Hillslope and Fluvial Processes Along the Proposed Pipeline Corridor, Burns Lake to Kitimat, West Central British Columbia

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Executive Summary

Hydrocarbon pipelines are currently proposed to cross west central British Columbia (B.C.) to access a deepwater port at Kitimat. The geology and geomorphology of the area is complex and destructive landslides are common. The northwest trending rugged topography poses serious challenges for pipeline development. Only certain valleys and passes are suitable for east–west oriented infrastructure. The terrain across west central B.C., with steep unstable rock masses and weak soils, places considerable constraints on pipeline development.

This paper provides an overview of the landscape, terrain, hillslope processes and fluvial processes found within the general area of the proposed pipeline corridor across west central B.C. The intent of this paper is to help formulate discussion, encourage more in-depth study, direct more detailed on-the-ground investigation, and stimulate investigation into possible safer alternative routes to the unstable terrain found in west central B.C. This paper does not discuss environmental consequences and risk associated with the proposed pipelines although the environmental consequences of an oil pipeline break do differ considerably from a break sustained by a natural gas pipeline.

The proposed corridor crosses three distinct physiographic units: the Nechako Plateau, the Hazelton Mountains, and the Kitimat Ranges. These units are distinct topographically as reflected in present day landforms, erosion, and landslides, and thus present different hazards to a pipeline.

The Nechako Plateau appears relatively benign; however, large landslides have occurred in volcanic rock overlying other older volcanic and sedimentary rock. Active bedrock spread is occurring to the east of Parrott Creek, possibly foreshadowing further movement along the northwest-southeast trending ridges running between Houston and Francois Lake. Along the Morice River, advance-phase glaciolacustrine sediments have historically experienced landslides. Road construction and wildfires have reactivated these landslides. The proposed pipeline corridor crosses an historic earth flow west of Owen Creek, glaciolacustrine sediment along Owen Creek, and probably buried advance-phase glaciolacustrine sediments near Owen Creek, Fenton Creek and Lamprey Creek.

The pipeline corridor follows the Crystal forest access road up Gosnell Creek. Shifting channels on active alluvial fans pose road maintenance challenges along a 10 km section of the road. Pipelines will likely present similar challenges crossing these fans. There is considerable lateral bank instability at the proposed Crystal Creek and Gosnell Creek crossing.

The proposed pipeline corridor dissects the floodplain (glaciofluvial and glaciolacustrine terrain) located immediately upstream from the Clore Canyon. No development of any sort has occurred to date upstream of the Clore Canyon so it is unclear how this terrain will respond to pipeline development.

The volcanic bedrock of the Hazelton Mountains is inherently unstable as evident in many prehistoric landslides. Three documented large landslides within the Bulkley Range of the Hazelton Mountains have severed the natural gas pipeline since its construction in the early 1970s; large landslides have also impacted forest roads and highways.

Deep-seated gravitational slope deformation is prevalent in the volcanic bedrock found in the Kitnayakwa, Clore and Bernie watersheds. Sackungen or slope sagging, indicative of slope deformation, indicates active slope movement that commonly foreshadows a pending landslide. A thorough geotechnical investigation is required to determine the stability of the bedrock and hillslope in areas of slope deformation. Avoidance of these unstable hillslopes is generally the preferred engineering development option.

The proposed corridor crosses through a mountainside to the southeast of the Clore Canyon. The highly fractured bedrock in the canyon is undergoing active mass erosion. This visibly

unstable rock reaches up to about 1200 m above sea level (asl) and extends around the mountain into an adjacent tributary valley. This bedrock along the north and west side of the mountain is extensively gullied and contains many landslide scarps and an actively moving landslide. Along the east side of the mountain, sackungen parallel the slope and extend through old landslide scarps. The active instability of the mountain slope places major constraints on development.

Steep narrow valleys characterize the Kitimat Ranges. Colluvial-fluvial fans are at the base of most steep gully channels in the Hoult Creek and Upper Kitimat watershed. These steep gully channels extend from the alpine onto the valley flat or directly into Hoult Creek or the Kitimat River. Many of these high-energy systems experienced debris flows during extreme rainstorms in the fall of 1978 and the fall of 1992. Debris flows commonly occur under seemingly "normal" storm events during summer convective storms and fall frontal rainstorms. Debris flows are powerful landslides that can damage or rupture pipelines.

Hunter Creek, a large active alluvial fan, has historically pushed the Kitimat River across the valley. The most recent catastrophic channel avulsion occurred in 1992. This avulsion was caused by road construction up the fan and the construction of a levée above the bridge crossing on Hunter Creek. Channel changes will likely recur on the fan during major flood events.

The Kitimat Trough, situated between Terrace and Kitimat, is an uplifted fiord. Sensitive glaciomarine sediments occupy much of the valley floor. Deep deposits of glaciofluvial sediments and postglacial materials (floodplain, alluvial fans and bogs) cover the glaciomarine sediments. These glaciomarine sediments have experienced large prehistoric and recent landslides. A high incidence of prehistoric landslides occur around Mink Creek, the Nalbeelah wet land complex, the foreslope of the Onion Lake Flats (fan-delta), Cecil Creek and Deception Creek.

Recent large flow slides occurred at Mink Creek (winter 1992-93) and Lakelse Lake in May and June 1962. A large submarine flow slide occurred in sensitive marine muds at the front of the fiord-head delta at Kitimat Arm in April 1975. These recent landslides serve to show the continuing sensitivity of the glaciomarine sediments in the Kitimat Trough and the marine sediments on the fan-delta at the fiord-head of Kitimat Arm. Natural and human caused factors such as increases in surface load, removal of lateral support by stream bank undercutting or excavation, vibration by heavy equipment, earthquake shock, high water pressures and interruption of intertidal drainage can trigger these landslides. Thus, the potential exists for landslides to occur during pipeline construction and in the future.

Glaciomarine sediments in the vicinity of Cecil Creek, Deception Creek, Wedeene River, Little Wedeene River, along the west side of Kitimat Arm and along Chist Creek will be encountered during pipeline construction. The pipeline corridor crosses features indicative of prehistoric flow slides near Cecil Creek through to the little Wedeene River. The presence of prehistoric flow slides in the glaciomarine sediments suggest a high probability that future landslides will occur. These failures commonly start with a small landslide from bank erosion or loading that exposes a layer of sensitive material. Then, they rapidly retrogress with a flow of material from the displacement basin. Pipelines crossing glaciomarine sediments must therefore avoid areas that lie within potential flow slide depletion zones as landslides will break or disrupt pipeline service.

Landslides travel long distances and damage linear infrastructure such as pipelines. Six large rock slides occurred in west central B.C. since 1978, five of these since 1999, and four since 2002. Three of the six rock slides severed the natural gas pipeline (Howson landslides in 1978 and 1999, and Zymoetz landslide in 2002). Damage to linear infrastructure commonly occurs in runout zones many kilometres from the initial landslide. This has occurred with recent landslides in west central B.C.; the longest traveled in excess of 4 km along a slope of 9°. Therefore, the potential for damage to pipelines extends to unstable terrain and potential landslides that start well outside the construction corridor.

Long periods of increasing precipitation and temperature are associated with most dated, large landslides across northern B.C. The climate of northern B.C. appears to have become warmer and wetter since the beginning of instrumental observations. There is evidence to suggest that landslide rates have increased in west central B.C. Climate change scenarios suggest a warmer and wetter climate for west central B.C. Therefore, the rate of landslide occurrence will likely increase and thus the likelihood of landslide impact to a pipeline will increase.

Recognition and avoidance of unstable terrain is the most efficient and cost effective method for management in landslide prone terrain. This requires detailed terrain stability mapping and geotechnical investigation to identify unstable slopes, runout zones, and depletion zones. Avoidance of unstable terrain is a difficult management strategy to adopt over many sections of the proposed pipeline corridor given the topographic constraints. Therefore, the unstable mountainous terrain across west central B.C. is not a safe location for pipelines. Eventually a landslide will sever a pipeline. An alternative safer route through B.C. needs investigation.

1 Introduction

Hydrocarbon pipelines are currently proposed to cross west central British Columbia (B.C.) to access the deepwater port at Kitimat (Figure 1). In west central B.C., these pipelines will cross to the north of the community of Burns Lake, extend west to the Morice River, continue west along the south side of the Morice River, up the Gosnell Creek drainage and across the Clore River valley. Then, the route follows the north side of the Kitimat River crossing the Kitimat Valley on the Onion Lake Flats, traveling south down the west side of the valley to a proposed terminal at tide water near the city of Kitimat. Two tunnels are proposed to connect the upper Clore valley through to Nimbus Mountain and through Nimbus Mountain to Hoult Creek. The corridor in west central B.C. crosses three physiographic units: Nechako Plateau, Hazelton Mountains, and Kitimat Ranges (Figure 1). The geology and geomorphology of the region is complex and destructive landslides are common. Geertsema et al. (2009) make this statement… **"The northwest trending rugged topography poses serious challenges for linear development. Only certain valleys and passes are suitable for east–west oriented infrastructure. Together with steep, unstable rock masses and weak soils, the terrain in west central B.C. places constraints on development."**

This paper provides a general overview of the landscape, terrain, hillslope processes and fluvial processes found within the general area of the proposed pipeline corridor across west central B.C. Published literature referenced in the paper pertains to the geographic area. Technical terminology is kept to a minimum. The paper contains information and interpretations based on my observations and experience gained over 30 years conducting field investigations, helicopter reconnaissance work, and aerial photograph interpretation while working in northwest B.C. as a Research Geomorphologist for the B.C. Forest Service.

The intent of the paper is to help formulate discussion, encourage more in-depth study, direct more detailed on-the-ground investigation, and stimulate investigation into possible safer alternative routes to the unstable terrain found in west central B.C. This paper is by no means a complete discussion of bedrock geology and surficial geology in the region nor does it answer geotechnical engineering concerns at specific site locations. There also is no attempt to discuss environmental consequences and risk, although the environmental consequences of an oil pipeline break do differ considerably from a break sustained by a natural gas pipeline.

1.1 Regional Setting

The topography of the Coast Mountains, Hazelton Mountains, and Nechako Plateau strongly influences precipitation and air temperature across the region. The predominant flow of moisture-laden air travels easterly from the Pacific Ocean. Mean annual precipitation values for coastal mountains generally exceed 2500 mm and many areas do experience >3500 mm. Precipitation decreases toward the east with a mean annual precipitation of 1322, 513, and 460 mm for Terrace, Smithers and Burns Lake, respectively, with 25 to 40% of this as snow (Canadian Climate Normals 1971-2000). Mean annual April snow pack at higher elevation is about 1400 mm snow water equivalent at Tsai Creek (Telkwa Watershed, 1369 masl, coastal-interior transition) and about 350 mm snow water equivalent at Lu Lake (Equity Silver Mine, 1308 masl, interior climate). Mean temperature in January is -4.3ºC, -8.9ºC, and -10.5ºC, and mean July temperature is 16.4ºC, 15ºC, and 14.3ºC respectively, for Terrace, Smithers and Burns Lake. Summer temperatures decrease by several degrees at higher elevations. The Coastal Western Hemlock Biogeoclimatic Zone occupies the main valleys in the Coast Mountains and the Sub-Boreal Spruce Zone occupies the main valleys in the interior. At higher elevations, Mountain-Hemlock, Engelmann Spruce-Subalpine Fir, and Alpine Tundra Zones occur (Meidinger and Pojar 1991).

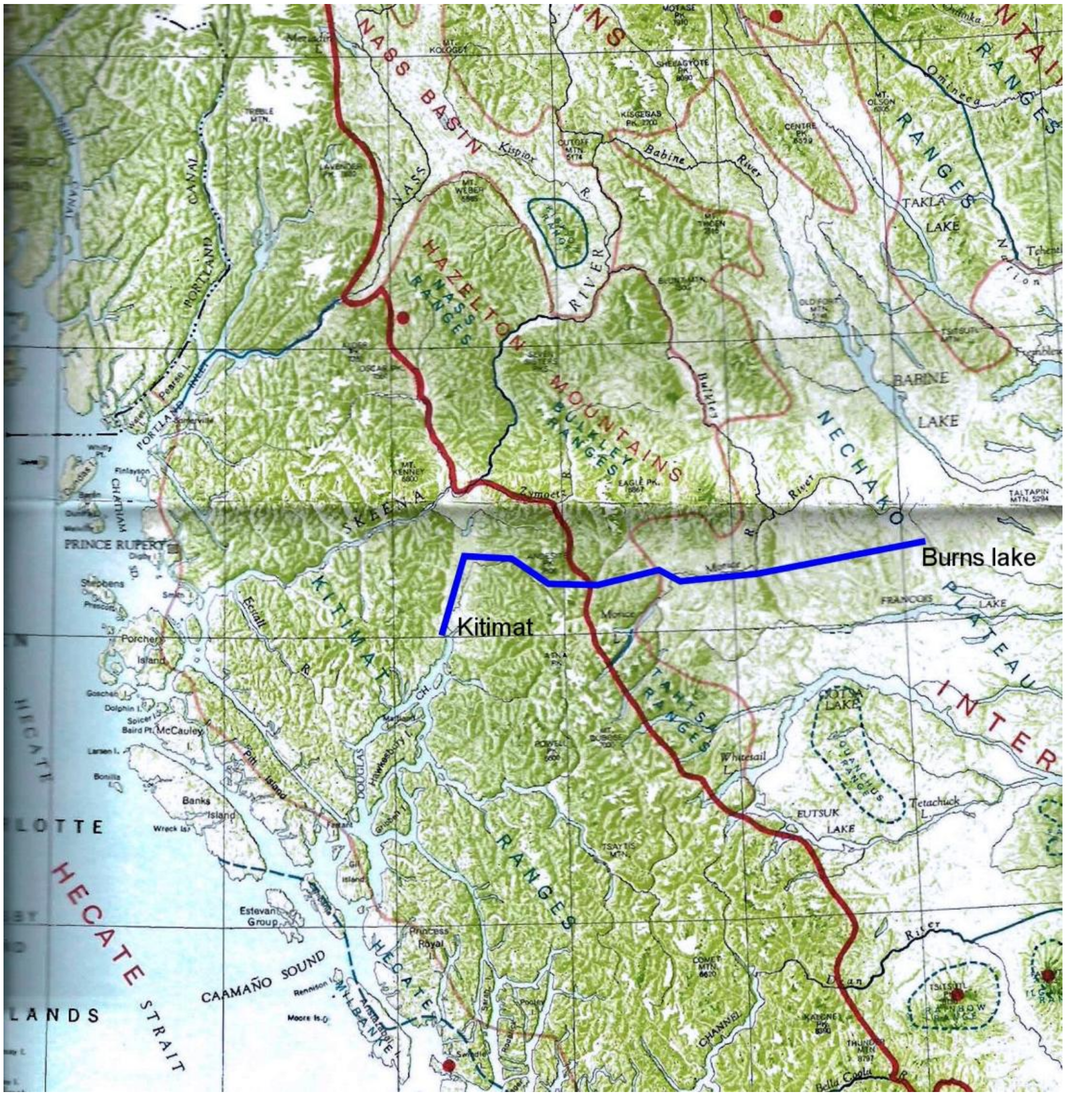

Figure 1: Map modified from Holland (1976) shows west central British Columbia physiographic regions and an approximate delineation of the proposed pipeline corridor, marked in blue, west from the community of Burns Lake to Kitimat.

1.2 Physiographic Regions

Physiographic regions and subdivisions of Holland (1976) and Mathews (1986) reflect present day topography and landforms; a result of similar geologic histories of mountain building, similar bedrock response to erosion, and similar contemporary erosional and depositional processes. Readers interested in an expanded introduction into the factors that have created the physiography and landscapes of British Columbia are encouraged to consult Church and Ryder (2010). Holland (1976) provides a detailed description of the physiographic regions in west central B.C. The Nechako Plateau, Hazelton Mountains and Kitimat Ranges including the Kitimat-Kitsumkalum Trough (Kitimat Trough) are the physiographic units from east to west, respectively (Burns Lake to Kitimat) crossed by the proposed pipeline corridor. These units are distinct topographically; distinguished in present day landforms, erosion and landslide processes.

1.2.1 Nechako Plateau

The Nechako Plateau is an area of low relief characterized by an expanse of flat or gently rolling landscapes. The plateau elevation sits between 1200 and 1500 masl, separated by wide valleys with elevations of 700 to 900 masl. Long narrow lakes occupy many of the subdued valleys, for example, Francois Lake. Gently dipping or flat lying lava that covers much of the Nechako plateau overlies older volcanic, sedimentary and intrusive rocks. Deep glacial sediments cover and obscure much of the bedrock ridges and knobs. Locally, bedrock is visible on bluffs above Houston, China Nose Mountain, Morice Mountain, Nadina Mountain and the ridge to the east of Parrott Creek.

Glacial ice covered the Nechako Plateau extending above the plateau and valleys to 2000-3000 masl during the last glaciation (Clague 1989). Grooves or lineation and drumlin ridges originating from glacier movement mark the landscape and show the direction of ice flow. Meltwater channels and eskers are recognizable features on the plateau. Numerous lakes and ponds now occupy depressions left by melting glacial ice.

1.2.2 Hazelton Mountains

The Hazelton Mountains lie west of the Nechako Plateau and east of the Kitimat Ranges of the Coastal Mountains. They extend from the Nass River southeastward toward Eutsuk Lake and comprise the Nass Ranges, Bulkley Ranges and Tahtsa Ranges. Volcanic and sedimentary rocks underlie the mountains. Many of the mountain peaks have cores of granitic rock.

The Bulkley Ranges sit west of the Bulkley River, south of the Skeena River and east of the Zymoetz River at Terrace following a southeasterly trend to Morice Lake. The Bulkley Range transitions into the Nechako Plateau to the east and south of the Telkwa Range. The ranges contain rugged mountain peaks and rounded lower elevation mountains. Rugged peaks shaped by alpine glaciation include the Seven Sisters peaks (2747 masl), Brian Boru Peak (2507 masl) in the Rocher Déboulé Range, Hudson Bay Mountain (2598 masl) and the Howson Peak (2759 masl). Rounded mountains with drumlins and fluted ridges on lower elevation (< 1900 masl) indicate that glaciers overrode these mountains during the maximum phase of the last glaciation (Stumpf 2001). In fact, all but the highest peaks were covered during the last glaciation. The Hazelton Mountains, with peaks sculptured by alpine glaciation bounded by wide valleys differ distinctively from the steep narrow glaciated valleys of the Kitimat Ranges.

1.2.3 Kitimat Ranges

The Kitimat Ranges of the Coastal Mountains comprise dome-like granitic mountains overridden by glacial ice. The mountains are relatively uniform in elevations at about 2200 masl. A few higher peaks project as Matterhorn-type features; Atna peak is the highest of these at 2724 masl. Glacial ice has carved steep-sided narrow valleys. Another characteristic feature is the long fiords that penetrate the range. The fiords are a product of intense glaciation of pre-existing valleys. The north south trending Kitimat valley, termed the Kitimat-Kitsumkalum Trough (Kitimat Trough) is a fiord filled with glacial and postglacial sediments (refer to section 2.4 for a more detailed discussion on the glacial history and glaciomarine sediments of the Kitimat Trough).

2 Hillslope and Fluvial Processes

Landslides and erosion are commonplace in the mountainous terrain of west central B.C. (Geertsema et al. 2006a). The landslides include shallow debris slides and flows, massive rapid moving rock slides, slow moving earth flows and rapid moving flow slides (refer to Cruden and Varnes 1996; Hungr 2005; and Geertsema et al. 2010 for landslide terminology and descriptions). Climate, topography, bedrock geology and surficial geology influence the type, frequency and occurrence of various hillslope processes within a physiographic unit. Hence, hillslope processes between Burns Lake and Kitimat are discussed within the context of recognized physiographic units within a described location, for example, Nechako Plateau—Burns Lake to the Morice River.

2.1 Nechako Plateau

The pipeline corridor west from Burns Lake to the Morice River Valley crosses 80 km of the Nechako Plateau. The plateau is gently rolling and climbs to the ridge of Equity Silver Mine then drops back toward the Morice River Valley (Burns Lake, 700 masl; Equity Silver Mine, 1400 masl; Morice River, 660 masl). Bedrock is commonly obscured by deep till (moraine) except along the northwest-southeast trending ridges that extend from Houston toward Francois Lake. Bedrock exposures occur near Houston, Equity Silver Mine and the bluffs to the east of Parrott Creek. Erosion has modified the landscape with meltwater channels cut into the underlying till and fluvial materials deposited as outwash. Streams tend to occupy glacial meltwater channels that flow toward the Bulkley River or Francois Lake (Morice River, Buck Creek, Maxan Creek, Tchesinkut Creek and Parrott Creek).

2.1.1 Burns Lake to the Morice River

The rolling and subdued terrain of the Nechako Plateau appears relatively benign in terms of erosion and landslides. However, erosion and landslides do occur. A natural erosional event in the early 1980s transported in the order of 250 000 m^3 of sand and gravel from a glacial fluvial terrace into and down Tchesinkut Creek (Figure 2). The eroded gully appears very similar in shape to early post-glacial erosion cut channels through the glacial fluvial terrace above Tchesinkut Creek. Interestingly, Plouffe (1996, 2000) describes sediments in the area containing advance-phase glaciolacustrine sediments (refer to the Morice River section for a more detailed discussion on advance-phase glaciolacustrine sediments). Glaciofluvial sediments likely cover glaciolacustrine sediments at the Tchesinkut Creek erosional site. A natural diversion of a stream channel onto the glacial fluvial terrace caused the erosion. This type of event, sometimes called a washout-flow, has occurred catastrophically in similar glaciofluvial and glaciofluvial-glaciolacustrine sediments across British Columbia (refer to Schwab (2000, 2001a) and Geertsema et al. (2010) for a description of the processes involved in a washout-flow). A similar type of erosional event could occur through the inadvertent redirection of seasonally running streams by access trails or ditches.

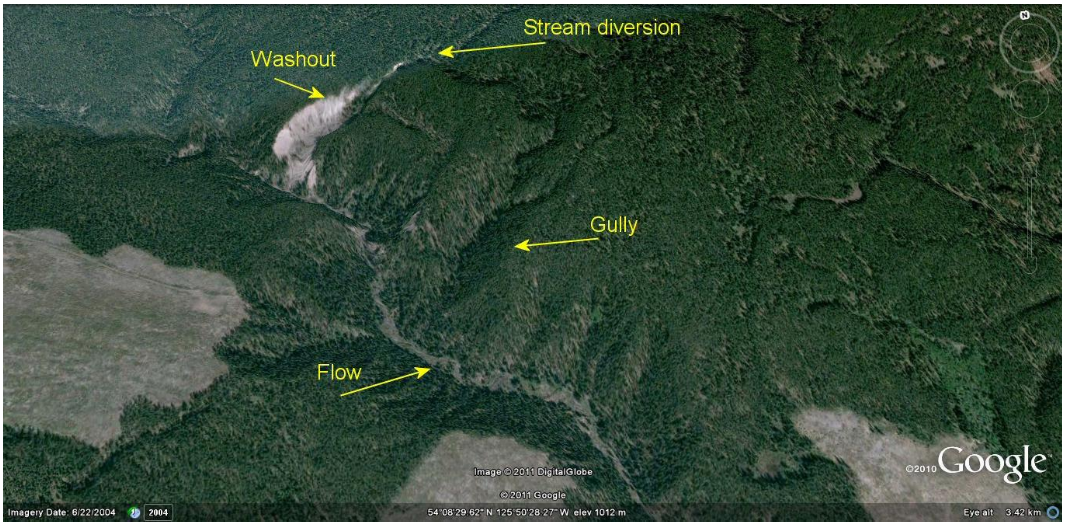

Figure 2: Tchesinkut Creek washout-flow occurred in the early 1980s. Note the point of natural stream diversion; washout site; flow down Tchesinkut Creek; and, the similarity in shape of the washout gully and the original gully down-cut through glaciofluvial-glaciolacustrine sediments.

Landslides have occurred along the northwest-southeast trending ridges that extend from Houston toward Francois Lake and presently active landslide movement is occurring along the ridge above Parrott Creek. The landslides at Buck Creek and Dungate Creek (Figure 3) are located about 25 km north of the pipeline corridor. These landslides occurred catastrophically prior to settlement in the Bulkley Valley at Houston. These events, although situated north of the pipeline corridor, demonstrate the instability of the volcanic bedrock.

Bedrock spread, a form of landslide movement, is active along the ridge above Parrot Creek within the general corridor for the pipelines (Figure 4). Geertsema et al. (2009) mentions these landslides but they remain unstudied. Bedrock geology along the ridge above Parrott Creek is an important factor in the instability of the ridge; it comprises flat and gently dipping lava that covers much older volcanic, sedimentary and intrusive rocks (Tipper and Richards 1976). The spread of upper bedrock layers on older rocks may continue gradually over a long period or may reach a point of catastrophic failure sometime in the future (Figure 5). The active bedrock spread occurring along the ridge near Parrott Creek may be an indication or foreshadowing of further movement at other locations along these ridges.

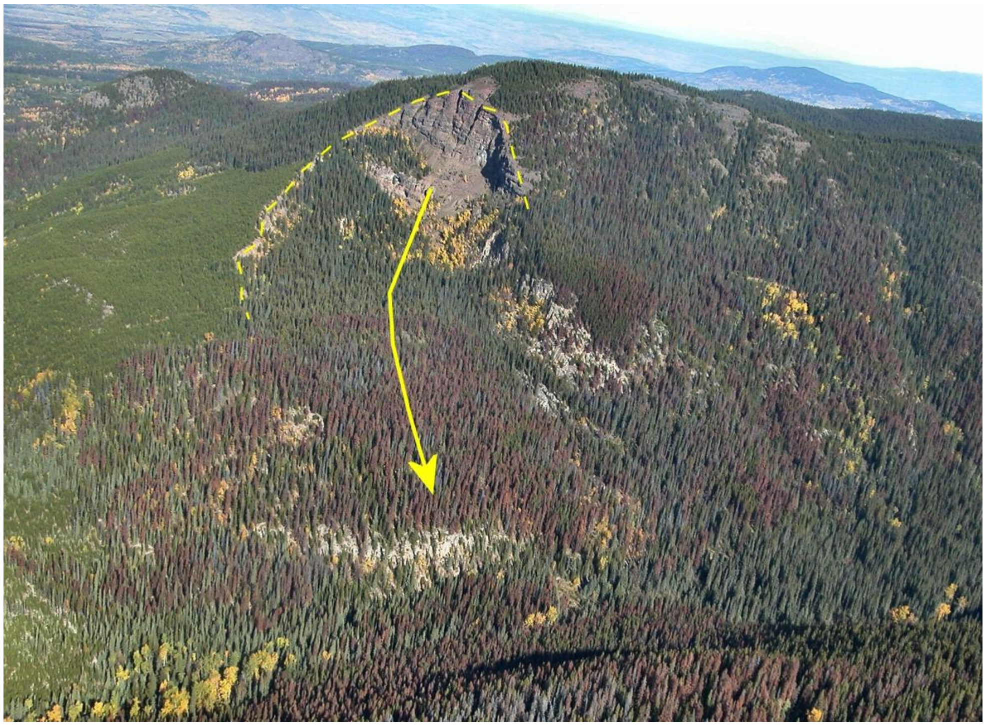

Figure 3: Dungate Creek landslide located southeast of Houston; gently dipping lava beds are visible in the headscarp of the landslide.

Figure 4: Bedrock spread located east of Parrott Creek. The overlaying volcanic bedrock has split apart and is slowly moving away from the scarp along a deeper surface of much older volcanic bedrock.

Figure 5: Bedrock spread lead to catastrophic landslides along a 2.5 km scarp (photo lower centre to upper right) and a 1.3 km scarp (photo distance) on the ridge above Parrott Creek. The landslides involved up to 150 and 50 Mm^3 of material, respectively. The yellow dashed line delineates the landslides' headscarp. The arrow shows the direction of movement.

2.1.2 Morice River

The pipeline corridor runs south of the Morice River for about 40 km crossing Owen Creek, Fenton Creek, Lamprey Creek, and Cedric Creek and then crosses the Morice River above Gosnell Creek and the Thautil River (Owen Creek 660 masl, Morice River crossing 730 masl). The present day Morice River floodplain occupies a large glacial meltwater channel cut through morainal material (till), glaciofluvial and glaciolacustrine sediments. Down cutting by the meltwater created low terraces and benches along the south side of the valley flat. Smaller streams presently cut down through the benched-terraced landform to reach the present day Morice River floodplain.

Advance-phase glaciolacustrine sediments were deposited in lakes formed as glaciers flowed out from the mountains advancing into the Bulkley and Morice valleys, blocking tributary valleys and damming rivers (Stumpf et al. 1997, 1998; Stumpf 2001). Advancing glaciers subsequently covered thick accumulations of lake sediments. Deep compact till and sometimes fluvial sediments that were also overridden and compacted by glacial ice generally bury advance-phase glaciolacustrine sediments. Postglacial bank erosion and contemporary erosion have been involved in large slump-earth flows along the Morice River, Houston Tommy Creek and Thautil River. Stumpf (2001) mapped the aerial extent and elevation of glaciolacustrine sediments along the Morice River at Houston (675 masl) south to Owen Lake (775 masl) and Houston Tommy Creek (865 masl). Stumpf did not study the Morice River to the west of Owen Creek. However, advance-phase glaciolacustrine sediments covered by till and other sediments likely occur up the Morice River valley to at least 775–800 masl. Glaciolacustrine sediments are visible in gullies and along the terrace scarps near Fenton Creek, Lamprey Creek and at about 800 masl roughly 10 km up the Thautil River.

A series of large, rapid, low gradient flow slides have occurred in the advance-phase glaciolacustrine sediments along Houston Tommy Creek with the most recent occurring in the early 1960s; this involved about 15 Mm^3 of material (Figure 6). The largest of the series of historical flow slides along Houston Tommy Creek is about 100 ha in size.

South of Houston along the Morice Forest Service Road (FSR), large slump earth flows were reactivated during a road up-grade in the mid 1970s and a massive wildfire in 1983; the largest is 1.5 km wide. The Forest Service in Smithers has detailed terrain maps of all the historic and active landslides between kilometre 6 and 27 on the Morice FSR (junction of the Morice FSR, Morice West FSR and Morice Owen FSR). Attempts to stabilize the road (Figure 7) have cost millions of dollars with the most recent stabilization work undertaken in February 2011 (per comm. B.C. Forest Service Engineering). The Morice West FSR also required stabilization at kilometre 33, with road realignment in 2004 and a rock buttress subsequently added to stabilize the road in 2008.

The proposed pipeline corridor crosses the glaciolacustrine sediments on the east and west side of Owen Creek. The Morice Owen FSR experienced considerable surface erosion of the fine glaciolacustrine sediments during construction in the early 1980s. The forest access road located along the west side of Owen Creek has experienced ongoing stability problems, within and to the south of the corridor. The corridor also crosses a large historic earth flow feature at approximately 1.5 km west of Owen Creek. Small landslide features are evident and active slope movement is likely occurring along the terrace scarps and slopes above Fenton Creek and Lamprey Creek.

The proposed pipeline crossing of the Morice River is upstream from the confluence of the Thautil River-Gosnell Creek and the existing forest road bridge. The terrain at the crossing is relatively flat, an expanse of glacial outwash sands and gravel; sediments at depth are unknown.

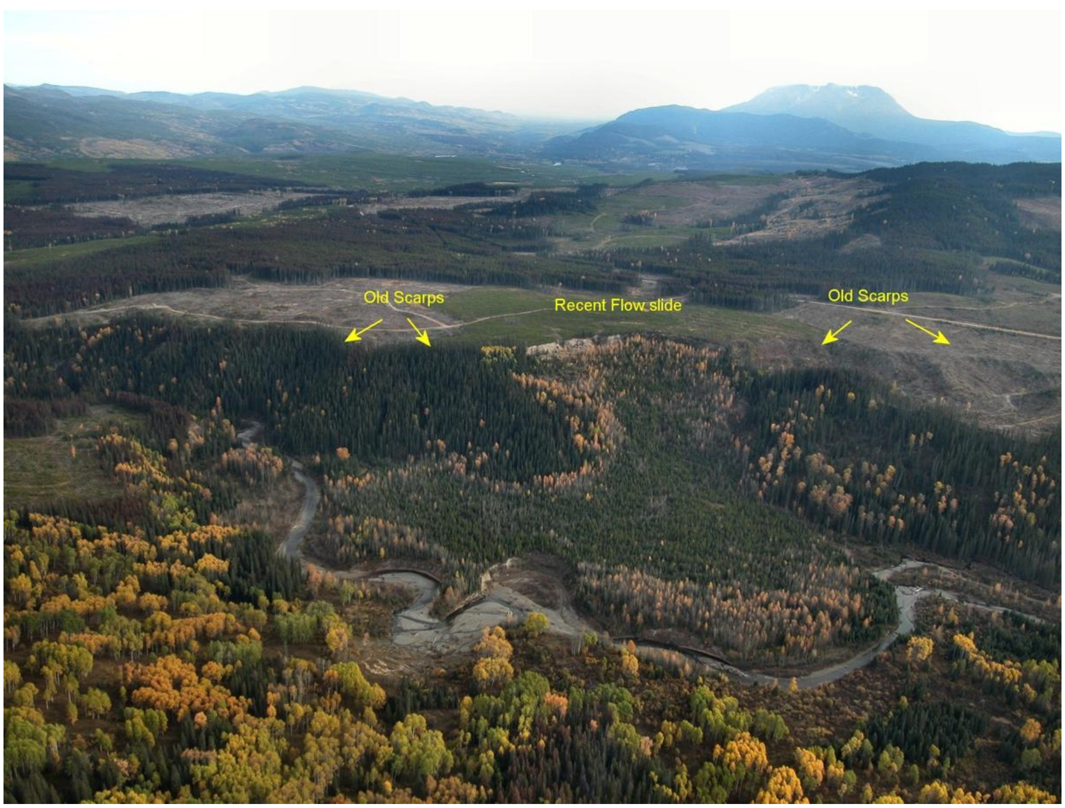

Figure 6: A low gradient flow slide in advance-phase glaciolacustrine sediment at Houston Tommy Creek. Older landslide scarps are indicated with arrows.

Figure 7: A reactivated slump earth flow after an up-grade of the Morice Road. Attempts to stabilize the road have cost millions of dollars over the past 30 years.

2.2 Hazelton Mountains

The pipeline corridor crosses through the Hazelton Mountains commencing at Gosnell Creek and extending through the Clore Valley to Nimbus Mountain situated on the eastern boundary of the Kitimat Range, a distance of about 47 km. The Tahtsa Ranges sit to the South and the Bulkley Ranges to the North. The bedrock is volcanic and shows signs of slope instability on many of the steeper hillslopes.

2.2.1 Gosnell Creek

The Gosnell Creek valley is a broad open valley modified by glaciation. The valley extends about 30 km from the Morice River junction (720 masl) to the pass dropping toward the Clore Valley (1000 masl). Gosnell Creek drains the Morice Range to the south and west and Heard Dome (Bulkley Ranges) to the north with elevations of about 1890 and 1950 masl, respectively. These mountains are part of the Hazelton Mountains physiographic region although the lower elevations of Gosnell Creek near its confluence with the Morice River are part of the Nechako plateau. Numerous glacial features (groves, lineation and drumlins) show the direction of ice movement within the valley. A blanket of ablation till (morainal material left as glacial ice melts), glaciofluvial sand and gravel, and present-day alluvium cover the valley bottom. Gosnell Creek occupies a glacial meltwater channel that connects through to the Morice River. Located at the junction of the Morice-Gosnell-Thautil valleys is a large flat expanse of glacial fluvial outwash.

The pipeline corridor follows the Crystal FSR along the south side of the Gosnell Valley. Here, a series of fluvial fans along a 10 km stretch are active during spring snowmelt and intense fall rainfall events, and episodically during summer thunderstorm activity (Wilford et al. 2005c). Wilford (2003) recorded 83 debris flood events on eight of the fans over the last 50 years.

Erosion on these fans has posed considerable road maintenance challenges over the past 15 years. Two large alluvial-colluvial fans situated in the pass between the Gosnell and Clore watersheds are presently undisturbed. Maintenance for a pipeline across these fans in the Gosnell watershed will be challenging due to shifting channels and erosion. Crystal Creek and upper Gosnell Creek flow north out of the Morice Range. These streams carry large quantities of sediment and show considerable lateral bank instability at the proposed pipeline crossing locations; thus, these locations may also prove challenging for construction and maintenance.

2.2.2 Upper Clore

The corridor right of way through the upper Clore crosses the mountainous terrain of the Bulkley Ranges over a distance of about 17 km. The corridor extends from the pass between the Gosnell and Clore valleys (1000 masl) and drops to the valley flat above the Clore Canyon and junction with the Bernie River (800 masl). Then, two tunnels are proposed. The first runs from above the Clore Canyon through a mountain to the southwest of the Clore Canyon into a tributary of the Clore (620 masl). The second tunnel crosses through Nimbus Mountain to Hoult Creek, a tributary of the Kitimat River. Nimbus Mountain is the divide between the Bulkley Ranges of the Hazelton Mountains and the Kitimat Ranges of the Coastal Mountains.

The upper Clore River watershed is typical of the glaciated terrain found within the Hazelton Mountains; a broad wide valley with higher peaks shaped by alpine glaciation, and ice rounded mountains at lower elevations. Sediments deposited in close proximity to glacial ice cover the valley bottom. These sediments include morainal, glaciofluvial and glaciolacustrine sediments. Colluvium (material that has moved down slope under the influence of gravity) is more prevalent on and below steeper slopes.

Glaciofluvial landforms composed of silt, sand and gravel dominate the valley flat of the upper Clore River. The Clore River has cut down through these sediments to create a series of benches, terraces and scarps. The Clore Canyon entrance controls the base river level on the valley flat and will continue to control the rate of future down cutting. The proposed pipeline corridor dissects the active floodplain located immediately upstream from the Clore Canyon. These glaciofluvial and glaciolacustrine sediments within the Clore basin have not undergone anthropogenic disturbances; hence, the effect of proposed development is unknown.

2.2.3 Sackungen

Tipper and Richards (1976) mapped and described the bedrock within the southwest portion of the Hazelton Mountains. The bedrock is predominately volcanic; originating from volcanic activity centered in the Howson Range (Telkwa Formation, Howson Facies). The reddish coloured well-bedded pyroclastic and flow rocks are of particular interest—large landslides have occurred in this volcanic bedrock within the Hazelton Mountains in recent years and have directly impacted the natural gas pipeline, roads and highways (Geertsema et al. 2009). The Zymoetz River rock avalanche occurred on June 8, 2002; it severed the natural gas pipeline and closed access to the Zymoetz River watershed for a year (Schwab et al. 2003; Boultbee et al. 2006; MacDougall and Hungr 2006). The most recent landslide occurred near Legate Creek in June 2007. Two lives were lost, Highway 16 was closed for 2.5 days, and travel was disrupted for two weeks. Large rock slide-avalanches have occurred about 25 km north of the upper Clore basin within the Kitnayakwa Watershed. The largest landslide has a length, width, and depth of 1.9 km, 350 m and 90 m, respectively; and volume of about 9 Mm^3. This landslide, described by Schwab and Kirk (2002), occurred about 220 years ago with adjacent events occurring about 50 and 460 years ago (Figure 8). On an adjacent slope that had not failed, they identified linear features including uphill-facing scarps (antislope scarps) and troughs trending parallel to slope contours. A distinct fracture line ran along the trough in most features. The German term "Sackungen" denotes these linear features in mountainous landscapes as slope sagging, gravitational spreading or deep-seated gravitational slope deformation. The presence of sackungen commonly indicates active slope movement and foreshadows a pending landslide (refer to Geertsema et al. 2010 for additional information on slope deformation and landslides).

Sackungen are prevalent in the volcanics on mountain slopes in the Kitnayakwa River valley and on forested slopes and alpine slopes in the Clore and Bernie watersheds. The landslide and sackungen features found on the west side of the Kitnayakwa occur within a well-bedded, fine-grained crystal-lithic red tuff. Harder andesitic rock overlies the red tuff. Weathering of the red tuff is extremely rapid in comparison to other harder rocks. This leads to fracturing and crumbling of the bedrock and general hillslope instability. Tipper and Richards (1976) found the fine-grained crystal-lithic tuff and lapilli tuff in association with other volcanic rocks throughout the Clore, Burnie, Kitnayakwa, and Zymoetz watersheds. Detailed geotechnical investigation is required to determine the stability of the bedrock and hillslope wherever these volcanic rocks and sackungen occur in areas proposed for development. Avoidance of these unstable volcanic rocks is generally the preferred engineering option.

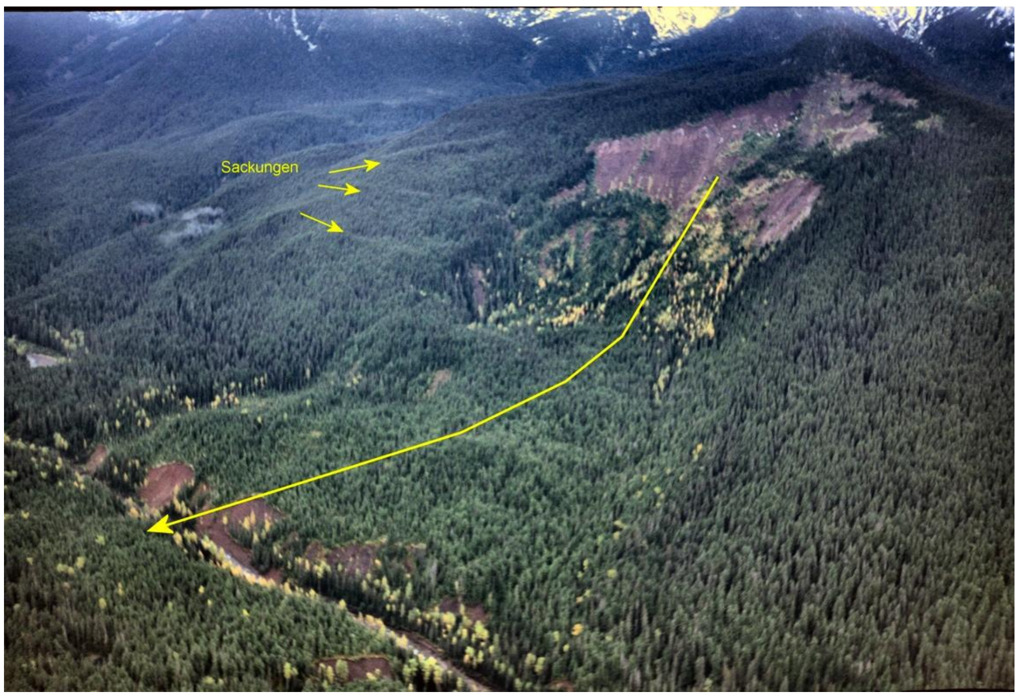

Figure 8: A landslide in the red tuff volcanic bedrock, Kitnayakwa watershed, occurred about 220 years ago. The small arrows point to sackungen that indicate active slope movement that foreshadow a pending landslide.

2.2.3 Clore River to Nimbus Mountain

The proposed Clore tunnel connects the Clore basin above the canyon through to a tributary stream of the Clore at the base of Nimbus Mountain—a distance of about 7 km. Tipper and Richards (1976) show a complex array of faults near the Clore Canyon—these faults are readily discerned on aerial photographs (BC 88038 164–167). The bedrock in the canyon is highly fractured and deeply weathered. Unstable bedrock reaches up to 1200 masl or possibly 1400 masl and extends around the mountain into the adjacent tributary valley. The central core of the mountain is probably quartz diorite; however, the volcanic bedrock at mid and lower elevations is extensively gullied with visible landslide scarps. A large distinct landslide feature located on the west shoulder appears to be actively moving, deflecting the creek across the valley (Figure 9). A series of large cirque shaped landslide scarps sit at about 1400 masl with deep gullies connecting down to the Clore River Canyon. Lineations, probably sackungen, indicative of active slope movement extend across the hillslope through the landslide scarps (Figure 10). Clusters of smaller landslide scarps sit along and down the west shoulder of the mountain. The instability of the volcanic rock on this hillslope will place major constraints on pipeline development.

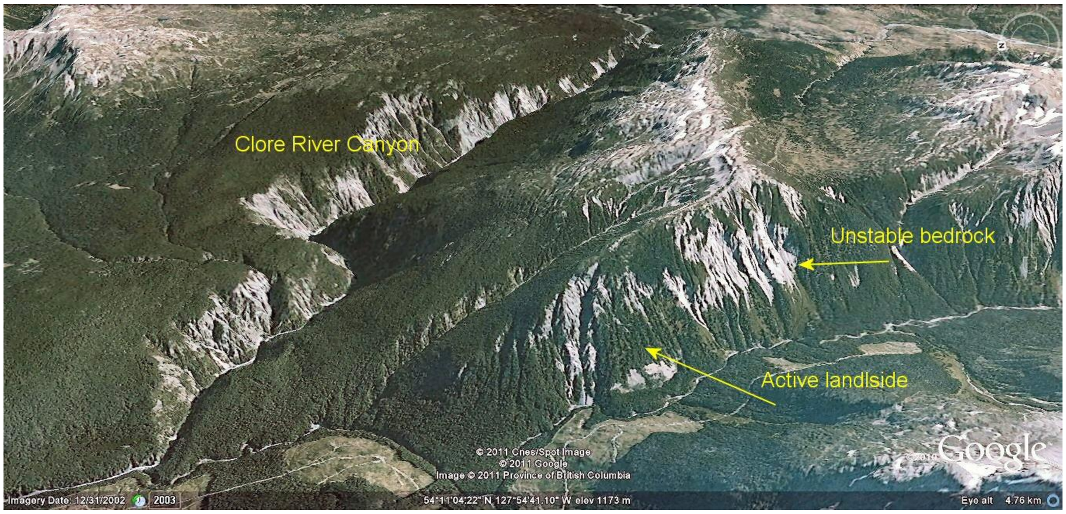

Figure 9: Google Earth image looking east from the general location of Nimbus Mountain. The volcanic bedrock below 1200 masl is unstable and extensively gullied with visible landslide scarps and void of trees. The large active landslide is pushing the creek across the valley.

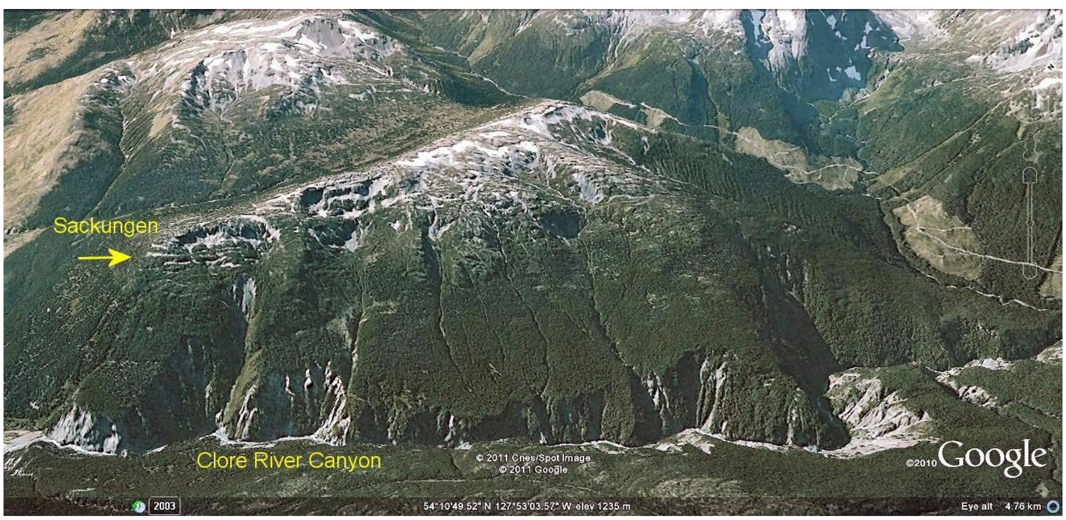

Figure 10: Google Earth image looking to the southwest over the Clore River Canyon. Note the cirque shaped landslide scarps extending down to the Clore Canyon and the Sackungen (arrowed) that indicate slope deformation.

2.3 Kitimat Range

Nimbus Mountain at about 2300 masl along with Andesite Peak, Beta Peak, and Cumulus Mountain delineate the eastern side of the Kitimat Range. The upper Kitimat valley to the west is a steep narrow glaciated valley indicative of the granite and diorite bedrock of the coast intrusion (Duffell and Souther 1964). Andesite bedrock is also found in Andesite Mountain, Hoult Creek, and Nimbus Mountain (note: Nimbus Mountain is the location of the proposed pipeline tunnel connecting the Clore River valley through to Hoult Creek and the upper Kitimat River Valley).

2.3.1 Hoult Creek

Hoult Creek is about 15 km long, originating in a cirque basin at 1100 masl on Nimbus Mountain. It joins Davies Creek shortly before entering the Kitimat River at about 260 masl. Landforms in the Hoult Creek watershed are typical of steep headwater basins within the Kitimat Range. Cirques ring the uppermost slopes with exposed bedrock and morainal and colluvial deposits of varying thickness. Valley walls are steep with exposed bedrock in the alpine and thin colluvium grading to deeper colluvium and morainal deposits on the lower slopes. Debris flow fans (colluvial-fluvial fans) coalesce along the lower slopes next to the creek. Steep gradient gully channels, originating in the alpine, collect and transport colluvial materials to the fans (Jakob et al. 2005; Wilford et al. 2005a, 2005b, 2005c). The steep gully channels and fans show evidence of frequent debris flows and snow avalanches—these hillslope processes pose ongoing concerns for pipeline development.

2.3.2 Upper Kitimat River Valley

The Kitimat River downstream of Hoult Creek-Davis Creek occupies a wider valley flat but is flanked and confined by steep mountain slopes rising to about 1500 masl. The elevation drop of the Kitimat River from the Davis Creek confluence to the Highway 37 Bridge is about 120 m (260–140 masl) over a distance of about 25 km; this is relatively steep indicative of the erosive power of the Kitimat River. Chist Creek from the north and McKay Creek from the south are the major tributaries that flow into the Kitimat River above the Highway 37 Bridge. The Kitimat River above the Highway 37 Bridge is a dynamic gravel bed river that has undergone considerable lateral movement across the floodplain over decades and often catastrophically during storms and floods. Lateral movement over time is from valley wall to valley wall through the middle reaches of the upper Kitimat River. Catastrophic movement of the channel has eroded the Kitimat Mainline forest access road on a regular basis. A pipeline could suffer the same fate.

Anecdotal information suggest that jökulhlaup or glacial outburst floods have originated in the headwaters of the Kitimat watershed in the late 1970s, late 1980s and as recently as February 2011. These glacial outburst floods have sent a sediment plume down the Kitimat River to tide water. They may occur catastrophically and may contribute to lateral and catastrophic channel movement on the upper Kitimat.

Surficial materials are complex within the valley. Glacial ice movement down the valley scoured and shaped bedrock outcrops and ridges and formed drumlin type features that parallel hillslopes from the valley bottom to the alpine. Colluvium and morainal materials of variable depth cover hillslopes. Deep deposits of glaciofluvial and glaciolacustrine sediment blanket lower elevations. Glaciomarine sediments often covered by other sediments occur up to an elevation of about 180–200 masl; extending to about 5 km upstream of the Kitimat-McKay River confluence. Interestingly, Hirsch Creek, situated to the south of the upper Kitimat, has eroded into a bank containing glaciomarine sediments. This resulted in a large slow moving slump-slide that closed the south access into the Hirsch drainage and is now an ongoing sediment source. Landslides also occur at mid elevations in glaciofluvial-glaciolacustrine sediments close to the entrance of McKay, Bolton, and Nalbeelah watersheds. In an assessment of terrain attributes associated with forest road development, Rollerson et al. (2001) found the glaciofluvial and glaciolacustrine terrain in the McKay and Bolton watersheds most problematic. Landslide problems are also associated with road development through glaciofluvial and glaciolacustrine terrain in the upper Kitimat valley.

The proposed pipeline corridor crosses the Hunter Creek alluvial fan situated at the outlet of a 63 km^2 watershed. Historically, geomorphic activity in the watershed has resulted in the transport of sufficient volumes of material with deposition on the valley flat to push the Kitimat River across the valley. The fan appears to have remained relatively stable for a period of approximately 250 years prior to events in 1987-1992 (pers. comm. D. Wilford 2011). The fan underwent active channel shifting with a major channel avulsion occurring in 1987 and 1992 (Figure 11). Wilford (2003) recorded 13 flood events on the fan since 1950 but attributed the channel avulsions in 1987 and 1992 to a climbing road constructed up the fan and to a bridge placed below the apex of the fan that has constricted flow. Control works constructed above the Hunter Creek Bridge attempt to stabilize stream movement and protect the bridge. However, the current channel is unstable and changes will recur with an influx of a large amount of sediment to the fan apex.

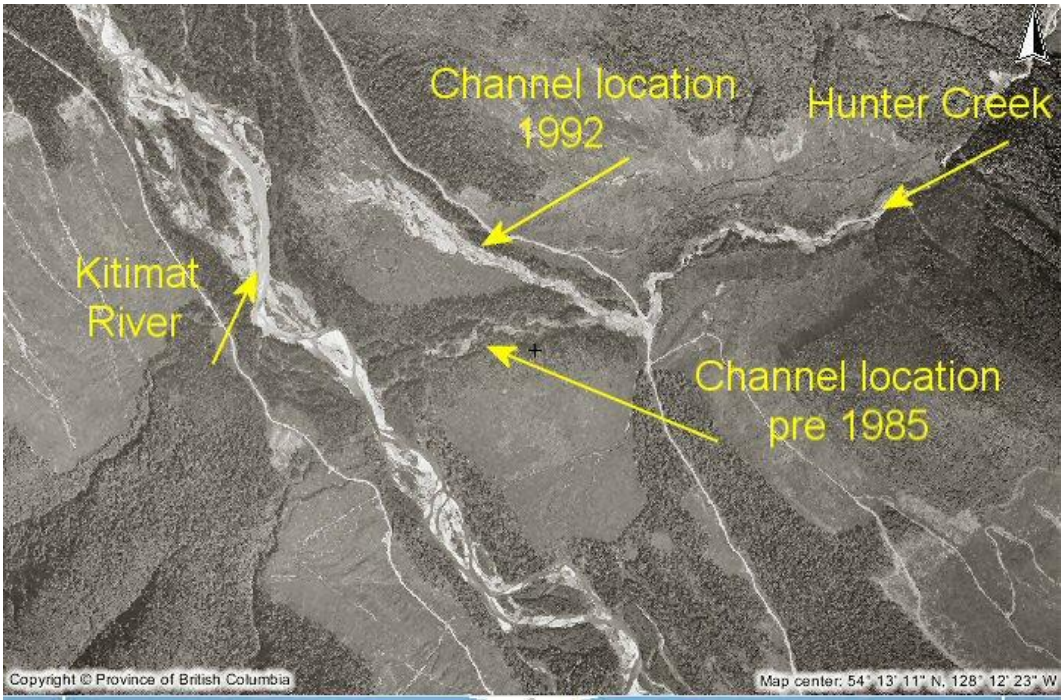

Figure 11: Hunter Creek fan experienced a catastrophic channel avulsion in 1987 and 1992. The stream channel remains unstable even with control measures placed above the bridge.

Fluvial-colluvial fans are situated at the base of most gully-stream channels that extend from the alpine to the valley flat along the north side of the upper Kitimat Valley. The channels and fans show varying levels of debris flow activity (B.C. Ministry of Forests 2001; Bovis and Jakob 1982; Wilford et al. 2005c), with many experiencing torrents during extreme events in the fall of 1978 and 1992. Debris flows have also occurred down some channels all the way to the Kitimat River. These debris flows tend to occur episodically during strong summer convective storms and fall frontal rainstorms (Jakob et al. 2006) but in many respects are "normal" occurrences for many debris flow channels (Wilford et al. 2009). Hence, they pose considerable problems for developed infrastructure such as pipelines and roads.

Chist Creek above the confluence with the Kitimat River cuts through glacial fluvial and glaciomarine sediments, forming terraces, steep scarps and benches. Ongoing bank erosion with the lateral movement of Chist Creek maintains a steep, high scarp along the west bank. Lateral stream movement above the confluence is in part a function of the large quantities of sediment transported into the reach from the Chist Creek watershed. The pipeline corridor, as proposed, crosses Chist Creek about 3 km upstream from the Kitimat River confluence, downstream from the Chist Creek bridge crossing. The corridor then climbs the glaciofluvial terrace onto the Onion Lake flats. Glaciomarine sediments are visible beneath the glaciofluvial sediments and are exposed at about 180 masl, downstream from the bridge crossing.

2.4 Kitimat Trough

The proposed pipeline corridor crosses the Kitimat Trough on the Onion Lake Flats, crosses Cecil Creek then proceeds down the west side of the valley (east of Iron Mountain), crosses the Wedeene and Little Wedeene Rivers and continues past the city of Kitimat to tide water; a distance of about 50 km.

The Kitimat Trough is a broad north-south trending valley ranging in width from 5 km to 15 km. Mountains 1000–1500 masl rise abruptly on both sides of the trough. Bedrock is granodorite of the coastal intrusion (Duffel and Souther 1964; Woodsworth et al. 1985). The trough situated between Terrace and Kitimat is an uplifted fiord, filled with glacial and postglacial sediments (Clague 1983). Clague (1984) describes the surficial geology and chronology of deglaciation (Figure 12). Glaciomarine sediments occupy much of the valley floor. However, deep deposits of glaciofluvial sediments and postglacial materials that include present day floodplains, alluvial fans and bogs, cover large areas of glaciomarine sediments. Till and colluvium mantle bedrock hillocks (Iron Mountain) and lower slopes of the main valley walls. The largest lake in the trough is Lakelse Lake, situated on glaciomarine sediments between the glacial fluvial deltas of the Onion Lake Flats and the airport south of Thornhill.

2.4.1 Glaciomarine sediments

Glaciomarine sediments situated within the valley between Terrace and Kitimat have experienced both large prehistoric landslides and recent landslides—and more landslides will occur in the future. Therefore, a description of the glaciomarine sediments, origin and sensitivity to landslides is important and warrants further discussion. Geertsema's (2004) thesis on landslides in sensitive glaciomarine sediments found between Terrace and Kitimat contains detailed technical information and references.

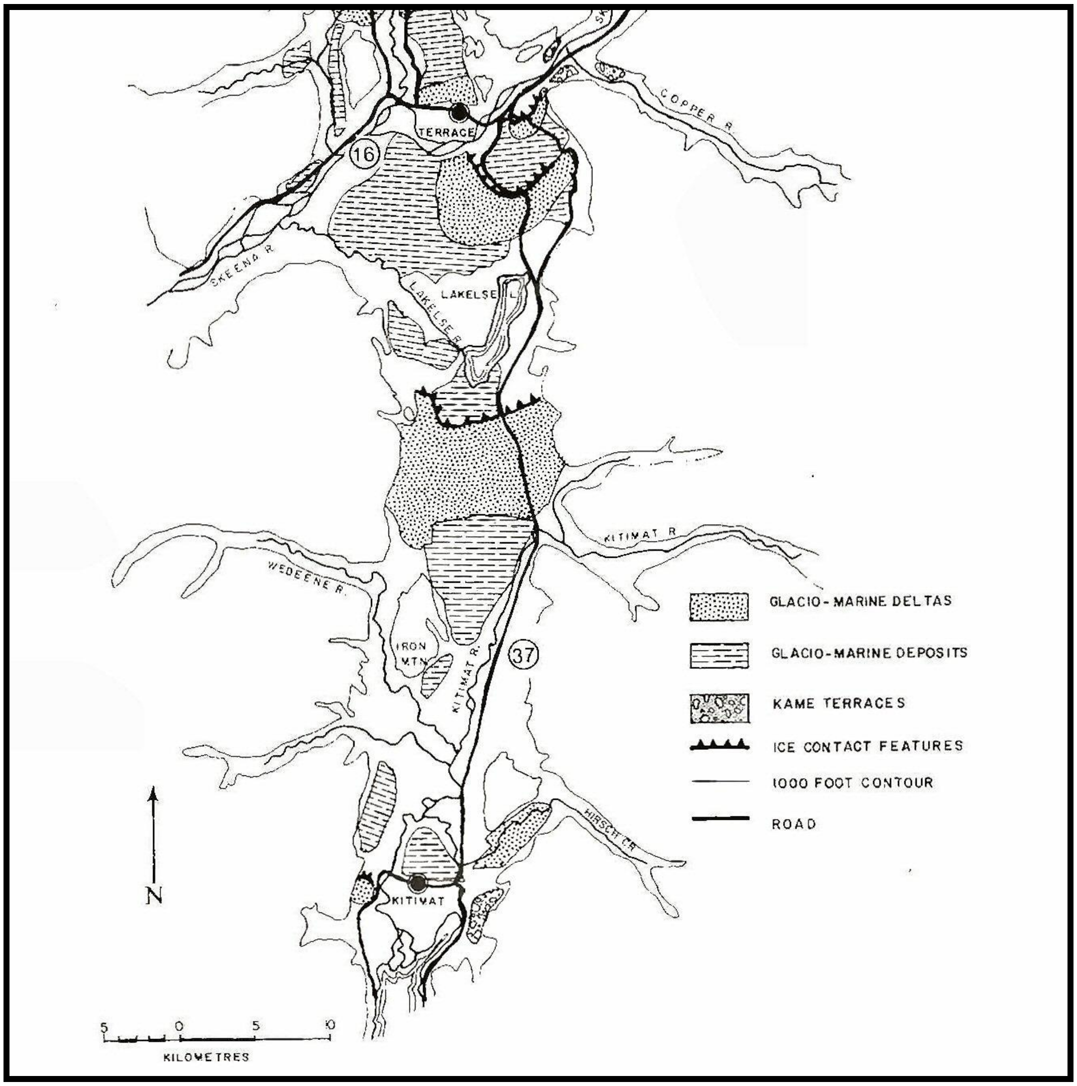

Figure 12: The surficial geology between Kitimat and Terrace as described by Clague (1984). The diagram is adapted from Gottesfeld (1985).

Clague (1984) documents the history of glacial retreat up the Kitimat valley and a general description is contained in Gottesfeld (1985). In summary, the weight of glacial ice depressed the coast of British Columbia (isostatic depression), including the fiord valley occupied by the Kitimat Trough. Melting of glacial ice commenced between 12 000 to 13 000 years ago. The land surface remained depressed as sea levels rose. The glacier terminus was in contact with the sea as ice retreated inland and to the north, seawater flowed in. Douglas Channel south of Kitimat was ice-free about 11 000 years ago. Glacial retreat halted or stood still at three locations in the Kitimat Trough marked by an expanse of nearly flat sand and gravel deposits: the first, a large arcuate moraine and small outwash remnant near Kitimat; the second, the massive fan-delta of the Onion Lake Flats; and third, the fan-delta at the location of the Terrace airport. The well-preserved ice contact features north of the Onion Lake fan-delta and at Thornhill north of the Terrace airport suggest an extremely rapid retreat of glacial ice. The Terrace-Thornhill area was ice-free about 10 100 years ago when ice withdrew from the Thornhill ice-contact. Rebound of the valley floor was slow and continued until about 8000 years ago when local sea levels subsided to near present-day levels. Shorelines 11 000 years old sit at about 200 masl, 10 100-year-old shorelines at about 120 masl, and 9300-year-old shorelines at about 35 masl.

A generalized description of the style of sediment deposition in the Kitimat Trough follows. Glacial melt water built a fan-delta of sand and gravel into the sea while finer sediments composed of rock flour, silt and clay minerals settled into a quieter marine environment beyond the fan-delta. A diagnostic feature of the fine sediments deposited in a marine environment (glaciomarine sediments) is the presence of marine shells. In salt water, clay and silt aggregate together to form floccules and settle in a random orientation. The resulting sediment has an open structure with high water content. The positive charge of the salt maintains the interparticle bond giving the sediment strength. Rainfall and groundwater (freshwater) gradually leach out salts from the glaciomarine clay with the gradual rebound of the land. At a lower salt content the repulsive forces between the particles is increased leaving saturated porous sediment prone to collapse. Collapse happens because of an imposed load caused by natural or human factors, for example, through an increase in surface loading, the removal of lateral support by stream bank undercutting or excavation, vibration by heavy equipment, earthquake shock, high water pressures and interruption of intertidal drainage. The result is the liquefaction of the sediment. The most notable difference in the character of the sensitive clay is the remarkable difference in strength between the undisturbed and remoulded glaciomarine sediments. The remoulded sediment behaves as a fluid. Hence, rapid landslide movement in glaciomarine sediments can occur on slopes as low as 2–3°.

2.4.2 Landslides in glaciomarine sediments

Recent landslides in glaciomarine sediments have occurred at Mink Creek and Lakelse Lake near Terrace and Khyex River near Prince Rupert:

- Septer and Schwab (1995) give an account of a flow-slide south of Terrace that occurred during rail bridge construction across Alwyn Creek. The landslide occurred at Mile 6.6 on the Canadian National railway line between Terrace and Kitimat on June 24, 1953. The landslide buried bulldozers and other construction equipment. A constructed S-shaped trestle bypasses the site.
- In May and June 1962, piles of earth placed beside Highway 37 on sensitive glaciomarine clays likely increased the surface load and triggered two massive extremely rapid landslides (Figure 13). The landslides, about 11 Mm^3 and 15 Mm^3, flowed into Lakelse Lake carrying vehicles and equipment. Sections of the highway and a provincial park campground were destroyed (Clague 1978; Geertsema and Schwab 1997).
- A landslide occurred sometime between mid December 1993 and early January 1994 into Mink Creek, a tributary of Lakelse River (Geertsema and Schwab 1995; Geertsema and Schwab 1996; Geertsema 2004; Geertsema and Torrance 2005; Geertsema et al. 2006b). The landslide likely started as a small failure along the creek that exposed sensitive clays in the cut bank. Once the sensitive materials were exposed, the landslide rapidly retrogressed along a slope of about 3°. About 23 ha slid and flowed into Mink Creek, filling the channel, extending downstream for about 1 km. Debris dammed the creek, raised water levels by 10 m and backed water up stream for 1200 m (Figure 14).
- A similar landslide occurred in glaciomarine sediments 35 km east of Prince Rupert on November 28, 2003 (Schwab et al. 2004a; Schwab et al. 2004b). The flow slide involved 4.7 Mm^3 of material, covered 32 ha, and moved rapidly on a 2.5° surface to in-fill the Khyex River over a length of 1.7 km and caused flooding upstream for a distance of 10 km. The landslide ruptured a natural gas pipeline and left the city of Prince Rupert and Port Edward without natural gas service for 10 days.

Figure 13: This large swampy area is the location of the May 1962 Lakelse flow slide. Highway 37 crosses the landslide depletion zone. The Provincial Park is located middle left of the photo.

Figure 14: The Mink Creek flow slide rapidly retrogressed along a slope of about 3°, approximately 23 ha flowed into Mink Creek, extending downstream for 1 km.

The recent landslides in the glaciomarine sediments were not the first. In the Kitimat Trough, there are hundreds of prehistoric landslides (Geertsema 1996, 1998; Geertsema and Schwab 1996, 1997; Geertsema 2004). Glaciomarine sediments line much of the valley floor between Kitimat and Terrace, although deep deposits of glaciofluvial sediment and post-glacial alluvium hide large areas. South of Kitimat, glaciomarine sediments are found up to 200 masl. Landslides have occurred in areas of exposed glaciomarine sediments (mud) and in some situations in mud blanketed by alluvium or glaciofluvial deposits. Numerous landslide features are located near Mink Creek, the Nalbeelah wet land complex, the foreslope of the Onion Lake flats, Cecil Creek and Deception Creek (Figure 15). Features are also visible along the terrace scarp of the Wedeene River and Little Wedeene River. Landslides dates extend from early post-glacial to the present with a third of the dated landslides falling between 3300 and 1900 years ago (Geertsema 2004). These landslides occurred during a cool wet period suggesting climate may control the overall incidence of landslides—possibly contributing to salt removal from the sediments. External triggering forces may also be a contributed factor, for example, stream bank undercutting or an earthquake.

2.4.3 Submarine flow slide

The present day Kitimat River transports sediment to a fan-delta at the fiord-head of Kitimat Arm. A fan-delta is a high-energy fluvial system subject to continuous and progressive sediment loading. Where underlain by soft marine muds, fan-deltas are prone to large-scale landslides.

- In April 1975, a large submarine flow slide occurred on the front of the fiord-head delta in Kitimat Arm south of the Kitimat Smelter; a portion of the headscarp was visible at Mickey's Cove. The landslide, with an estimated volume of 55 Mm^3, happened about 1 hour after an extreme low tide (Prior et al. 1982, 1984). The slide generated a tsunami 8.2 m high, causing considerable property damage (Murthy 1979; Murthy and Brown 1979). Site loading by construction activities during an extreme low tide was the probable landslide trigger.

These recent large landslides serve to show the sensitivity of the glaciomarine sediments in the Kitimat Trough and the marine sediments on the fan-delta at the fiord-head of Kitimat Arm. Natural and human caused factors trigger these landslides, as previously discussed. Pipeline construction will encounter glaciomarine sediments in the vicinity of Cecil Creek, Deception Creek, Wedeene River, Little Wedeene River, along the west side of Kitimat Arm and along the east side of Chist Creek. The pipeline corridor crosses features indicative of prehistoric flow slides near Cecil Creek through to the little Wedeene River. The presence of glaciomarine sediments and prehistoric flow slides suggest that there is a high probability for future large landslides; hence, landslides will likely break or disrupt pipeline service. Therefore, pipelines or other infrastructure placed on or crossing glaciomarine sediments must avoid areas that lie within potential flow slide depletion zones.

Figure 15: Foreslope of the Onion Lake Flats (fan-delta) to the east of Cecil Creek. Roads follow arcuate ridges that outline prehistoric flow slides. The ridges are visible in the clearcut (photo centre) and in the area reforested (photo centre-left).

3 Regional Landslides

A wealth of information on hillslope geomorphology and landslides is presented in Geertsema et al. (2010) and specifically on landslides in west central B.C. in Clague (1978), Septer and Schwab (1995), Schwab et al. (2003), and Geertsema et al. (2006a, 2009). A map showing the distribution of large landslides in west central B.C. is not available although research in progress conducted by the B.C. Forest Service documents the location of hundreds of recent and prehistoric landslides (pers. comm. M. Sakals 2011). Landslides are associated with the volcanics found in the Hazelton Mountains; there are massive bedrock slides, complex rock slides and avalanches, bedrock spread, earth flows, debris flows-floods and mountain slopes showing evidence of on-going slope deformation (sackungen). Although landslides are not as numerous on the Nechako plateau, complex rock slides and bedrock spreads are associated with flat and gently dipping lava flows that cover much older volcanic and sedimentary rocks. Many slow and rapid moving earth flows have historically occurred in the advance-phase glaciolacustrine sediments found along the Morice River and its tributaries—natural and human disturbance have reactivated these earth flows. Debris flows and debris floods are common in the steep terrain of the Kitimat Range; most colluvial–fluvial fans have experienced events during episodic storms and even more "normal" storm events. Sensitive glaciomarine sediments found up to 200 masl within the Kitimat Trough have experienced hundreds of large prehistoric flow slides. Recent large flow slides demonstrate the ongoing sensitivity of the glaciomarine sediments to natural or human caused factors.

Landslides and erosion have historically occurred at different rates within the physiographic units situated between Burns Lake and Kitimat. Landslide rates reflect the bedrock geology, surficial geology, and past and present day climate. An understanding of the past is commonly the basis for predicting the future. Inherent structural weaknesses in bedrock or surficial material combined with slope geometry render a slope unstable. Hence, the location of historic landslides can help predict the probable locations for future catastrophic landslides within a geographic area—sites of similar bedrock geology, surficial geology and geological processes (refer to Geertsema et al. (2010) for an in-depth discussion on the cause and triggers of landslides).

4 Landslides and Linear Infrastructure

Landslides damage linear infrastructure such as pipelines, roads, railroads, and power transmission lines (Geertsema et al. 2009). Damage frequently occurs in the landslide runout zone after landslide debris has traveled, in some cases, many kilometres from the initial slide. This is evident in recent large complex landslides that transformed from bedrock slide to avalanche to debris flow (Schwab et al. 2003). Geertsema and Cruden (2008) document long runout landslides. Six large rock slides occurred in west central B.C. since 1978, five since 1999, and four since 2002. Three of the six rock slides severed the natural gas pipeline, for example, the Howson landslides in Telkwa pass in 1978 and 1999, and the Zymoetz landslide in 2002 (Geertsema et. al 2009). All these rock slides had a long runout with the longest travel distance up to 4.3 km along travel angles as low as 9°. Therefore, the potential for damage to linear infrastructure extends to landslides that initiate well outside the construction corridor (Geertsema and Clague 2011). Catastrophic or slow movement will sever or deform a pipeline where it crosses unstable terrain. For example, a transmission tower within the Telkwa watershed situated on a massive slow moving landslide requires periodic adjustment as the landslide mass moves down slope—a pipeline would not withstand such movement. Large landslides in glaciomarine sediments commonly start with a small landslide from bank erosion or loading that exposes a layer of sensitive material and rapidly retrogresses with a flow of material from the displacement basin. Earth flows and slides damage infrastructure located in the zone of depletion by carrying it along during movement. The Khyex River flow slide in sensitive glaciomarine mud is an example where the landslide retrogressed up a 2.5° slope from the riverbank consuming 32 ha and rupturing the natural gas pipeline. Pipelines or other infrastructure, if crossing glaciomarine sediments, must avoid areas within potential depletion zones.

5 Climate and Landslides

Intense rainfall commonly triggers shallow landslides such as debris slides and flows. Schwab (1997, 1998 and 2001b) dated debris slides, avalanches, and flows using tree ring analysis. He concluded from the work that most debris slides, debris avalanches and debris flows occurred during six major storms over the past 150 years. Most landslides (31% of total inventoried) occurred in the fall of 1917. This rainstorm event encompassed the B.C. north coast including the Kitimat Range. The B.C. north coast has yet to re-experience meteorological conditions similar to the event of October 28 to November 19, 1917. The most recent meteorological event that caused considerable destruction to transportation roads and bridges occurred on October 30 - November 1, 1978 (Septer and Schwab 1995). Meteorological conditions that prevail during landslide triggering storms along the B.C. north coast commonly involve a warm frontal system followed by a cold front that extends south to incorporate subtropical moisture (Jakob et al. 2006).

Deep-seated landslides such as large rock slides, earth flows, and flow slides tend to have longer hydrological response times. Responses to increased precipitation take place seasonally, annually or over a number of years; it takes time for water to penetrate deeply into unstable zones within a landslide mass. Geertsema et al. (2006b, 2007) found some landslides occurred after long periods of above average precipitation, for example, the earth flow-spread at Mink Creek occurred during the winter of 1993-94 after a 10 year wet period; in addition, the large number of prehistoric flow slides found between Terrace and Kitimat occurred during a period of wetter climatic conditions. The rock slide-avalanche-flow at Zymoetz River June 8, 2002 and Harold Price June 23, 2002 occurred after a winter of above average snowfall (Schwab et al. 2003). The Sutherland rock slide-debris flow occurred on July 13, 2005 after a wet spring (Blais-Stevens et al. 2007). The Todagin River rock avalanche of October 3, 2006 followed an abnormally wet summer (Sakals et al. 2011).

Egginton (2005) found that long periods of increasing precipitation and temperature are associated with most of the dated large landslides across northern B.C. She also notes that the climate of northern B.C. has become warmer and wetter since the beginning of instrumental observations but that the apparent trends are complex due to ocean-atmosphere oscillations such as the Pacific Decadal Oscillation and the El Niño Southern Oscillation. Catastrophic landslides at high elevations in mountainous terrain are also responsive to increased temperature (Evans and Clague 1994; Holm 2004). Melting of glaciers has resulted in the debuttressing of unstable rock slopes causing deep-seated slope deformation. The melting of ice in rock glaciers has caused the collapse of unstable rubble, for example, the Howson landslide in 1999, and the Harold Price landslide in 2002 (Schwab et al. 2003). Climate change scenarios based on data obtained from the Canadian Institute for Climate Studies predict a progressively warmer and wetter climate for Terrace (Geertsema et al. 2006; 2009). There is evidence to suggest that landslides in west central B.C. have recently increased (Geertsema et al. 2007). Considering this fact with the presented climate change scenarios, large landslide occurrence will likely increase and thus the likelihood of landslides destroying or disrupting pipelines, and other linear infrastructure, will also increase.

The above discussion tends to look at large events, big storms and catastrophic large landslides, however it should not be ignored that many small landslides and erosion events occur across the landscape at a much higher frequency. Although small, these events can also disrupt linear infrastructure, such as pipelines, and given their higher frequency, they are more likely to rupture pipelines on an ongoing basis.

6 Conclusion

The geology and geomorphology of west central B.C. is complex and destructive landslides are common. Various landslide types have occurred along the proposed pipeline corridor within the defined physiographic units:

- bedrock spread in flat lying volcanic rock of the Nechako Plateau;
- earth flows in advance-phase glaciolacustrine sediments;
- rock slides and rock avalanches in the weak volcanic rock of the Hazelton Mountains;
- debris flows in the steep valleys of the Kitimat Range; and
- flow slides in the glaciomarine sediments of the Kitimat Trough.

These landslides serve to illustrate the terrain instability along the pipeline corridor—from mountaintop to valley bottom. Landslides have damaged pipelines in west central B.C. Long runout landslides have traveled many kilometres from the initiation zone; therefore, the potential for damage to pipelines extends to unstable terrain and landslides that start well outside the construction corridor. Flow slides in glaciomarine muds have consumed pipelines located in depletion zones; therefore, pipeline locations must avoid potential depletion zones. Periods of increasing precipitation and temperature are associated with recent large landslides in west central B.C. Climate change scenarios project a warmer and wetter climate; therefore, the likelihood of landslide-mass erosion events affecting a pipeline or other linear structures will increase with a probable increase in landslide occurrence.

Recognition and avoidance of unstable terrain is the most efficient and cost effective method for management in landslide prone terrain. This requires detailed terrain stability mapping and geotechnical investigation to identify unstable slopes, runout zones, and depletion zones. However, avoidance of unstable terrain is a difficult management strategy to adopt over many sections of the proposed pipeline corridor. Therefore, the unstable mountainous terrain across west central B.C. is not a safe location for pipelines. Eventually a landslide will sever a pipeline. Although difficult, an alternative, safer route through B.C. needs investigation.

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