TRAVELS IN THE CANADIAN CORDILLERA

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RÉSUMÉ

Le fahrboschung d'un mouvement de terrain est un paramètre important dans l'analyse de risque. Ici, nous examinons la première utilisation du concept au Canada, appliquée au glissement de terrain Frank, en Alberta. Nous présentons aussi 61 autres exemples de fahrboschungs associés aux glissements de terrain qui ont eu lieu dans les Cordillières canadiennes, la plupart étant situés dans le nord-est de la Colombie-Britannique. Nous avons aussi divisé les fahrboschungs selon des intervalles appartenant à certains groupes de glissements de terrain. Ceux-ci sont, par ordre de croissance, les sédiments glaciomarins sensibles, les coulées de terre générées par des glissements rocheux, les diamictons dérivés des ardoises, les sédiments glaciolacustres provenant d'une phase d'avancement glaciaire, les avalanches rocheuses, les glissements rocheux-coulées de débris, les glissements rocheux-avalanches de débris et les avalanches rocheuses.

ABSTRACT

The travel angles of landslides are important parameter in risk analyses. Here we examine the first use of the concept in Canada, applied to the Frank slide. We also report on travel angles of an additional 61 long runout landslides in the Canadian Cordillera, mostly in northern BC. The lowest travel angles we report belong to the following groups (in ascending order) sensitive glaciomarine sediments, earth flows generated by rock slides, diamicts derived from clay shales, advance phase glaciolacustrine sediments, rock avalanches on glaciers, rock slide – debris flows, rock slide debris avalanches, and rock avalanches in general.

1. INTRODUCTION

When landslides of considerable consequence have occurred, we should ask what risks are posed by similar landslides which might occur in similar materials in similar terrain under similar conditions. Here, we discuss the first attempt to answer this question in the Canadian Cordillera. It took place in the Crowsnest Pass in south western Alberta in 1911, after the Frank Slide. We put the results of that inquiry among an additional 61 historic landslides, mostly in northern British Columbia. Together, they illuminate some of the problems in estimating the extent of landslide hazard. We suggest that knowledge of the history of the travel angle concept in the Cordillera is useful in the understanding of, and application to areas of landslide hazard in this region.

2. THE FIRST HAZARD MAP

On October 3, 1911, the Commission appointed to investigate Turtle Mountain arrived at Frank "to examine the mountain and to delimit the area likely to be affected in case of further rock slip" (Geological Survey of Canada, 1912, p 12 – 13). The Commission, R.A. Daly (Research Professor of Geology at Massachusetts Institute of Technology), W.G. Miller (Provincial Geologist Ontario), George S. Rice (Coal Mining Engineer, United States Bureau of Mines) submitted their report on 2 December, 1911," with maps, sections, and photographs of a character such as to make a more voluminous text unnecessary" (Daly *et al.*, 1912, p 12). There are two maps in the Report: one, a detailed (1:9600) topographic map of the mountain was placed at the service of the Commission by W.H. Boyd, Chief Topographer of the Geological Survey of Canada. Based on the map, Boyd had also prepared an interesting and instructive model of the mountain. (Daly *et al.*, 1912, Plate 4) The model consisted of 9 parallel cardboard topographic sections through Turtle Mountain. These 9 sections appear to be profiles 1 to 9, forming figures 2 to 10 in the Report.

The second map in the Report took the first as a base for an outline of the "approximate…area endangered if north Peak Block should fall." The Commission used an analogy with the 1903 slide to trace the limits of danger. The analogous peak in the 1903 slide would be the Centre Peak of Turtle Mountain; unfortunately the exact location and topography of Centre Peak was not surveyed before the Slide and substantially displaced in the Slide.

There was, however, one photographic view of Centre Peak before the Slide (Report, Plate 13); the camera station from which it was taken was re-occupied and a similar view captured after the Slide (Plate 14). The limited perspective of these two Plates did not give a unique solution for both the position and the height of Centre Peak. However, if Centre Peak were close to the line of one of the Profiles, then a rapid, approximate and non-unique solution to the position and height of Centre Peak was available. The position of Centre Peak on Profile 9 was scaled and interpolated from the photography.

Centre Peak, 600 feet (183 m) east of the Slide scarp on Profile 9 and 420 feet (128 m) above it, allowed a line (sloping at 1 in 3) to be drawn from the peak to the tip of the

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Proceedings of the 4th Canadian Conference on Geohazards : From Causes to Management. Presse de l'Université Laval, Québec, 594 p.

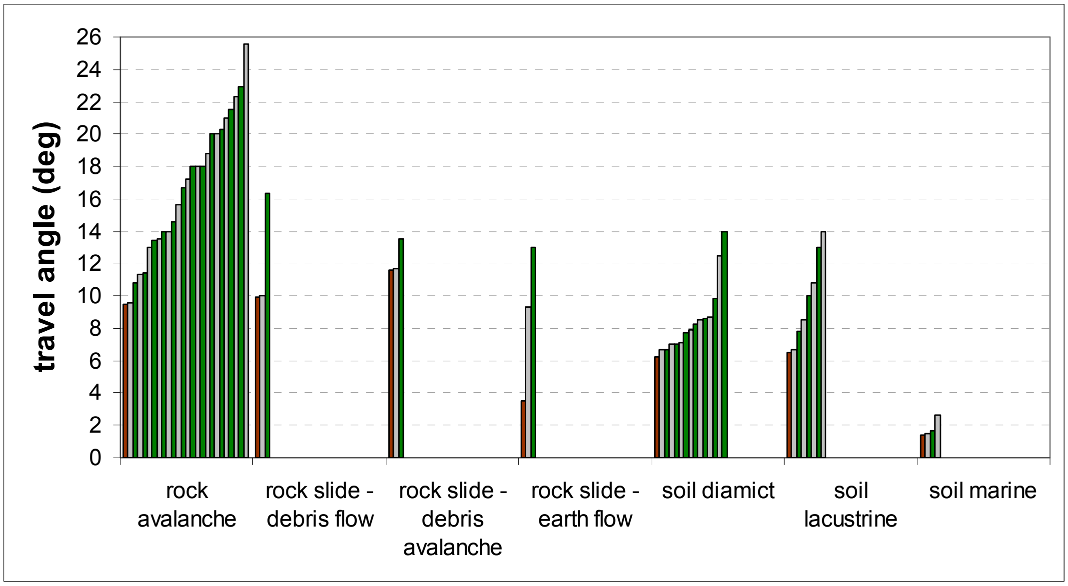

Figure 1. Travel angles of 61 long runout landslides in the Canadian Cordillera.

slide deposits on Profile 9. Centre Peak was by this estimate, 7520 feet (2292 m) high, 317 feet (97 m) higher than Boyd's surveyed height of South Peak after the slide. The slope west from Centre Peak is tan $^{-1}$ 0.7 (35º), a slope parallel to the undisturbed western slope of Turtle Mountain on Profile 9 and a confirmation of the plausibility of Boyd's reconstruction. The simple numbers suggest some rounding. Boyd did not name the plunge of the line from the Peak top to the tip of the Slide; we will call this angle, the peak travel angle.

Focussing then on North Peak, Boyd sketched traces of fractures parallel to the two sets he had mapped so as to surround the North Peak on the west side (Map 2.) Assuming these fractures were perpendicular to bedding, their intersection would also be perpendicular to bedding. It would provide an axis for sliding which daylighted on the slope below North Peak (shown on profile 4). The travel of the displacing rock would parallel the north margin of the Frank Slide and extend to the tip of the hypothesized North Peak Block slide at an angle of 18.5º (arctan 0.333) from North Peak. The margins of the hypothetical slide were then sketched parallel to the travel direction, from the lateral margins of the crown of this slide. The construction of the 'Area endangered…" was then a simple geometrical analogue with the travel of Centre Peak in the Frank Slide. Allan (1931) used a similar technique to construct a Large Danger Zone for the South Peak of Turtle Mountain.

A dynamic interpretation of the kinematics of rock slides was not offered until 1932 (Heim, 1932, pp 126-136). Skermer's translation noted "Since it is a question of finding the extreme limits of the imminent landslide, the energy line has to be drawn down from the highest point of the probable slide mass" (p. 130) However, " the inclination of the straight line between the uppermost scarp edge and the tip of the tongue of the stationary rubble stream has long since been considered a characteristic factor for landslides"(p. 129) and 'After several studies, I found the character of a rock avalanche could best be compared by using the angle of reach of the central stream line." (p. 106). For the purposes of comparison, we, too, have used this angle, termed "the travel angle" by Cruden and Varnes (1996, Figure 3-7) in this paper. We remember that, in some cases, it is a conservative estimate of the peak travel angle first employed in 1911. The travel angle of the Frank Slide along profile 9 is 15.4°.

3. TRAVEL ANGLES OF OTHER CORDILLERAN LANDSLIDES

Here we consider the travel angles of an additional 61 historic, large, long runout landslides in the Canadian Cordillera (Fig. 1; Table 1 in Appendix 1). Data was obtained from the literature and from measurements from TRIM and other digital elevation models. The locations of the landslides are listed in the references located in Appendix 1. We consider both landslides in rock and soil. We group the rock movements into rock avalanches and rock slides that trigger movements in soil, including debris flows, debris avalanches, and earth flows. Some of the landslides in the general rock avalanche category could perhaps be added to one of the latter categories following more detailed assessments. The soil landslides include long runout movements in glaciomarine and glaciolacustrine sediments and in diamicts usually interpreted to be tills.

3.1 Rock slides

Twenty six long runout rock slides in our dataset had travel angles ranging from 9.5 to about 26º. These rock avalanches occur in a variety of settings (Geertsema *et al.* 2006). Many begin as rock falls on unstable cirque walls, others are associated with mountain top deformation, some occur on sedimentary dipslopes, usually associated with faults. In northern BC, Geertsema *et al.* (2007) found that large rock slides tended to occur in years of above average temperature. Some rock avalanches are triggered by earthquakes and one happened during a heavy thunderstorm (Egginton et al 2007). The lowest travel angles for rock avalanches occurred on glaciers. Travel angles at Kendall Glacier (Fig. 2) and Devastation Glacier were 9.5 and 9.6º, respectively.

Figure 2. The 1999 Kendall Glacier rock avalanche near McBride, BC, likely triggered during a thunderstorm, had a travel angle of 9.5º.

A subset of ten additional rock slides that transformed into soil movements also had very low travel angles. Both the McCauley and Harold Price rock slides transformed into channelized debris flows with travel angles of about 10º. Rockslides at Pink Mountain and Sutherland River transformed into debris avalanches but did not channelize into flows. They had travel angles of 11.6 and 11.7º, respectively.

The lowest travel angles involving rock occurred where rock slides have triggered earth flows in cohesive diamicts derived from shales. The most spectacular of these occurred on a tributary of Muskwa River in 1979 (Fig. 3). A rotational rock slide of about 3 M m^3 triggered a 12-15 M m^3, 3.25 km long earth flow. The travel angle of the landslide was 3.5º. We attribute the low travel angle in this material to undrained loading (Hutchinson and Bhandari 1971), by the triggering rock slide. Landslides in similar materials in northern BC that are not triggered by rock slides have travel angles above 6º.

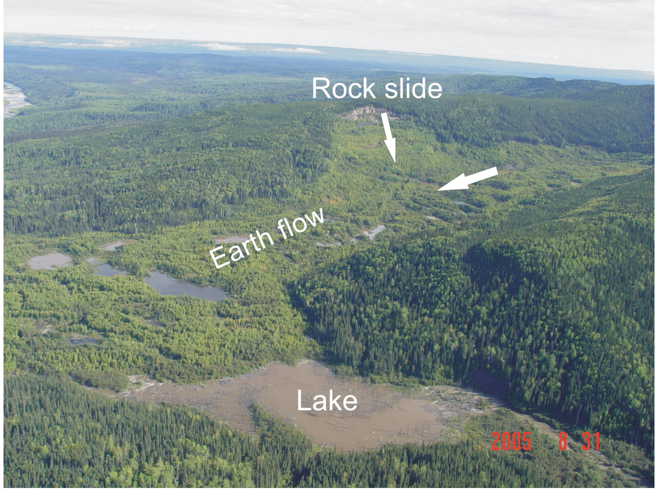

Figure 3. The 3.25 km Muskwa rock slide – earthflow had a travel angle of 3.5º. The flow in a low stone content clayey diamict was triggered by undrained loading caused by the rock slide.

3.2 Landslides in soil

Rapid translational landslides in soil can move in various modes. They may also retrogress, advance, and widen. In many cases movement occurs along two or more treads separated by steeper pitches. In areas such as on the plateau above Buckinghorse River, BC, landslides typically move along surfaces of about 3-4º, flow over the edge of bedrock escarpments, and come to rest in valley bottoms.

Other parameters too are important for landslides that occur on the edges of plateaus, such as the distance of retrogression, and especially in the sensitive clay literature, R/H (R is retrogression distance, H is the height of the original ground surface above the rupture surface) is a useful metric.

The landslides in glaciolacustrine sediments in our dataset all involve advance phase lake sediments rather than retreat phase lake deposits. This means they were all covered by till, rather than overlying till. These landslides had travel angles between 6.5 and 14 º.

Landslides in diamicts (interpreted to be tills) had travel angles even lower than those in lake sediments from 6.2 to 14 º (Figures 4 and 5). These all occurred in northeastern BC in sediments derived from clay shales with low clast contents. Tills in most other parts of the Cordillera are stronger and move on steeper gradients. It should be cautioned that when a rupture surface is covered it is possible to miss a buried glaciolacustrine unit.

The steeper travel angles in the data set belong to smaller landslides that entered the mainstem of Buckinghorse River. Landslides entering its tributaries had lower travel angles. This may be explained by the deeper incision of the river relative to its tributaries, increasing the overall slope to the river.

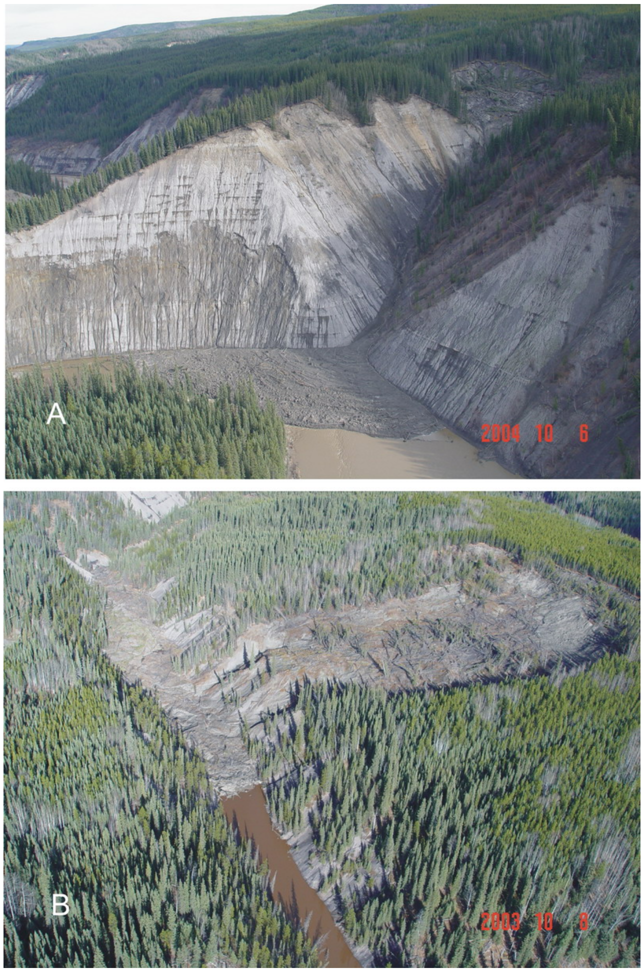

Figure 4. Contrasting flows in the Buckinghorse area. The very wet flow in (a) travelled 600 m at 12.5º. Because the landslide entered a large river, its dam was short-lived. (b) a 700 m flow in with a travel angle of 8.5 º impounded a small tributary of Buckinghorse River. The dam has remained in place for approximately a decade.

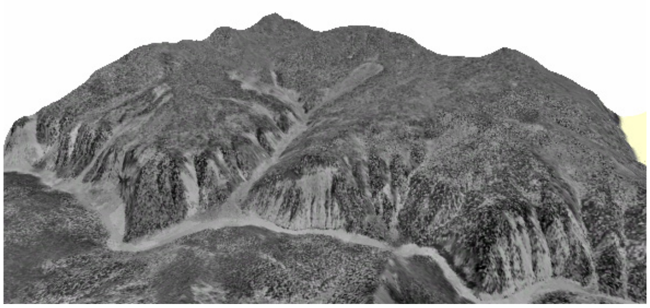

Figure 5. Large low-gradient landslides and smaller, steeper, closely spaced ones on the south slopes of Buckinghorse River. The 1730 m long retrogressive landslide (centre) occupies a buried valley and has a travel angle of 6.7º. The steeper smaller landslides typically have 17 or 18º travel angles.

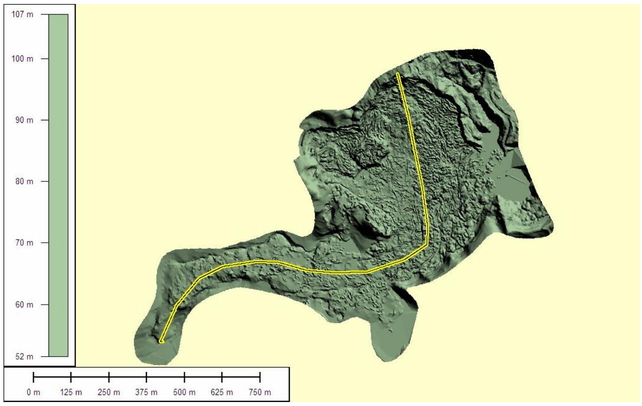

Figure 6. Employing the angle of the central stream line of an earth flow – spread in sensitive glaciomarine sediments at Mink Creek yields a travel angle of 1.7º.

The lowest travel angles in our dataset belong to the landslides occurring in sensitive glaciomarine sediments. A landslide that travelled 3 km, including about 1.6 km into Lakelse Lake in 1962 (BC Ministry of Transportation and Highways 1962), had a travel angle of at most 1.4º. The tip of the displaced mass has not been accurately plotted on the lake bottom. Movement between the crown of the landslide and the edge of the lake occurred on a gradient of 0.2-0.4º. The earth flow – spread at Mink Creek (Geertsema *et al.* (2006) (Fig. 6) had a travel angle of 1.7º.

4. DISCUSSION AND CONCLUSIONS

Hungr *et al.* (2005) and Corominas (1996) have demonstrated a negative correlation between angle of reach and landslide volume. We too have plotted landslide volume vs tan of travel angle, although many of the landslide volumes have not yet been calculated (Fig. 7). In our dataset this negative correlation is less clear. What is clear, however, is the relationship between material type and travel angle. A more rigorous subdivision of rock avalanches into for example, rock fall – debris flows and rock slide debris flows, might result in more precise groupings.

The lowest travel angles we report belong to the following groups (in ascending order) sensitive glaciomarine sediments, earth flows generated by rock slides, diamicts derived from clay shales, advance phase glaciolacustrine sediments, rock avalanches on glaciers (eg. Kendall Glacier), rock slide – debris flows, rock slide debris avalanches, and rock avalanches in general. The sensitive clay landslides have travel angles that are an order of magnitude lower than the rock avalanches. Some of the translational landslides in diamicts and lake sediments plot between the rock slides and the glaciomarine landslides,

The travel angle of a landslide is an important component of risk analysis. In the cases of rock slides and debris flows risk zonation requires knowledge of potential travel

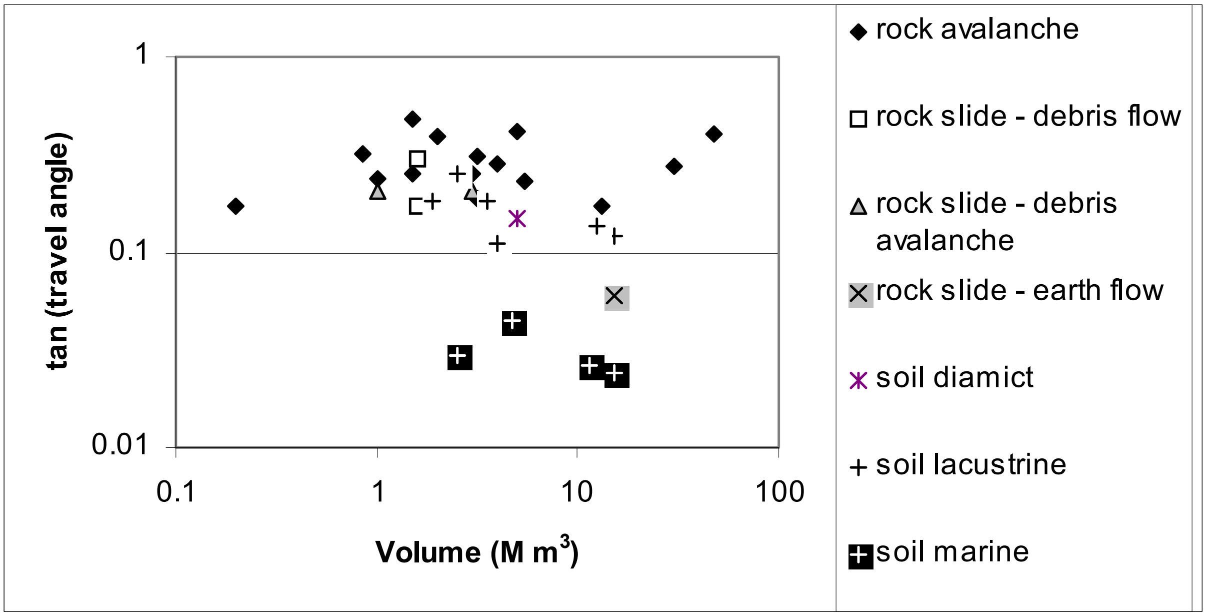

Figure 7. Plot of volume vs. H/L for 31 Cordilleran landslides in various materials. Translational landslides in soil tend to have lower travel angles than rock avalanches. The glaciomarine landslides in quick clays occupy the lowest position on the graph.

distances. A set forward can be established from a minimum travel angle and a maximum travel distance for an area. This is also the case for translational landslides in waterlain sediments and in tills. However in these sediments the issue of setbacks becomes important as well. Many of these landslides are retrogressive, and penetrate into level to gently sloping terrain. Minimum travel angles of landslides should play a role in developing setback criteria on incised plateaus.

The Province of BC is considering guidelines for setbacks based on travel angles in the Peace River area. Tracing an angle of 7 degrees upslope from the centerline of streams in a GIS captures most of the mapped landslides in this area. Alberta Environment has published draft environmental guidelines for setbacks (Standards and Guidelines Branch 1998).

5. ACKNOWLEDGMENTS

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APPENDIX! 1

Table 1. Landslide data.

Name	Date	Volume (M m^3)	Length (km)	Travel Angle (°)	Reference
Rock Avalanches					
Frank Slide	1903	30	3.1	15.4	Daly et al (1912)
Tweedsmuir Glacier	1979		1.3	20.3	Evans and Claque (1999)
Jarvis Glacier	1979		2.4	16.7	Evans and Claque (1999)
Towagh Glacier	1979		4.4	11.3	Evans and Claque (1999)
North Creek	1986	1-2	2.8	14.6	Evans and Claque (1999)
Frobisher Glacier I	1990		3.1	18.8	Evans and Claque (1999)
Frobisher Glacier II	1991		2.4	22.3	Evans and Claque (1999)
Kshwan Glacier	Sept 92 - May 93	3.2	2.3	17.2	Mauthner (1996)
Kendall Glacier	1999	0.2	1.2	9.5	Couture and Evans (2002)
Ha Ha	Pre 1974		2.0	18	MOFR
Tutzizzi	Pre 1974		0.95	20	MOFR
Howson II	1999	1.5	2.7	25.6	Schwab *et al.* (2003)
Tetsa	1988		2	14.0	Geertsema (2006)
Chisca	mid 1990’s	1	1.5	13.5	Geertsema (2006)
Turnoff Creek	1992	4	2	15.6	Geertsema (2006)
Mosque Mountain	mid 1990’s	5	1.2	22.9	Lu *et al.* (2003)
Verney – Bishop’s Bay	2002-03	.85	1.1	18	Geertsema (2006)
Tim Williams	1956	3	3.7	14	Evans and Clague (1999)
Todagin	2006	1-3	1.9	21.5	MOFR
Bonnet Plume, YK			3.79	13.4	MOFR
Pandemonium Ck	1959	5.5	8.6	13	Evans and Clague (1999)
Rockslide Pass, NWT			4.48	11.4	MOFR
Hope		48	3.1	22	Bruce and Cruden (1977)
Devastation Glacier	1975	13	7	9.6	Evans and Clague (1999)
Mount Munday	1997	3.2	4.7	10.8	Evans and Clague (1999)
Mount Meager	1986		3.7	20	Evans and Clague (1999)
B. Landslides involving soil (flowslides) **1. Glaciomarine sediments**					
Mink Creek	Dec 93 - Jan 94	2.5	1.6	1.7	Geertsema *et al.* (2006b)
Khyex River	28 Nov. 2003	4.7	1.85	2.6	Schwab *et al.* (2003)
Lakelse North	June 1962	15	3 +	1.4	MOTH (1962)
Lakelse South	May 1962	11.5	1.1	1.5	MOTH (1962)
2. Glaciolacustrine sediments					
Attachie	May 1973	12.4	1.5	7.7	Fletcher et al (2002)
Inklin	1979	2-3	0.7	14	Geertsema (1998)
Sharktooth	1980	3-4	1.2	10.8	Geertsema (1998)
Halfway	Aug 1989	1.9	1	10	Bobrowsky and Smith (1992)
Flatrock	October 1997		0.65	13	Geertsema (2006)
Mess	1996?		1.7	8.5	MOFR
Houston Tommy		15	1.2	6.7	MOFR
Houston Tommy		4	.1.05	6.5	MOFR
3. Diamictons (mostly clayey tills)					
Scaffold Creek	mid 1990’s		0.55	8.6	Geertsema (2006)
Halden Creek	mid 1990’s	5	0.55	8.7	Geertsema and Clague (2006)
Halden II	1980’s		0.6	7.7	MOFR
Buckinghorse	mid 1990’s		1.73	7.1	Geertsema (2006)
Buckinghorse	mid 1990’s		1.73	6.7	Geertsema (2006)
Buckinghorse	mid 1990’s		1.05	6.7	Geertsema (2006)

Name	Date	Volume (M m^3)	Length (km)	Travel Angle (°)	Reference
Buckinghorse	mid 1990’s		1	7.9	Geertsema (2006)
Buckinghorse	mid 1990’s		1.55	8.3	Geertsema (2006)
Buckinghorse	mid 1990’s		1.4	6.2	Geertsema (2006)
Buckinghorse	2004		0.6	12.5	MOFR
Buckinghorse	mid 1990’s		0.7	8.5	Geertsema (2006)
Buckinghorse	mid 1990’s		0.92	7	Geertsema (2006)
Buckinghorse	mid 1990’s		0.82	14	Geertsema (2006)
Buckinghorse	1980’s		0.86	9.8	MOFR
Trutch	1997-2004		0.77	7	MOFR
C. Landslides involving rock and soil **1. Rock slump – earth flows**					
Muskwa	1979	15	3.25	3.5	Geertsema (2006)
Muskwa-Chisca	2001		1.75	13	Geertsema (2006)
Grizzly, NWT			4.22	9.3	MOFR
2. Rock slide - debris flows					
Zymoetz	2002	1.6	4.3	16.3	Boultbee *et al.* (2006)
McAuley	2002			10	Evans et al (2003)
Harold Price	2002	1.6	4	9.9	Schwab *et al.* (2003)
3. Rock slide - debris avalanche					
Nomash	1999			13.5	Guthrie et al (2003)
Pink Mountain	2002	1	2	11.6	Geertsema (2006)
Sutherland	2005	3	3	11.7	Blais-Stevens *et al.* (2007)