

Landslide susceptibility, hazard and risk assessments along pipeline corridors in Canada



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ABSTRACT

Two large gas pipeline projects, Yukon Alaska Highway Pipeline and Mackenzie Gas Project Pipeline are under different stages of development in northern Canada. Both proposed pipeline routes cross rugged, harsh environments in permafrost terrain, therefore, may be at risk from natural hazards.

Landslide inventory and hazard assessments are essential in qualifying or quantifying risk along linear infrastructure and in assessing environmental impacts. The Geological Survey of Canada has for several years contributed to hazard assessments by performing baseline geological regional studies. This paper presents the work that was carried out along two pipeline routes in northern regions. Both proposed routes are over 800 km-long. Landslide inventory and qualitative parametric landslide susceptibility maps were carried out for both, showing good correlations between landslide distribution and landslide susceptibility maps. In the Mackenzie Valley Pipeline Corridor, most landslides (99%) have occurred in fine unconsolidated sediments and shallow slopes. In the Yukon Alaska Highway Corridor, the majority has occurred in unconsolidated sediments (65%) but a few landslides (15%) have occurred in bedrock with high relief. Thus, our preliminary investigations indicate that there is a slope hazard in both corridors to be considered during pipeline development.

RÉSUMÉ

Deux projets de gazoducs au Nord-Ouest du Canada sont en différents stades de développement (Yukon et Vallée du Mackenzie). Les deux routes proposées traversent des environnements difficiles entourées de pergélisol. Par conséquent, elles peuvent être exposées aux risques naturels.

L'inventaire des glissements de terrain et des évaluations de risque sont essentiels dans la qualification ou la quantification des risques le long des infrastructures linéaires. La Commission géologique du Canada, depuis plusieurs années, a contribué à l'évaluation des aléas géologiques en réalisant des études de bases régionales. Cet article présente les travaux menés le long de deux tracés. Les deux routes proposées sont plus de 800 km de long. L'inventaire et les cartes de susceptibilité de glissement de terrain paramétriques réalisés montrent de bonnes corrélations entre distribution et cartes de susceptibilité de glissements de terrain. Dans la vallée du Mackenzie, les glissements de terrain (99%) ont eu lieu dans des sédiments fins non-consolidés en pentes douces. Au Yukon, la majorité a eu lieu dans des sédiments, mais certains ont eu lieu dans la roche en place en haut-relief. Nos investigations préliminaires indiquent qu'il y a danger de mouvements de terrain à prendre en considération lors du développement des pipelines.

1 INTRODUCTION

In order to assess environmental impacts of landslides, landslide inventory and hazard assessments are essential in qualifying or quantifying risk along linear infrastructure such as pipelines (Muhlbauer 2004). The Geological Survey of Canada (GSC) has for several years contributed to hazard assessments by providing essential baseline geological information. This paper presents the work that was carried out recently by the GSC along two pipeline routes in northern regions of Canada. Two large gas pipeline projects, the Yukon Alaska Highway Pipeline (TransCanada Pipelines 2009) and the Mackenzie Gas Project Pipeline (Mackenzie Gas Project 2004), are under different stages of development

in Canada's northwest and sub-Arctic regions. Both proposed pipeline routes, which are over 800 km-long, cross rugged and harsh environments that encompass permafrost terrain. Sections of these pipeline routes intersect critical geological regions and areas prone to geological hazards, such as landslides including debris flows, earthquakes due to active faults, subsidence from karstic erosion, permafrost degradation and its impacts on slope stability and rock glacier distribution.

This paper will present analyses derived from results of landslide mapping and inventorying in the Mackenzie Valley and in southern Yukon. As part of the hazard assessment activity, frequency-magnitude relationships for debris flow fans along the Yukon Alaska Highway Pipeline route are analyzed. Steps taken to establish

these relationships and to produce maps showing zones susceptible to debris flows and hyperconcentrated flows will be presented. In conjunction with mapping and inventorying, a landslide susceptibility mapping method has been adapted for pipelines. It is intended that our results will facilitate improved decision-making for planning, building, and maintaining safe and economically viable pipeline routes in Canada's northern regions.

2 STUDY AREAS

2.1 Mackenzie Valley, Northwest Territories

The Mackenzie Valley Study Area (MVSA) covers an area extending 540 km by 20 km to either side of the Inuvik–Tulita section of a proposed gas pipeline route that will connect the Mackenzie Delta reservoirs to the northern Alberta oil and gas facilities. Thus, the MVSA measures approximately 24,000 km² (Fig. 1). Winters are cold with low levels of precipitation and summers are relatively warm with moderate levels of precipitation. The vegetation cover is dominated by coniferous forest, although wetland/shrub land is dominant near Inuvik (Cihlar & Beaubien 1998; Wulder & Cranny 2005). Ninety-nine percent of the MVSA is covered by unconsolidated sediments, which are dominated by morainal (60%), lacustrine (18%), and alluvial (10%) deposits (Aylsworth et al. 2000). Three types of permafrost were encountered along the proposed pipeline route: continuous (90–100% occurrence), extensive discontinuous (65–90% occurrence), and intermediate discontinuous (35–65% occurrence) (Heginbottom & Radburn 1992). The permafrost thickness ranges from 0 m – 60 m in Norman Wells to 100 m–200 m in Inuvik and the active layer thickness ranges from 0.5 m in Inuvik to >1.5 m in Norman Wells (Wolfe 1998).

2.2 Alaska Highway Corridor in Yukon

The proposed pipeline route intends to follow the Alaska Highway in Yukon. Thus, the study area is defined by a 20 km wide corridor along Yukon's Alaska Highway Corridor (YAHC; Figs. 1 and 2). The total distance is approximately 950 km, which means approximately 19,000 km². The Alaska Highway is a vital transportation route as 70% of tourists in Yukon travel this highway, which also sees about 80% of all goods shipped in Yukon. In addition, about 85% of Yukon's population lives along the Alaska Highway.

Kluane Ranges are found to the southwest and the Yukon Plateaus to the northeast. From west to east, the corridor is situated on the Yukon Plateaus, the Kaska Mountains, Liard Lowland, and Mackenzie Mountains. The area is seismically active with The Tintina Fault running through the Kaska Mountains and the Denali Fault, through the western part of the corridor (Fig. 2; Huscroft et al. 2004).

The climate is sub-Arctic, experiencing long, cold winters, short, mild summers and receiving low to moderate levels of precipitation. The climate in the western part of the study area is more moderate, but becomes more harsh and continental towards the east. The corridor lies within the Boreal Cordillera Ecozone dominated by black and white spruce with meadows and open forests of trembling aspen (Huscroft et al. 2004).

Permafrost distribution is highly variable within the corridor. It occurs frequently on hillslopes, plateaus and summits. Sporadic permafrost is encountered east of Haines Junction, whereas regions west of Haines Junction are characterized by extensive discontinuous permafrost (Clague 1981; Huscroft et al. 2004).

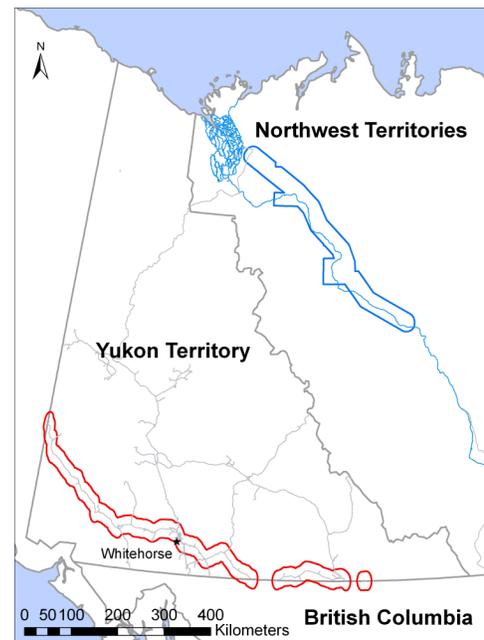


Figure 1. Location map of the two pipeline corridor areas studied, the Mackenzie Valley Study Area (MVSA) outlined in blue and the Yukon-Alaska Highway Corridor (YAHC), outlined in red.

3 METHODOLOGY

3.1 Landslide mapping and inventorying

In the Mackenzie Valley, over 800 1:30,000-scale aerial photos were interpreted for landslide mapping and integrated in a digital database. For each landslide entry, the landslide type and size, location, morphological parameters, relative age (2004 being the reference year), activity, material type, flight line, air photo number, and topographic map sheet were recorded.

Along the Yukon Alaska Highway Corridor, a total of 1612 landslides (from a total of 2018 geohazard features) were identified through air-photo interpretation using photos from 107 flight lines. Timing of landslide events was not determined as air-photos were taken in different years and at different scales. A similar geo-database has been developed for this landslide inventory.

In both case studies, field visits were carried out to validate aerial photograph interpretation and investigate specific landslide sites. Photographs of landslides were taken and added to the digital database.

3.1.1 Debris flow frequency-magnitude relationships

Nine debris fans were studied along the Alaska Highway corridor between the Alaska-Yukon border near Beaver Creek and the south end of Kluane Lake (Fig. 2). The objective of the study was to document late Holocene to historic debris flow activity on the fans and to assess the risk that debris flows pose to the highway and other infrastructure in the corridor. Dendrochronology and tephrochronology were used to date surfaces on the fans and estimate the recurrence interval of debris flows.

3.2 Landslide susceptibility mapping

Qualitative and quantitative methods are used to map susceptibility (van Westen et al. 1999). In the MVSA, a qualitative parametric method was adapted (Riopol et al. 2006). The parametric method was divided in steps where data layers (parameters) were chosen, given weights as well as rated within each parameter. For example, a clay-rich deposit in the surficial geology parameter would have a higher rating than a coarser deposit. The given weights and ratings were based on expert knowledge. A parametric equation was formulated where six layers were defined as variables and the weights as factors:

$$SI = 0.3S1 + 0.05S2 + 0.3G + 0.05P1 + 0.2P2 + 0.1L \quad [2]$$

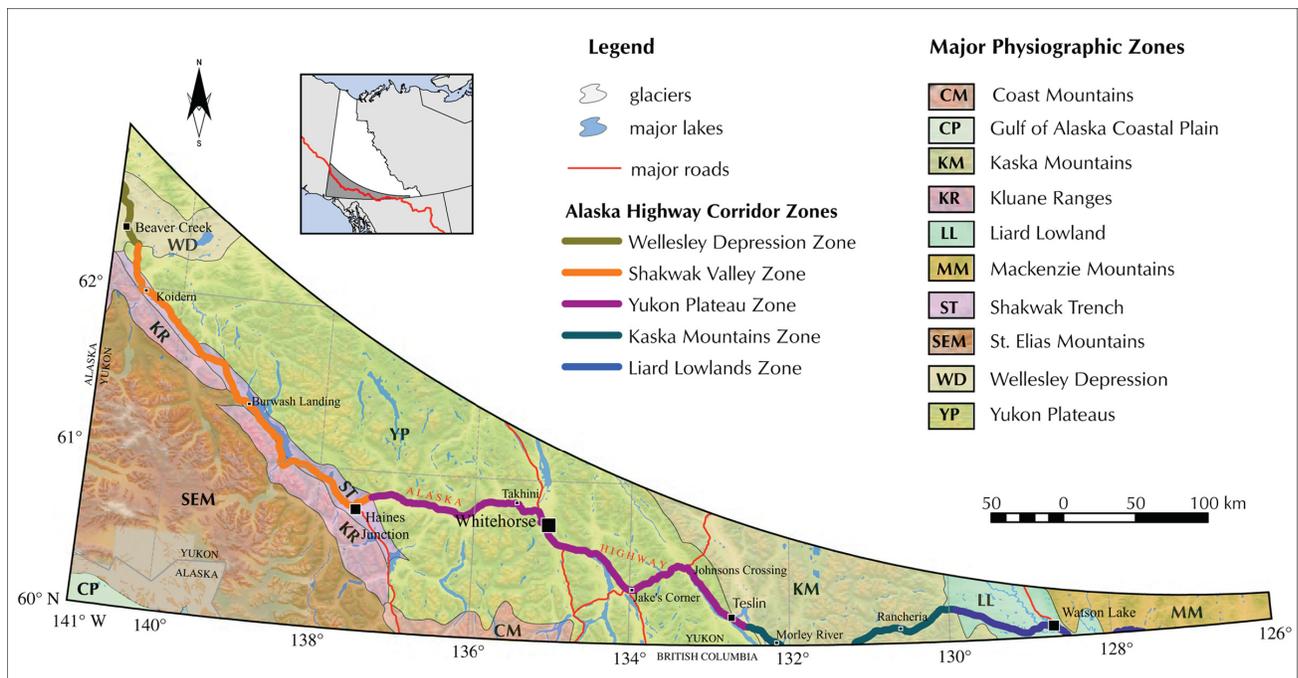


Figure 2. Alaska Highway Corridor showing main physiographic zones (modified after Huscroft et al. 2004). The large lake located in the Kluane Ranges is Kluane Lake.

The codes for the parameters and their respective weight are given in Table 1.

Hence, each pixel (25 m x 25 m) represented a sum of all the weighted parameters and their rating in the form of a susceptibility index (SI) value. The resulting susceptibility indices, values ranging from 1 to 10, were classified in three landslide susceptibility zones using a natural break classifier i.e., low (1.0 to less than 3.5), moderate (3.5 to less than 5.5), and high (5.5 to 10.0).

For the YAHC, another landslide susceptibility map was created but only for debris flows (Table 1). The parametric equation had 5 parameters:

$$SI = 0.3DD + 0.3S1 + 0.2G + 0.15P + 0.05S2 \quad [1]$$

Parameter	Code	Weight (%)	Parameter	Code	Weight (%)
Mackenzie			Yukon		
Slope angle	S1	30	Slope Angle	S1	30
Slope Aspect	S2	5	Slope Aspect	S2	5
Surficial Geology	G	30	Surficial Geology	G	20
Permafrost Type	P1	5	Permafrost Type	P	15

Permafrost - Ice Content	P2	20	Dist. to drainage	DD	30
Land Cover	L	10			
Total	SI	100	Total	SI	100

Table 1. Weights assigned to the six parameters.

4 RESULTS

4.1 Landslide distribution and susceptibility mapping in the Mackenzie Valley

Over 1800 natural terrain hazard features (e.g. karstic sink holes, rock glaciers, etc.) were mapped in the MVSA, including 1751 landslides. Results indicate an average density of one landslide per 5 km² and show that the dominant landslide types are retrogressive thaw flows (29%) and active layer detachments (26%) where rock falls (10%), debris flows (10%), earth slides (9%), and retrogressive thaw slides (5%) are second in order of importance (Fig. 3). About 47% of all landslides took place in morainal deposits. The relative age of landslides was estimated based on tone, texture, and vegetation re-

growth parameters, where 38% were classified ancient (>50 years old), 40% intermediate in age (10 to 50 years old), and 22% recent (<10 years old), the reference year being 2004 (Couture & Riopel 2007, 2008a).

Results also indicate a very small number of rockslides in the MVSA (outcropping bedrock represents only 1% of the study area) but where they occur, they are often ten times larger in size than any other landslide types. About 65% of the landslides occurred in extensive discontinuous permafrost and most of them occurred in zones with low to moderate ice content. Half of the landslides occur on south and southwest facing slopes and around two thirds of the mapped landslides took place where slope angles were lower than 10°.

Validation of the landslide susceptibility model in a pilot study area within the MVSA revealed a good correlation between landslide occurrence and the calculated landslide susceptibility zones. Figure 4 shows the landslide susceptibility map in the pilot zone. Susceptibility zones in red, yellow, and green represent areas having respectively high, moderate, and low landslide susceptibility indices. The total areas covered by low, moderate, and high indices are respectively 20%,

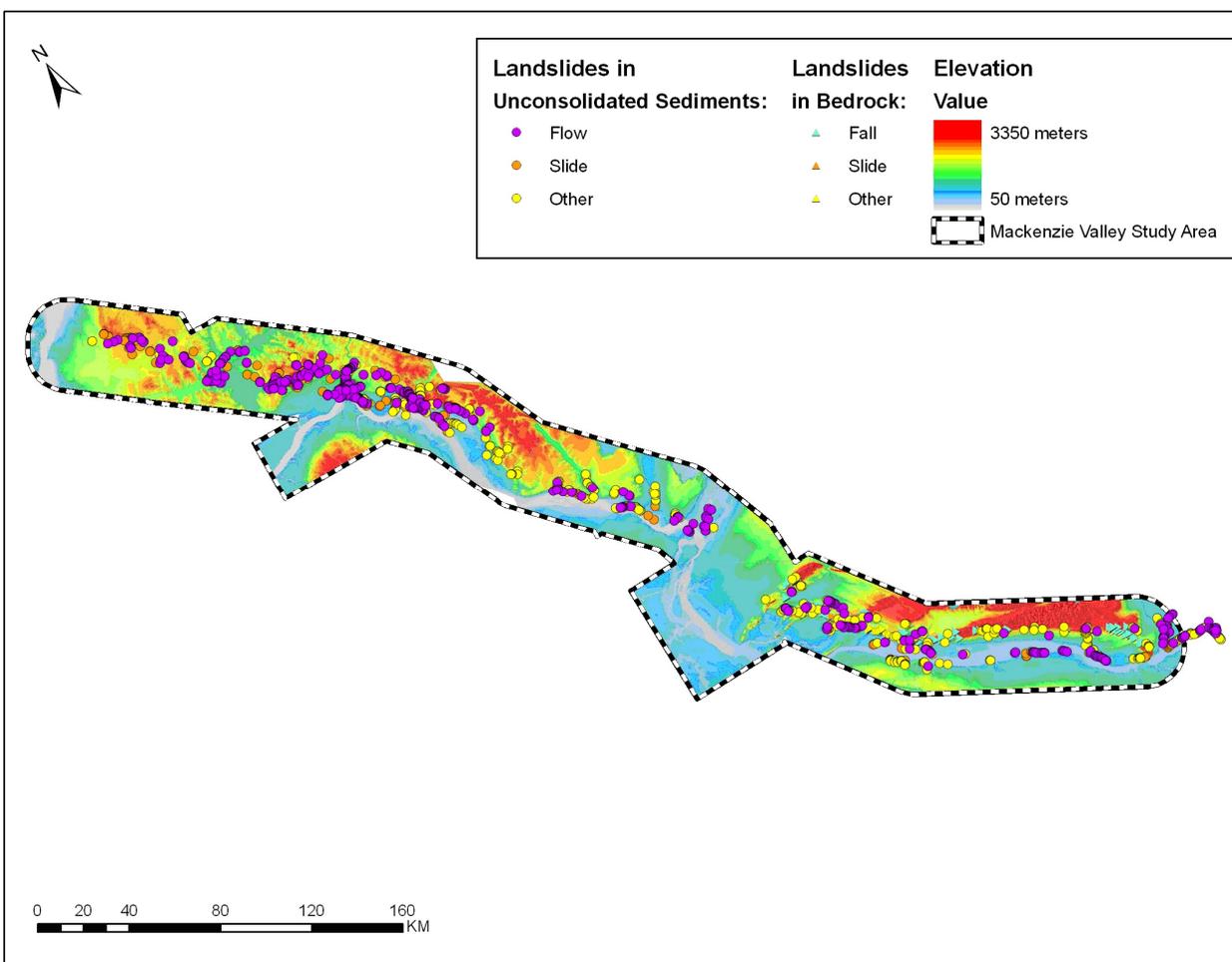


Figure 3. Landslide inventory map superimposed on a digital elevation model of the study area in the Mackenzie Valley (adapted from Couture & Riopel 2008b). Refer to Figure 1 for location of the MVSA.

56%, and 8%. The high landslide susceptibility terrains are mostly located along river banks and lake shores where steeper slopes are present and in areas where geological units are mainly composed of fine-grained

deposits that are more prone to landslides, such as lacustrine plain deposits.

Within the pilot study area, a total of 499 landslides were mapped along the pipeline corridor (about 16 km-wide corridor along the pipeline route). Eighteen (3.6%) of them fall in the low SI areas, whereas 208 (41.7%) and 273 (54.7%) landslides were found in moderate and high SI areas, respectively. From the 273 landslides mapped in the high susceptibility zones (red), about 46% of them are retrogressive thaw flows and 40% are active layer detachments. Thus, only a small percentage of the pipeline length in the pilot study area falls in the high susceptibility zone (9%). The percentage of the pipeline length falling in moderate and low susceptibility zones are respectively 17% and 74% (Fig. 4).

4.2 Landslide inventory and debris flow susceptibility mapping along the Alaska Highway in Yukon

In the YAHC, a total of 1612 landslides were identified on air-photos, which represents about 1 landslide per 12 /km². The main landslide types were: debris flows and fans (28%), debris slides (31%), earth slides/flows (5%), rock slides (11%), rock falls and topples (4%), karstic depressions (5%), solifluction (8%), and combined retrogressive thaw flows and active layer detachments (1%). Rock glaciers were also identified (6%). A landslide distribution map reflects dominant landslide activity in unconsolidated sediments at 64% (Fig. 5).

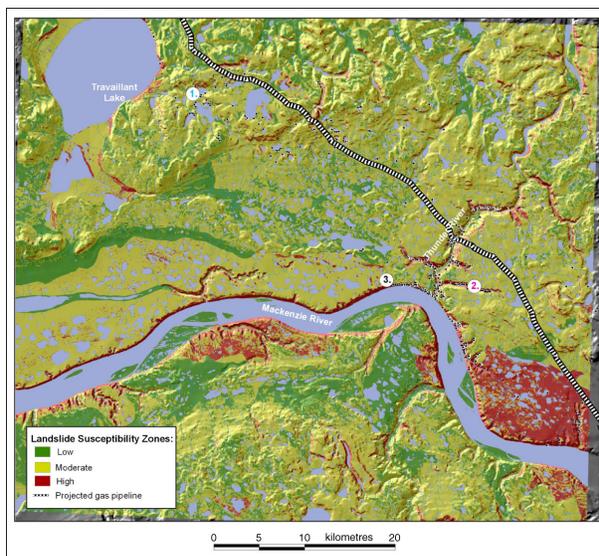


Figure 4. Landslide susceptibility map of the TTPS (Travilliant-Thunder Pilot Study) draped over a shaded relief. Pie chart indicates the percentage of pipeline length (dashed line) falling in the susceptibility zones.

A debris flow susceptibility map was created for the the YAHC (Fig. 6). The susceptibility index values varied from 0.1- 9.4. Natural breaks were used to divide the indices in low (green), medium-low (yellow), medium-high (orange) and high zones (red). For validation, the debris flow inventory was overlain on the susceptibility map. Consequently, we observed a very good correlation between the mapped debris flow deposits and the susceptibility zones.

A total of 69% of the mapped debris flow deposits occur downstream from a high (red) susceptibility zone; 28% occur downstream from the med-high (orange) susceptibility zone (Fig. 6). For this area, only 6% of the Yukon-Alaska highway falls within the high susceptibility zone, 17% in the medium-high zone, 45% in the medium-low zone, and 32% in the low susceptibility zone.

4.3 Debris flow processes and frequencies, Yukon Alaska Highway Corridor

For the debris flow deposits west of Kluane Lake and adjacent to the Alaska Highway, preliminary results show that debris fans were built during and shortly after deglaciation and have only been modified to a small degree since the White River eruption around 1000 years ago. White River tephra lies at or near the present fan surface at most of the sites. At some sites, however, debris and hyperconcentrated flows overtopped modern stream banks and spread thin layers of sediment on the adjacent fan surface. No tephra was present in pits dug on these surfaces, thus these debris flows are probably less than 1000 years old. White spruce growing on these surfaces are generally 150-200 years old, but they may not closely delimit the ages of the debris flows because spruce in the Yukon are periodically killed by wildfire and disease and rarely older than 200 years. We found evidence for multiple debris flows, separated by soil layers that in two cases included woody debris, some of which in growth position. We found trees with up to two levels of adventitious roots which grow when buried by a thin layer of sediment. Trees with adventitious roots provide evidence that they were covered by hyperconcentrated debris flow sediments at least once during their lifetime. The axial streams have been significantly modified during the past several decades to lessen the likelihood of damage to the Alaska Highway. Channel works include large-diameter highway culverts, levees, and berms bordering the streams. Some of the latter extend from the highway to near the apexes of the fans. Many of the berms and levees have been eroded during periods of high flow. We tentatively conclude that any future debris flows along this investigated reach of the Alaska Highway will be restricted to present stream

crossings. Although these debris flows may cause significant erosion higher on the fans, especially near their apexes, they are likely to deposit sediment on the lower parts of the fans crossed by the Alaska Highway.

5 DISCUSSION AND CONCLUSIONS

Landslide inventories for the two study areas provided the baseline geoscientific information needed to assess the landslide types and distribution. In the MVSA, most of the landslides have occurred in fine unconsolidated sediments and on shallow slopes. In the YAHC, a good majority has occurred in unconsolidated sediments (65%) but there are also a few landslides (15%) that have occurred in bedrock with high relief.

The qualitative parametric approach used in both areas seems to have provided good landslide susceptibility maps and a preliminary hazard assessment for the corridors. Landslide susceptibility mapping could be improved in both areas by trying other susceptibility methods for comparison. Another approach to landslide susceptibility mapping would be to distinguish landslide types that have unique parameters. For example, a susceptibility map for bedrock related landslides and another for sediment related failures. Adding new parameters with better resolution could also refine the susceptibility models. Examples of additional parameters could include forest fire occurrence as forest fires degrade the insulation effect of the vegetation layer above frozen ground and therefore change the thermal regime of permafrost. Furthermore, a higher resolution

permafrost distribution map would likely improve the landslide susceptibility models.

From our preliminary, site specific debris flow deposit investigations, we tentatively conclude that any future debris flows along the investigated reach of the Alaska Highway will be restricted to present stream crossings.

In both pipeline corridors, slope failures are prominent. More slope failures in the MVSA seem to be affected by permafrost than ones in the YAHC. Therefore, one can anticipate a larger influence on climate change on landslide occurrence in the Mackenzie Valley than along the Alaska Highway in Yukon.

Most landslides that could affect the pipeline corridor have occurred in sediments with shallow slopes in the MVSA, but in the YAHC, the slope failures have also been initiated in steep bedrock terrain. Thus, our preliminary investigations indicate that there is a slope hazard in both corridors to be considered during development of the pipelines.

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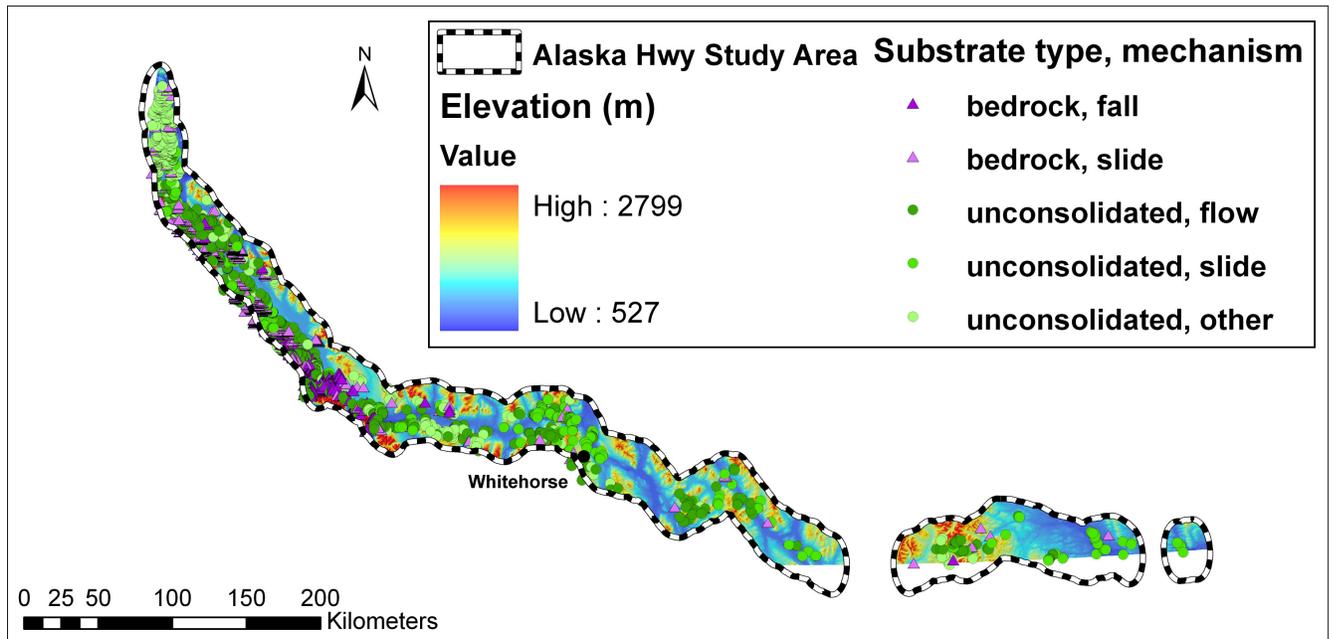
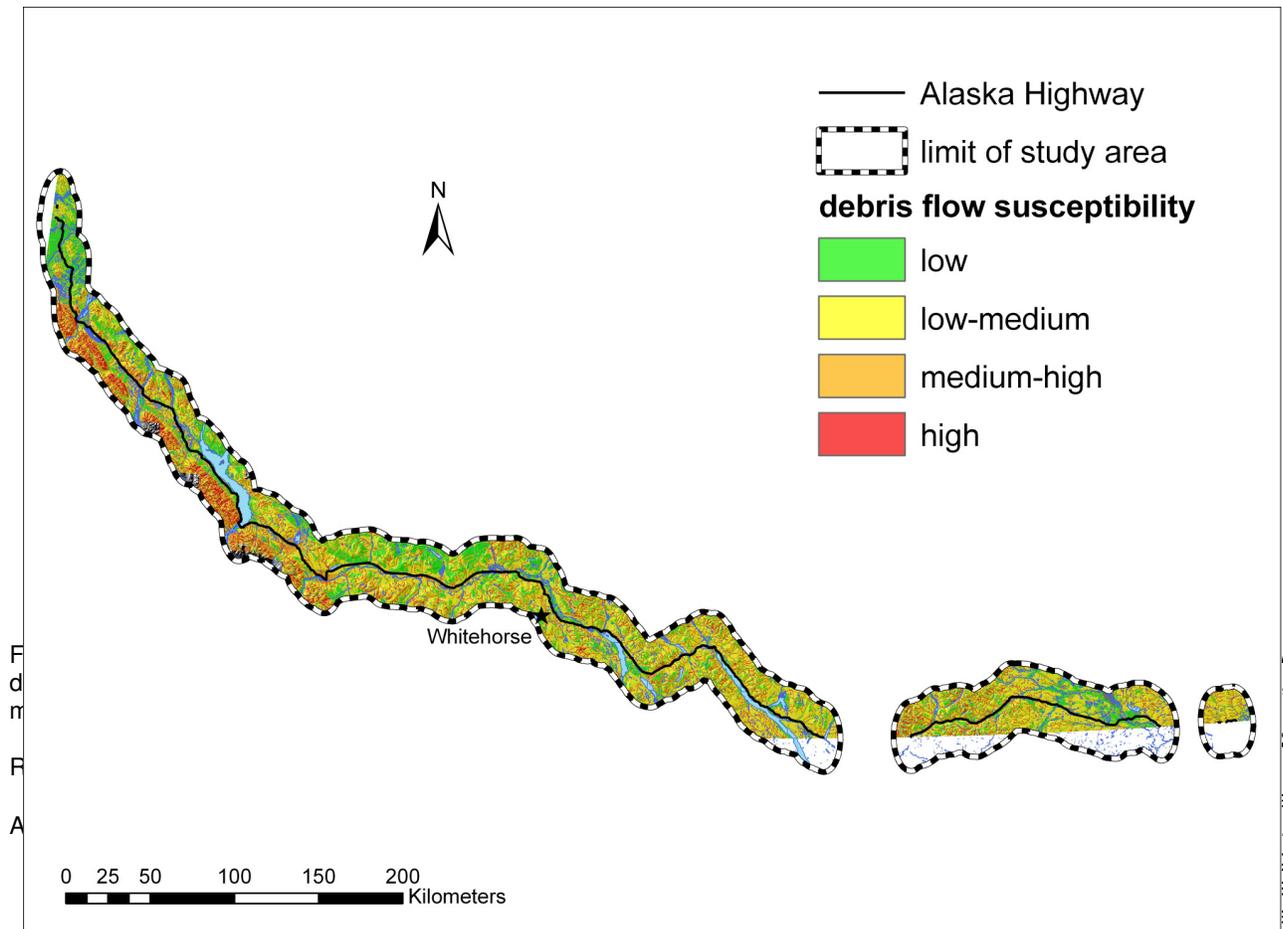


Figure 5. Landslide distribution map overlain on digital elevation model. Triangles represent landslides in bedrock and circles, landslides in unconsolidated sediments.



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