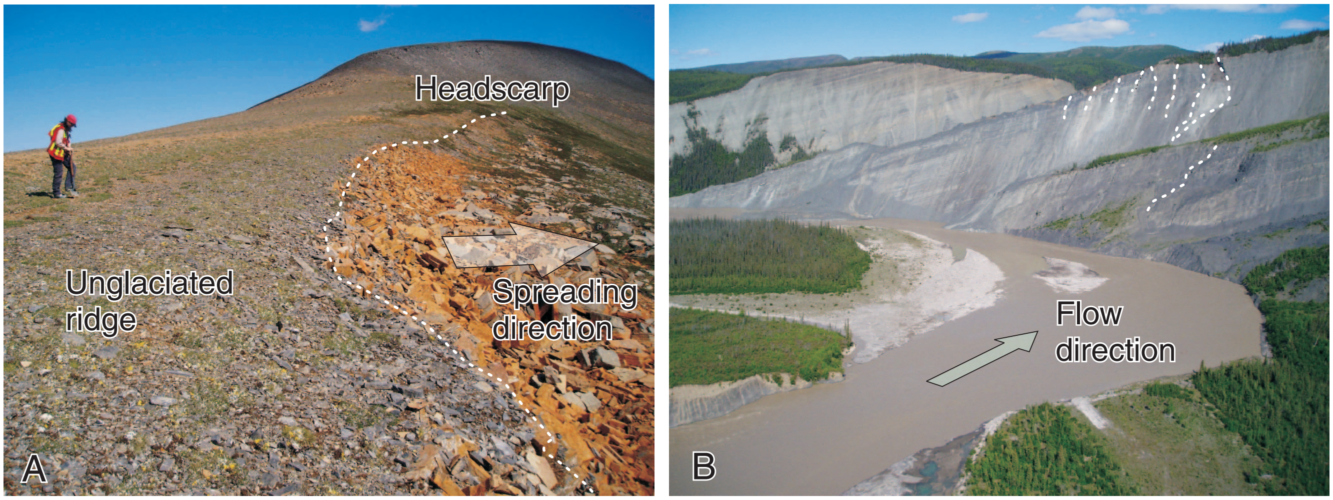

Figure 5. A) Delorme Range, Mackenzie Mountains: weathered bedrock and unglaciated terrain; gravitational spreading is expressed as sagging of the mountain slope toward the valley. **B)** Redstone River, Mackenzie Mountains: gravitational spreading in weak shale exposed through postglacial fluvial incision and uplift.

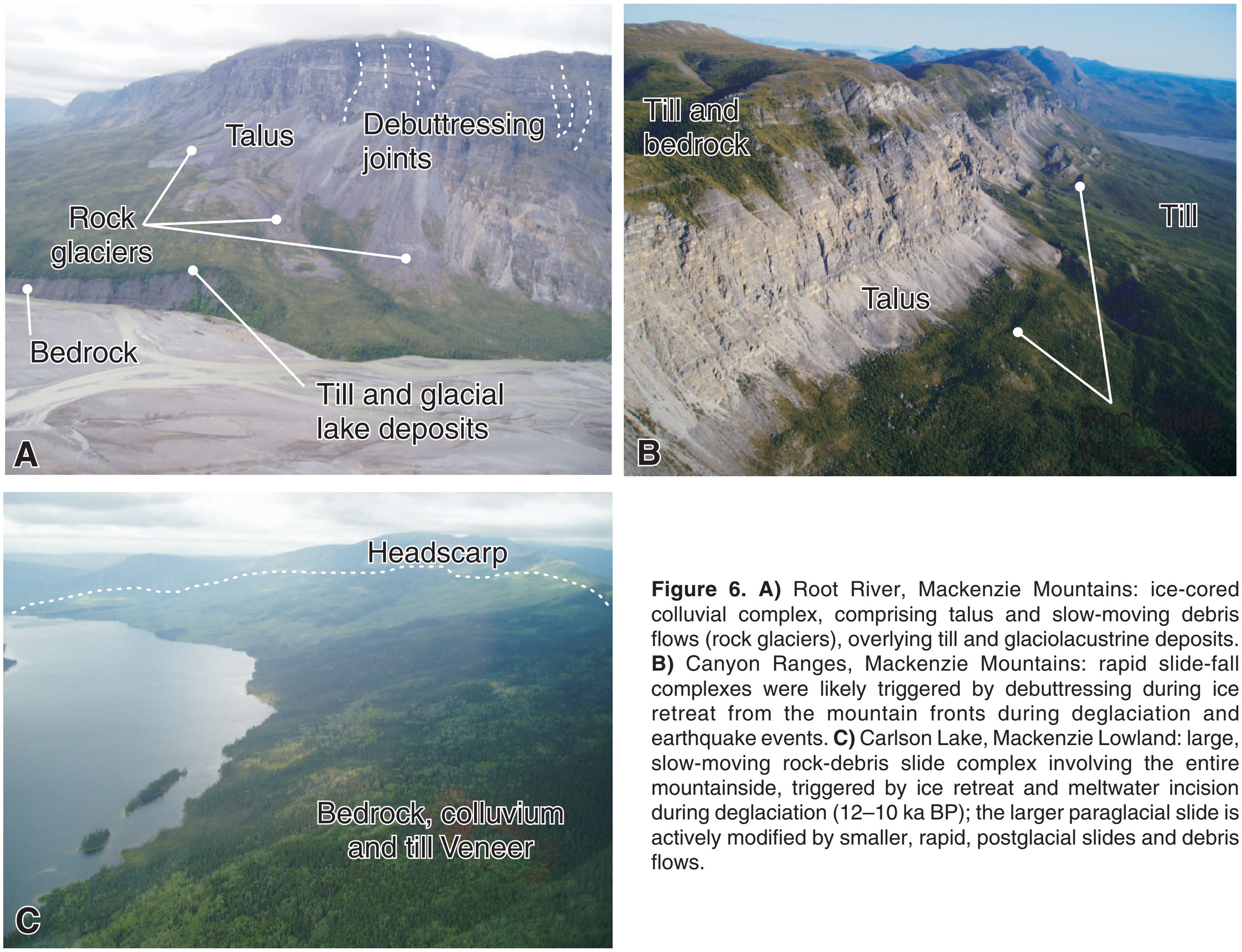

Figure 6. A) Root River, Mackenzie Mountains: ice-cored colluvial complex, comprising talus and slow-moving debris flows (rock glaciers), overlying till and glaciolacustrine deposits. **B)** Canyon Ranges, Mackenzie Mountains: rapid slide-fall complexes were likely triggered by debuttressing during ice retreat from the mountain fronts during deglaciation and earthquake events. **C)** Carlson Lake, Mackenzie Lowland: large, slow-moving rock-debris slide complex involving the entire mountainside, triggered by ice retreat and meltwater incision during deglaciation (12–10 ka BP); the larger paraglacial slide is actively modified by smaller, rapid, postglacial slides and debris flows.

seismic activity. Gravitational spreading rates are low (on the order of cm/a), although they are a precursor to many catastrophic rock falls and debris flows (Evans and Savigny, 1994; Huscroft et al., 2004).

Landslide complexes

Landslide complexes involve flow and slides of large volumes of mineral soil, surficial debris, bedrock, and organic matter. Large landslides occurring over several square kilometres and involving the sliding and avalanching of millions of cubic metres of rock and debris were probably triggered by fluvial incision and relaxation of valley sides during ice retreat, and/or by seismic events. Many landslide complexes have been continuously active since glaciation. In montane and lowland valleys, large slow-moving rotational/translational slide complexes were triggered by debuttressing during retreat of ice, channel incision by meltwater, and early postglacial uplift. At present, these 'paraglacial' landslides (cf. Church and Ryder, 1972) are being actively modified by smaller, rapid slides and debris flows. Terrain affected by complex landslides usually displays irregular, chaotic, or hummocky topography, bounded upslope by arcuate scarps, seepage, and small ponds (Fig. 6A–C).

Figure 7. A) Wrigley, Mackenzie River valley: initiation of an active-layer detachment on an 8° slope; detachment of the organic layer exposes underlying, frozen, fine-grained lake sediments and till. **B)** Delorme Range, Mackenzie Mountains: multiple active-layer skin flows on a 3° slope, involving water-saturated glaciolacustrine sediment, till, and weak shale over frozen surficial materials. **C)** Root River, Mackenzie Lowlands: active-layer detachments evolving into retrogressive-thaw flows, triggered when the site was disturbed by taiga fire and channel erosion. **D)** Mackenzie River (Camsell Bend), Great Slave Plain: retrogressive-thaw flow triggered by cutbank erosion and debris falls that expose frozen glaciolacustrine sediments. **E)** Mackenzie River (Old Fort Point, NTS 96 C), Mackenzie Lowland: retrogressive-thaw slide triggered by cutbank erosion of thick, frozen glacial deposits; remobilized blocks of glaciolacustrine and outwash deposits are actively sliding over discontinuously frozen till and bedrock.

Figure 8. A) Mackenzie Mountains, northwest of Wrigley Lake (NTS 95 M): cryoplanation terraces formed above the limit of montane and continental glaciation. **B)** Delorme Range, Mackenzie Mountains: colluvial fan and glaciolacustrine deposits reworked by gelifluction on a 6° slope. **C)** Mackenzie River valley, Great Slave Plain: organic-filled depressions and thermokarst thaw lakes formed in glaciolacustrine deposits. **D)** Mackenzie River valley, Great Slave Plain: beaded channel form indicative of thermal erosion of permafrost by stream water; modern channel incises a glaciolacustrine plain abutting the Camsell Range.

Active-layer detachments, retrogressive-thaw flows, and retrogressive-thaw slides

Detailed ground investigations are required to identify these types of thaw features because they are not distinguishable at a 1:50 000 mapping scale. Active-layer detachments are shallow slope failures involving the separation and downslope movement of saturated surficial material and vegetation (Aylsworth et al., 2000; Fig. 7A). Detachments are triggered by unusually warm temperatures or disturbance of the vegetation mat (e.g. by taiga fires, stream incision, or land-use practices) and occur when the increasing weight of the thawed material in the active layer overcomes the cohesive strength of the material (Dyke 2000). Active-layer detachments expand laterally and retrogressively as adjacent ice-rich sediment thaws. Active-layer glides typically involve sliding of intact, thawed ground on underlying frozen sediment. Skin flows involve the flow of water-saturated sediment (Aylsworth et al., 2000; Fig. 7B). On slopes ranging from 3 to 15°, active-layer detachments develop into retrogressive-thaw flows and slides if removal of water-saturated sediment continually exposes massive ice and ice-rich sediment at depth (Aylsworth et al., 2000). Once initiated, the headwall gradually erodes upslope as massive ground ice or ice-rich sediment thaws in the scarp, and the resulting water-saturated sediment flows downslope away from the headscarp. Thaw flows and thaw slides have a characteristic bowl shape, steep headwall, and low-angle tongue (Fig. 7C, D). Flows stabilize if scarp faces become buried by debris, the ice content of exposed sediment decreases, the scarp slope decreases, or the flow becomes stabilized by vegetation.

Figure 9. A) Delorme Range, Mackenzie Mountains: *rillenkarren* formed by the surface dissolution of limestone by precipitation and snowmelt. **B)** Willowlake River, McConnell Range: sinkhole formed by underground dissolution of limestone and inward collapse of rock and till; water level in the sinkhole fluctuates seasonally and annually. **C)** Redstone River, Mackenzie Mountains: calcium-rich spring with 25 m high tufa terrace deposited after glaciation. **D)** Nahanni Plateau, Mackenzie Mountains: limestone pavement scoured by continental ice and overlain by veneer of till with granitic erratics. **E)** Root River, Mackenzie Mountains: abandoned sinkhole truncated by glacial erosion of valley. **F)** Nahanni Plateau, Mackenzie Mountains: deranged cave passages exposed by glacial erosion of valleys.

Active-layer detachments, thaw flows, and thaw slides may become reactivated if stream erosion, rising water, or wave action erodes the toe of the scarp, moving debris away from the slope face (Fig. 7E). Similar to the northern part of the Mackenzie River valley transportation corridor (Couture et al., 2005), retrogressive-thaw flows are the most common type of slope failure in ice-rich, fine-grained glaciolacustrine, glaciofluvial, and morainal terrain in the study area.

Cryoplanation and gelifluction

Mountaintops beyond the limits of continental and montane glaciation have been locally modified through cryoplanation. Freeze-thaw weathering and gelifluction operating over hundreds to millions of years have transformed rounded mountaintops, giving rise to benches, terraces, and pediment surfaces (Fig. 8A). Gelifluction, the slow gravitational downslope movement of water-saturated, seasonally thawed material, is presently confined to middle and lower slopes in the Mackenzie Mountains. Landforms produced by gelifluction include uniform sheets of cryoturbated material, stone stripes, and tongue-shaped lobes (Fig. 8B).

Thermokarst and thermal erosion

Terrain susceptible to thermokarst activity is confined to outwash and glaciolacustrine deposits in valley floors and over the plain (Fig. 8C, D). Thermokarst is characterized by topographic depressions with or without standing water, produced by the selective thawing of ground ice. Changes in climate, environmental conditions, and human activity can trigger thermal erosion by stream and lake water. Landform assemblages include thaw lakes and beaded drainage. Thaw-related subsidence can trigger retrogressive-thaw flows and debris slides.

Karst processes

Karst landforms are observed where limestone and dolomite outcrops. Active surface and underground solution leads to the collapse and subsidence of the surface in catchment areas and precipitation of carbonate at springs (Fig. 9A–C). Preglacial features (e.g. limestone pavements, sinkholes, and caves) were extensively modified by continental ice and montane ice during the last glaciation (Fig. 9D, E).

LANDSLIDE ANALYSIS

High relief, steep slopes, heavy precipitation, a range of surficial deposits and bedrock, and a complex tectonic, climate-change and glacial history interact to produce a variety of landslide types in the Mackenzie River watershed. Earth materials most susceptible to failure are thrust-folded bedrock (sandstone, limestone, shale, and mudstone) and colluvial, glaciolacustrine, alluvial, and organic deposits containing discontinuous permafrost. Till and glaciofluvial outwash are the most stable earth materials. Rapid landslides in bedrock dominate in mountainous terrain. Slow-moving landslides in the lowlands, valleys, and plains remobilize partly frozen glacial debris. Retrogressive-thaw flows and thaw slides dominate where glaciolacustrine deposits are found. The highest landslide densities occur in terrain underlain by shale and mudstone, and those areas of discontinuously frozen glaciolacustrine sediments, till, and outwash with slopes of 27% or less.

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REFERENCES

AMEC Americas Limited

2005: Landform sensitivity atlas, Mackenzie Gathering System and Mackenzie Valley pipeline preliminary engineering alignment sheets; submission IPRCC.PR.2005.01 to National Energy Board by Imperial Oil Resources Ventures Limited, scale 1:30 000.

Aylsworth, J.M., Duk-Rodkin, A., Robertson, T., and Traynor J.A.

2000b: Landslides of the Mackenzie valley and adjacent mountainous and coastal regions; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 167–176.

Church, M. and Ryder, J.M.

1972: Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation; Geological Society of America Bulletin, v. 83, p. 3059–3072.

Couture, R., Riopel, S., Farley, C., and Singhroy, V.

2005: Regional terrain hazards and landslide mapping, Mackenzie Valley: project description and preliminary results from the 2005 field campaign and mapping; *in* 33rd Annual Yellowknife Geoscience Forum Abstracts Volume, (comp.) E. Palmer; Northwest Territories Geoscience Office.

Cruden, D.M. and Varnes, G.J.

1996: Landslide types and processes; *in* Landslides: Investigations and Mitigation, (ed.) A.K. Turner and R.L. Schuster; National Academy Press, Washington, D.C., Transportation Research Board Special Report 247, p. 36–75.

DiLabio, R.N.W.
2005: NRCAN’s research program related to the Mackenzie Valley Pipeline; *in* 33rd Annual Yellowknife Geoscience Forum Abstracts Volume, (comp.) E. Palmer; Northwest Territories Geoscience Office.

Duk-Rodkin, A. and Lemmen, D.S.
2000: Glacial history of the Mackenzie region; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 11–20.

Dyke, L.D.
2000: Stability of permafrost slopes in the Mackenzie valley; *in* The Physical Environment of the Mackenzie Valley, Northwest Territories: A Base Line for the Assessment of Environmental Change, (ed.) L.D. Dyke and G.R. Brooks; Geological Survey of Canada, Bulletin 547, p. 177–186.

Evans, S.G. and Savigny, K.W.
1994: Landslides in the Vancouver–Fraser Valley–Whistler region; *in* Geology and Geological Hazards of the Vancouver Region, Southwestern British Columbia, (ed.) J.W.H. Monger; Geological Survey of Canada, Bulletin 481, p. 251–286.

Huntley, D. and Duk-Rodkin, A.
2006: Landslide processes in the south-central Mackenzie River valley region, Northwest Territories; Geological Survey of Canada Paper, Current Research 2006-A9.

Huscroft C.A., Lipovsky, P.S., and Bond, J.S.
2004: A regional characterization of landslides in the Alaska Highway corridor, Yukon Territory: digital compilation; Yukon Geological Survey Open File 2004-18(D), CD-ROM.

Geological Survey of Canada Project Y51-5001