FURTHER TRAVELS IN THE CANADIAN CORDILLERA

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ABSTRACT

The travel angles of landslides continue to be an important parameter in risk analyses. We report on travel angles of 112 long runout landslides in the Canadian Cordillera, expanding on our 2008 study of 61 landslides. The lowest travel angles we report belong to the following groups (in ascending order) sensitive glaciomarine sediments, early deglacial earth flows in lake sediments, diamicts derived from clay shales (they may involve permafrost), glaciolacustrine sediments, earth flows generated by rock slides, confined and unconfined debris flows generated by rock slides, rock avalanches on glaciers, dry planar rock avalanches, and undifferentiated rock avalanches.

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 112 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.

1. A WORKING HYPOTHESIS

The IAEG Commission on Landslides & other Mass Movements on Slopes in its first technical publication (Varnes, 1984) asserted principles. The first principle, "the past and present are keys to the future" meant that " natural slope failures in the future will most likely be in geologic, geomorphic and hydrologic situations that have led to past and present failures…we have the possibility to estimate the style, frequency of occurrence, extent and consequences of failures that may occur in the future."

This principle, "long found useful in geology", was not supported by any reference. Perhaps it was an echo of "Within the limits of a physiographic subdivision, where similar geologic processes have been working on similar materials arranged in geologically similar ways, the tendency toward landsliding is likely to be characteristic of the locality" (Peck,1975 ,p.133). Varnes (1975) had previewed the second edition of his classification (Varnes, 1978) at the Symposium where Peck presented his paper..

A contemporary editor of Lyell's Principles of Geology has remarked that "the present is the key to the past" is a frequent summing up of the philosophy of the Principles (Secord, 1997,p. xxi). While no key is indexed, in the first paragraph of Chapter 5, Theoretical Errors which have retarded the Progress of Geology", Lyell(1830) wrote "…some geologists… infer that there has never been any interruption to the same uniform order of physical events. The same assemblage of causes, they conceive, may have been sufficient to produce, by their various combinations, the endless diversity of effects, of which the shell of the earth has preserved the memorials, and, consistently with these principles, the recurrence of analogous changes is expected by them in time to come."

Geological inference is subject to the problem of induction described by Lyell's countryman, Hume (1772, Section 4, Sceptical Doubts concerning the operation of the Understanding) in Beauchamp (1999).

In reality, all arguments from experience are founded on the similarity, which we discover among natural objects, and by which we are induced to expect effects similar to those which we have found to follow from such objects. And though none but a fool or a madman will ever pretend to dispute the authority of experience, or to reject that great guide to human life; it may surely be allowed a philosopher to have so much curiosity at least, as to examine the principle of human nature which gives this mighty authority to experience, and makes us draw advantage from that similarity, which nature has placed among different objects. From causes which appear similar, we expect similar effects. This is the sum of all our experimental conclusions."

Hume's challenge to philosophers was taken up, nearly two centuries later, by Popper who approached the problem of induction through Hume." Hume, I felt, was perfectly right in pointing out that induction cannot be logically justified. He held that there can be no valid logical arguments allowing us to establish that those instances of which we have no experience resemble those of which we have experience.

Consequently even after the observation of the frequent or constant conjunction of objects, we have no reason to draw any inference concerning any object beyond those of which we have had experience…I found Hume's refutation of inductive inference clear and conclusive. But I felt completely dissatisfied with his psychological explanation of induction in terms of custom or habit." Popper (1989, p. 42).

Popper was led by logical considerations to replace Hume's psychological theory of induction with a theory of trial and error,of Conjectures and Refutations. "Without waiting passively for repetitions to impress or impose regularities upon us, we actively try to impose regularities upon the world. We try to discover similarities in it, and to interpret it in terms of laws invented by us. Without waiting for premises, we jump to conclusions. These may have to be discarded later, should observation show that they are wrong." (Popper, 1989, p.46)

The principles proposed above by Varnes, Peck and Lyell might then be regarded as unverifiable conjectures subject to refutation by further observations. Popper (1972 ,p.22) suggested that "the best-tested " conjecture be preferred by pragmatic persons. To our knowledge none of these conjectures about landslides has been tested, perhaps because they were not postulated with that end in view. Our more recent consensus on landslide terminology (Picarelli et al., 2005) allows the extension of Peck's Principle to become "Landslides of similar type in similar materials under similar conditions are caused by similar processes". Such a working hypothesis should be useful in predicting the type of movement in an apparently stable natural slope, allowing some progress on a difficult practical problem.

We can use the travel angles of similar landslides in similar materials to assess controls on the movements of these landslides

2. TRAVEL ANGLES OF CORDILLERAN LANDSLIDES

Here we consider the travel angles of 111 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, LiDAR, and other digital elevation models. The locations of the landslides are listed in the references located in Table1. 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 and earth flows. Some of the landslides in the undifferentiated 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. There is a special category we consider with prehistoric glaciolacustrine flows, thought to be associated with lake drainage.

2.1 Rock slides

The first rock avalanche described from Western Canada was the Frank Slide (McConnell and Brock, 1904, Cruden, 2003). It fell within the Hungr et al. (2012, p.56) definition of a rock avalanche as an "extremely rapid, massive, flow-like motion of fragmented rock from a large rock slide or rock fall". The Working Classification of Landslides (Cruden and Couture, 2011) would name these two types of avalanche as a complex rock-slide debris-flow and a complex rock-fall debris-flow. The new sample of 9 rock slides from the Rockies are characterized by well exposed rupture surfaces following bedding in the sedimentary rock masses and dipping at angles close to the basic friction angles of the rock masses. Their travel angles average 15.8 degrees with a coefficient of variation of 0.22. So their mean is not significantly different from the mean travel angle, 16.5 degrees, of all 26 rock avalanches collected in our previous paper (Geertsema and Cruden, 2008).

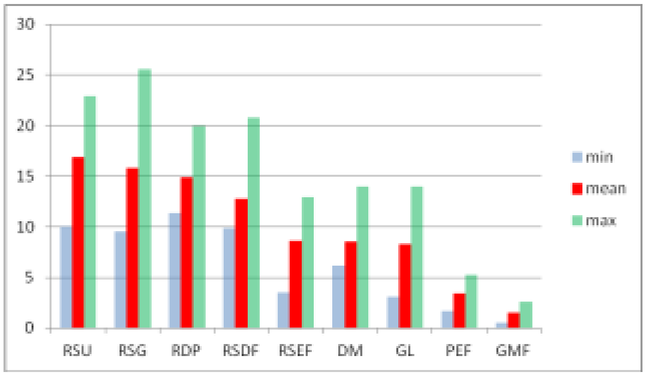

Figure1. Travel angles (degrees) of long runout landslides in the Canadian Cordillera.

Thirty three long runout rock avalanches in our dataset had travel angles ranging from 9.5 to about 26º and occur under a variety of conditions (Geertsema et al. 2006). Many begin as rock falls on unstable cirque walls, others are associated with mountain top deformation, some occur on dry sedimentary dipslopes,. We break our sample into undifferentiated rock avalanches, RSU in Figure 1, rock avalanches travelling on glaciers, RSG, and dry rock slides down dipping bedding planes, RDP. Mean travel angles are similar for these groups ranging from 17 to 16 to 15, respectively. Interestingly, both the highest (25.6 and lowest (9.5) came from, the middle group, rock avalanches on glaciers (Table 1).

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

2.2 Landslides in rock and soil

A subset of twelve additional rock slides that transformed into soil movements also had very low travel angles. In our 2008 paper we broke these into rock slide – debris flows and rockslide debris avalanches (unconfined flows). Here we join the small datasets and refer to the secondary movement as *debris flow*. The mean travel angle for this category is 12.8, lower than for primarily movements in rock. Both the 2010 Mt Meager (Guthrie et al 2013), 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. These rock slide generated earth flows have long travel distances but lack super-elevation and run-up features, attesting to relatively low velocities when compared to the rock avalanches.

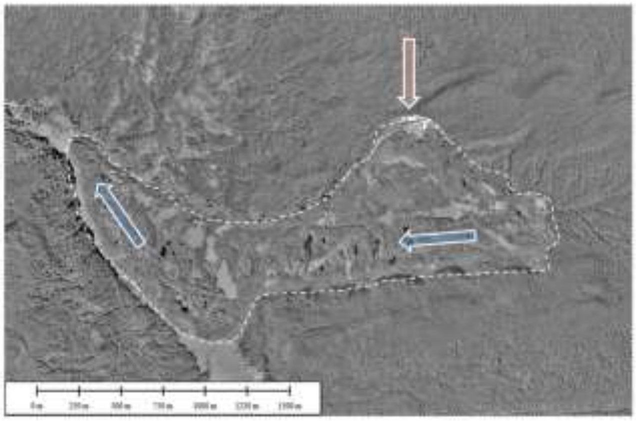

Figure 3. The 3.25 km Muskwa rock slide – earthflow (dashed polygon) had a travel angle of 3.5º. The flow (blue arrows) in a low stone content clayey diamict was triggered by undrained loading caused by the rock slide (red arrow).

2.3 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. This allows for movement of displaced material from supporting a temporary scarp, but also increases the travel angle, by incorporating steeper slopes.

The landslides in glaciolacustrine sediments in our dataset mostly 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 3.1 and 14 º. An exception to this is the 2013 Hasler landslide near Chetwynd, which has a travel angle of 5.7 deg. in post-glacial lake sediments. The two lowest travel angles occured in prehistoric (likely early post glacial) spreads likely triggered by river erosion. They had travel angles of less than 4 deg (Table 1).,

Landslides in diamicts (interpreted to be tills) and in massive clay deposits had travel angles even lower than those in lake sediments from 6.2 to 14 º (Figure 4). 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.

Figure 4. The 2008 Temple Creek landslide. The very wet flow travelled 1 km at 9º.

A special subset of prehistoric landslides is found in the Dawson Creek area. We mapped 36 flows on the shores of ancestral Glacial Lake Peace. These landslides typically dissected ancient shorelines, thus we think that they probably happened in response to lake drawdown (Figure 5). These flows had extremely low travel angles, with a mean of 3.4 deg, and on slopes under 2 deg. (Fig 1, Table 1).

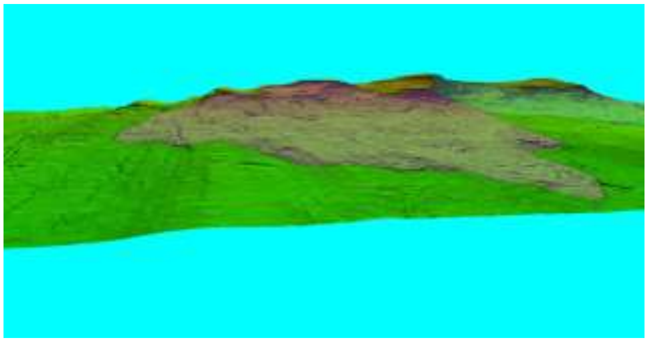

Figure 5. LiDAR oblique of a 350 ha landslide (93P 16) that flowed 2.6 km to the north, yielding a 2.4º travel angle. The crown dissected shoreline features of Glacial Lake Peace. We suspect the landslide may have been associated with rapid drawdown of the glacial lake.

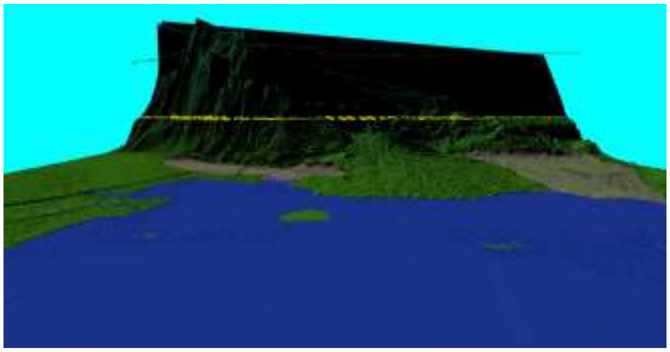

Figure 6. LiDAR image of the 1962 Lakelse landslides involving sensitive glaciomarine sediments. The zones of depletion are shown in gray. The zones of accumulation are hidden from view beneath the surface of Lakelse Lake. The North (left) and South (right) yielded travel angles of less than 0.5 and 1.0º, along 1.5 and 1.2 km paths, respectively. The actual travel distances are greater and travel angles, lower due to the unmeasured zones of depletion. The yellow line represents the 200 m ASL marine limit. View East.

The lowest travel angles in our dataset belong to the landslides occurring in sensitive glaciomarine sediments. A landslide that travelled 3 km, including about 1.5 km into Lakelse Lake (Fig 6) in 1962 (BC Ministry of Transportation and Highways 1962), had a travel angle of at most 0.5º. 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 0.5º. The earth flow – spread at Mink Creek (Geertsema et al. (2006) had a travel angle of 1.7º.

3. DISCUSSION AND CONCLUSIONS

The travel angles we report belong to the following groups (in ascending order) sensitive glaciomarine sediments, prehistoric flows in lake sediments, likely associated with lake drainage, flows and spreads in glacial lake sediments, flows in diamicts and massive clays derived from clay shales, earth flows generated by rock slides, , dry rock avalanches, rock avalanches on glaciers, and finally undifferentiated rock avalanches. The sensitive clay landslides have a mean travel angle that is an order of magnitude lower than that of the rock avalanches. Many 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 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 from the margins of incised plateaus.

While material characteristics is the most important variable controlling the travel of our sample of landslides, variations in behaviour within groups in our dataset point to other variables which remain to be investigated.

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Table 1. Landslide data.

Name	**Year**	**Volume (M m^3)**	**Length (km)**	**Travel Angle (⍰)**	**Reference**
A. Landslides in rock					
1. Rock Avalanches (undifferentiated) n= 17 mean 17.0					
Frank Slide	1903			18	Cruden
Verney	2002-03		1.1	18	Geertsema (2006)
Tutzizzi	Pre 1974		0.95	20	Geertsema and Cruden (2008)
Ha Ha	Pre 1974		2.0	18	Geertsema and Cruden (2008)
Mosque Mountain	mid 1990's	5	1.2	22.9	Lu et al. (2003)
Bonnet Plume, YK			3.79	13.4	Geertsema and Cruden (2008)
Todagin	2006	1-3	1.9	21.5	Geertsema and Cruden (2008)
Pandemonium Ck	1959	5.5	8.6	13	Evans and Clague (1999)
Hope		47	3.1	21	
Mount Meager	1986		3.7	20	Evans and Clague (1999)
North Creek	1986	1-2	2.8	14.6	Evans and Claque (1999)
Mt. Kitchener	Prehistoric	39	3.2	12	Cruden (1976)
Medicine Lake	Prehistoric	4.1	1.1	18	Cruden (1976)
Beaver Flats South	Prehistoric	4.8	3.0	14	Cruden (1976)
Brazeau Lake	1933			18	Cruden (1982)
Jonas Ridge North	Prehistoric	5.4	3.3	15	
Maligne Lake	prehistoric	498	5.5	10	Cruden (1976)

2. Rock avalanches on glaciers n= 11 mean = 15.8					
Jarvis Glacier	1979		2.4	16.7	Evans and Claque (1999)
Towagh Glacier	1979		4.4	11.3	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	92 - 93	3.2	2.3	17.2	Mauthner (1996)
Kendall Glacier	1999	0.2	1.2	9.5	Couture and Evans (2002)
Tim Williams	1956	3	3.7	14	Evans and Clague (1999)
Howson II	1999	1.5	2.7	25.6	Schwab et al. (2003)
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 Steele	2007		5.8	18	Lipovsky et al (2008)
3. Dry rock slides n = 5 mean = 14.9					
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)
Rockslide Pass, NWT			4.48	11.4	Eisbacher (1979)
Jonas Ridge South	prehistoric	10	2.5	20	Cruden (1976)
B. Landslides involving rock and soil **1. Rock slide– earth flows n=3 mean = 8.6**					
Muskwa	1979	15	3.25	3.5	Geertsema (2006)
Muskwa-Chisca	2001		1.75	13	Geertsema (2006)
Grizzly			4.22	9.3	Jermyn and Geertsema (in press)

2. Rock slide - debris flows (confined or unconfined) n=9 mean =12.8					
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)
Legate Creek	2007		2.5	20.8	Schwab pers. com.
Mount Meager	2010	48.5	12.7	9.8	Guthrie et al (2012)
Nomash	1999			13.5	Guthrie et al (2003)
Pink Mountain	2002	1	2	11.6	Geertsema et al. (2006)
Vanessa	2008		1.1	11.3	
Sutherland	2005		3	11.7	Blais-Stevens et al. (2007)
C. Landslides involving soil **1. Glaciomarine flows n= 4 mean = 1.6**					
Mink Creek	93 - 94	2.5	1.6	1.7	Geertsema et al. (2003)
Khyex River	2003	4.7	1.85	2.6	Schwab et al. (2003)
Lakelse North	June 1962	15	>1.5	<0.5	Geertsema (2006)
Lakelse South	May 1962	11.5	>1.2	<1	Geertsema (2006)
2. Glaciolacustrine sediments n=11 mean = 8.4					
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	1.2	10.8	Geertsema (1998)
Halfway	1989	1.9	1	10	Bobrowsky and Smith (1992)
Flatrock	Oct 1997		0.65	13	Geertsema (2006)
Mess Creek	1996?		1.7	8.5	Geertsema and Cruden (2008)

Houston Tommy I			1.05	7.7	Geertsema (2006)
Houston Tommy II			.95	7.4	Geertsema (2006)
Hasler	2013		0.17	5.7	
93P spread 1	prehistoric		1.9	4.1	
93P spread 2	prehistoric		0.8	3.1	
3. Diamictons (mostly clayey tills – that may involve permafrost) n=16 mean = 8.5					
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	Geertsema and Clague (2006)
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)
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	Geertsema (2006)
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	Geertsema (2006)
Trutch	1997-2004		0.77	7	Geertsema (2006)
Temple Creek	2008		1	9	
4. Prehistoric lakeshore flows n=36 mean=3.4					
93P 1			1.6	3.9	

93P 2			1.2	3.8	
93P 3			2.5	3.0	
93P 4			0.8	2.6	
93P 5			1.2	5.0	
93P 6			1.6	3.4	
93P 7			1.6	3.6	
93P 8			1.5	3.6	
93P 9			1.0	1.7	
93P 10			1.6	3.0	
93P 11			1.4	2.9	
93P 12			1.5	3.4	
93P 13			1.3	2.8	
93P 14			1.8	2.8	
93P 15			1.8	2.7	
93P 16			2.6	2.4	
93P 17			1.3	3.2	
93P 18			1.3	2.8	
93P 19			0.9	3.6	
93P 20			1.0	3.3	
93P 21			1.5	4.1	
93P 22			1.0	4.3	
93P 23			0.8	4.4	
93P 24			0.7	3.9	
93P 25			1.9	3.2	

93P 26			1.5	3.5	
93P 27			0.9	5.3	
93P 28			0.6	3.8	
93P 29			1.0	2.4	
93P 30			1.0	2.6	
93P 31			0.6	4.7	
93P 32			0.6	4.5	
93P 33			1.0	2.8	
93P 34			1.0	3.5	
93P 35			2.2	3.9	
93P 36			0.5	3.3	