Rock avalanches on glaciers in the Coast and St. Elias Mountains, British Columbia

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Abstract : Evidence from the Cordillera of northwest North America and other mountain regions of the world suggests that rock slopes adjacent to glaciers are particularly prone to catastrophic failure. At least 17 rock avalanches are known to have occurred on slopes adjacent to glaciers in the Coast and St. Elias Mountains of British Columbia since 1899. The rock avalanches range in volume from 1 M m^3 to about 13 M m^3, the largest being the 1975 Devastation Glacier landslide in the southern Coast Mountains. Some of the rock avalanches show excessive travel distances relative to path heights. The long travel distances are thought to result from the low friction of the glacier surface over which the rock avalanche travelled. Landslides of similar volume may show contrasting mobility; those with longer run-outs leave thinner debris sheets. Debutressing of the slopes caused by twentieth century glacier downwasting and retreat is at least partly responsible for most of these landslides. The occurrence of rock avalanches on destabilised rock slopes adjacent to glaciers is an important geotechnical response to climate warming and the dramatic world-wide loss of glacier ice in the twentieth century.

Introduction

In the last several decades, a number of major landslides which originated on slopes above glaciers have been documented in the mountainous regions of the world (e.g., G. Plafker, private communication, 1996; Hewitt, 1988; McSaveney et al. 1992; McSaveney, 1993). These include the well known Sherman Glacier rock avalanche (est. vol. 10 M m^3; Shreve, 1966; McSaveney, 1978), one of many rock avalanches triggered by the 1964 Alaska earthquake (M_s 8.4) that fell onto glaciers (Post, 1967). In some cases the landslides have run beyond glacier margins and have caused major destruction and loss of life at distant locations downstream. Examples include the 1962 and 1970 Huascaran landslides in the Peruvian Andes (Morales, 1966; Plafker and Ericksen, 1978) and the 1987 Parraguirre event in the Chilean Andes (Casassa and Marangunic, 1993; Hauser, 1993). In addition, many mountain slopes adjacent to glaciers show indications of non-catastrophic deformation (e.g., Evans and Clague, 1994). This evidence suggests that rock slopes adjacent to present glaciers are particularly prone to movement that may lead to catastrophic failure. Because of this, the geotechnical response of these rock slopes is emerging as a key theme in the study of the impacts of climate change (Evans and Clague, 1993, 1994; O'Connor and Costa, 1993; Watson et al., 1996; Haeberli et al., 1997).

The recent Intergovernmental Panel on Climate Change (IPCC) report on *Impacts, Adaptations and Mitigation of Climate Change* notes that climate warming since the nineteenth century has resulted in massive glacier ice loss in the glacierised mountains of the world (Watson et al., 1996). Twentieth century glacier ice loss is well documented in the Coast and St. Elias Mountains of the Canadian Cordillera (e.g., Mathews, 1951; Ryder, 1987; Clague and Evans, 1993). It is manifested in the retreat of glacier margins and the lowering of glacier surfaces due to thinning. Clague and Evans (1993) showed that Grand Pacific and Melbern glaciers, two of the largest valley glaciers in British Columbia, have decreased over 50% in volume in the last few hundred years, representing a total ice loss of 250-300 km^3. Melbern Glacier has thinned 300-600 m and retreated 15 km during this period; and about 7 km of this retreat occurred between the mid-1970s and 1987.

Landslides caused by glacier downwasting and retreat are common on steep slopes adjacent to glaciers in northwestern North America. For example, at least three large rock avalanches have occurred in the twentieth century at Mt. Rainier, Washington, on valley and cirque walls that were partially supported by glacier ice during the Little Ice Age (O'Connor and Costa, 1993), including the 1963 Little Tahoma Peak event (est. vol. 11 M m^3 ; Crandell and Fahnestock, 1965). Of the 29 large rock avalanches known to have occurred in the Canadian Cordillera since 1899, 17 (59%) have taken place on slopes adjacent to glaciers that have experienced twentieth century downwasting (Fig. 1; Evans and Clague, 1988, 1994, 1998). Where catastrophic failure has not taken place, mountain slopes that have recently been debuttressed frequently show evidence of slow limited deformation, including bulging, cracking and the presence of antislope scarps formed by differential movement in the rock mass (Bovis, 1982, 1990).

Table 1. Rock avalanches on glaciers in the Coast and St. Elias Mountains, British Columbia 1899-1999. Data is incomplete due to uncertainty about extent and position of some source areas and debris volumes. H/L is the tangent of the fahrböschung.

No.[a]	Name	Location[b]	Date	H (m)[c]	L (m)[d]	V (M m^3)[e]	H/L	Lithology
1	Ferris Glacier	SE	1899	-	-	-	-	
2	Capricorn Creek	CM	1920s	-	-	-	-	granodiorite
3	Devastation Glacier	CM	1931	-	-	-	-	Quaternary volcanics
4	Devastation Glacier	CM	1947	-	1500	2-4	-	Quaternary volcanics
5	Tim Williams Glacier	CM	1956	935	3700	3	.25	tuff/argillite
6	Pandemonium Creek	CM	1959	2000	8600	5.5	.23	granodiorite
7	Devastation Glacier	CM	1975	1220	7000	13	.17	Quaternary volcanics
8	Tweedsmuir Glacier	SE	1979	500	1350	-	.37	-
9	Jarvis Glacier	SE	1979	720	2440	-	.30	limestone
10	Towagh Glacier	SE	1979	880	4350	-	.20	diorite
11	Mount Meager	CM	1986	1340	3680	0.5 – 1.0	.36	Quaternary volcanics
12	North Creek	CM	1986	745	2850	1-2	.26	granodiorite
13	Frobisher Glacier 1	SE	1990	1032	3050	-	.34	diorite
14	Frobisher Glacier 2	SE	1991	976	2380	-	.41	diorite
15	Salal Creek	CM	1992	-	-	-	-	granodiorite
16	Kshwan Glacier	CM	1992-93	675	2205	3.1	.31	granodiorite
17	Mount Munday	CM	1997	875	4700	3.2	.19	gneiss

a Numbers correspond to those in Fig. 1.
b CM = Coast Mountains, SE = St. Elias Mountains
c H = Vertical height of path
d L = Total horizontal travel distance
e V = Rock avalanche volume

This paper summarises the known occurrences of rock avalanches on glaciers in the Coast and St. Elias Mountains in the period 1899 to 1999 (Fig. 1; Table 1). Two recent rock avalanches on glaciers in the Coast Mountains of British Columbia are described, and the mobility of rock avalanches in glacial and non-glacial environments is compared. The paper enlarges on previous work (Evans and Clague, 1988) and is based on ongoing field research by the authors augmented by analysis of large-scale topographic maps and digital elevation models (DEMs) prepared for several of the cases discussed.

Rock avalanches on glaciers 1899-1999

Rock avalanches on glaciers occur in remote areas of Canada and may escape detection before the debris becomes unrecognisable as landslide debris. Thus the record of 17 events reported in this paper is undoubtedly incomplete. This minimum estimate yields an average frequency of one event per 6 years for the entire period of record from 1899 to 1999. Since 1955, the frequency is one event per 3.5 years. This compares with a pre-1964 frequency of one large rock avalanche every 2 years for the Chugach Mountains of south-central Alaska (McSaveney, 1978). The rock avalanches listed in Table 1 range in volume from ca. 1M m^3 to 13 M m^3 , the largest being the 1975 Devastation Glacier rock avalanche which occurred in the Mount Meager Volcanic Complex in the southern Coast Mountains.

St. Elias Mountains

Six of the 17 rock avalanches (35%) have occurred in the St. Elias Mountains (Table 1). In September 1899, three great earthquakes, with magnitudes of 8.3, 7.8, and 8.3, occurred in the Yakutat Bay area of southeast Alaska (Tarr and Martin, 1912; Stover et al. 1979). These earthquakes triggered widespread landsliding in southeast Alaska and adjacent southwest Yukon and northwest British Columbia. The landslides included a rock avalanche onto Ferris Glacier (Fig. 1; Field, 1968). The debris of the Ferris Glacier landslide is visible on the maps of the International Boundary Commission surveyed at the turn of the century, and is a major component of the extensive supraglacial debris cover of the glacier. Other rock avalanches were probably triggered in the Canadian St. Elias Mountains by these massive earthquakes but were not reported due to the remoteness of the region. More recently, the 1979 St. Elias earthquake (M_s 7.2) triggered large rock avalanches in southeastern Alaska (Lahr et al., 1979), including the extraordinary Cascade Glacier rock avalanche (G. Plafker, private communication, 1996; Monastersky, 1992). Aerial photographs taken in August 1979 over the St. Elias Mountains in British Columbia show a number of fresh deposits of rock avalanches that are thought to have been have been triggered by the earthquake. An example is the Towagh Glacier rock avalanche (Fig. 2). The most recent documented events in the St. Elias Mountains occurred at Frobisher Glacier in 1990 and 1991 (Table 1).

Fig. 1. Map showing location of rock avalanches on glaciers known to have occurred in the period 1899-1999. Numbers correspond to those in Table 1.

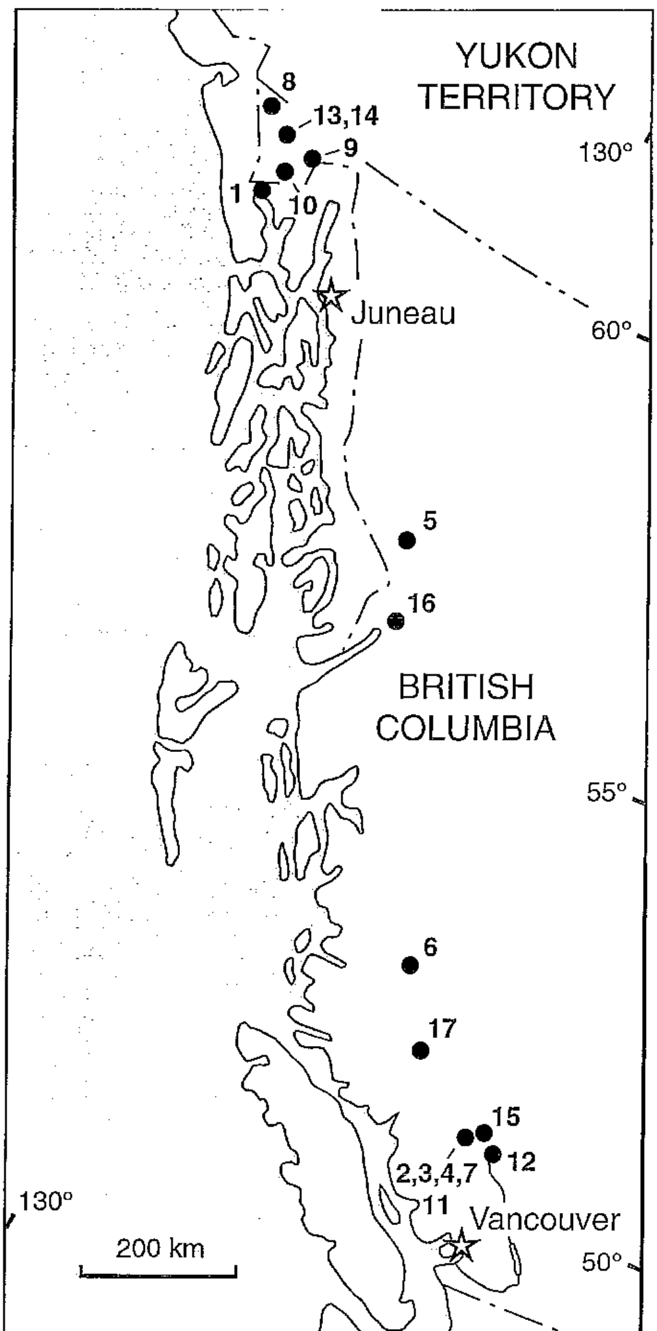


Fig. 2. Vertical aerial photograph of the Towagh Glacier rock avalanche, St. Elias Mountains, British Columbia, thought to have been triggered by the February 1979 St. Elias earthquake (M_s 7.2). Photograph taken on August 22, 1979 (National Air Photo Library A25292-169). Scale bar is approximate.

Coast Mountains

Eleven of the documented events (65%) have occurred in the Coast Mountains of British Columbia, including five rock avalanches in the Garibaldi Volcanic Belt (Table 1). Two recent events in the Coast Mountains are described in more detail below.

Field investigations have shown that detachment surfaces of many of these landslides intersect the slopes below Little Ice Age trimlines and were thus exposed during recent glacier retreat (Evans and Clague, 1988, 1990, 1994; Evans et al., 1989). Following initial failure, a rock avalanche may come to rest on the glacier without travelling beyond its margins (e.g. Tim Williams Glacier; Evans and Clague, 1990), be contained within the glacier foreland (e.g. North Creek; Evans and Clague, 1988), or travel a considerable distance downvalley beyond the Little Ice Age limit (e.g. Pandemonium Creek; Evans et al., 1989).

Fresh rock avalanche debris is commonly characterised by complexly overlapping flow lobes and lithologic segregation related to the location of rock units in the detachment zone (Evans and Clague, 1990, 1998). In all cases, the debris sheet has sharp, well-defined margins. Deformation of the debris by glacier movement changes its form, and within about 50 years it is unrecognisable as a rock avalanche deposit (Evans and Clague, 1990). Rock avalanche deposits are an important part of the sediment budget of the glaciers in question, although the residence time of the debris in the glacier system may be quite limited. When carried to the toe of the glacier, rock avalanche debris produces blocky end moraines which then become a source of sediment for downstream fluvial systems.

Two recent rock avalanches in the Coast Mountains

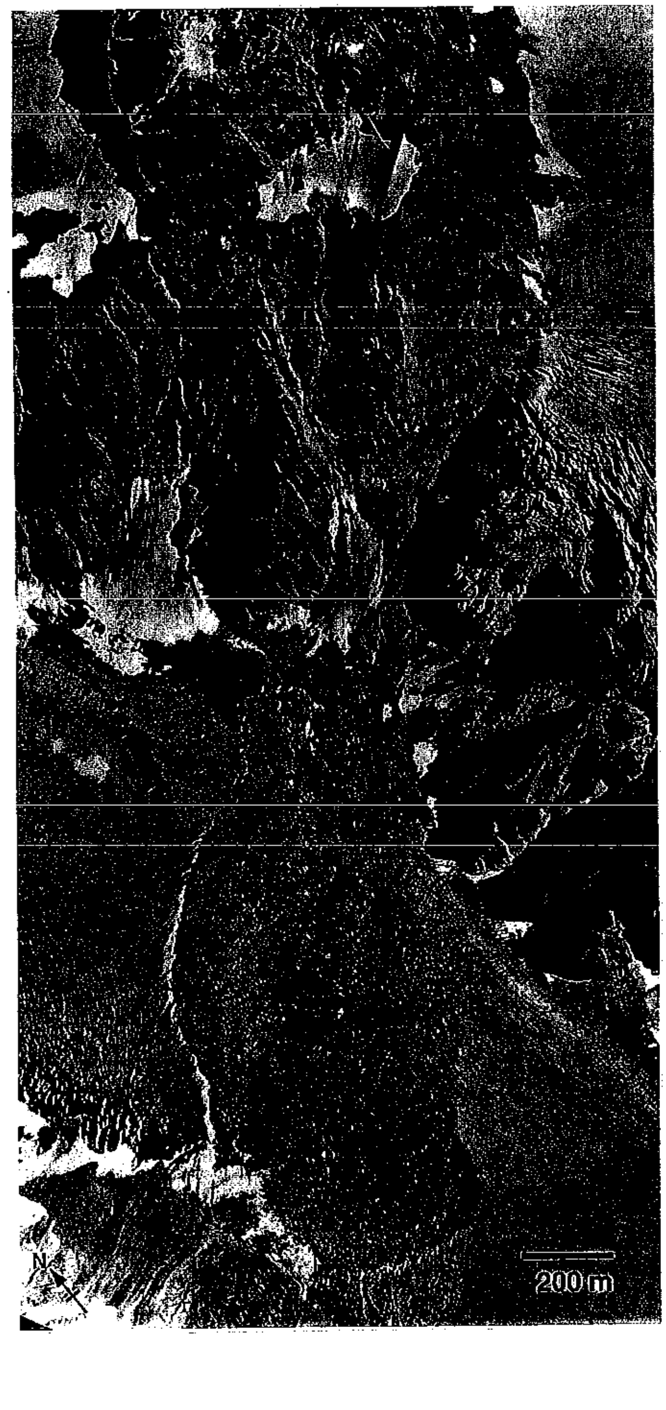
Two recent rock avalanches in the Coast Mountains of British Columbia serve to illustrate the contrasting mobility of rock avalanches of approximately the same source volume. Both rock avalanches involved about 3.2 M m^3 of rock, contained neglibible amounts of glacial ice, and stopped on the glacier surface.

Kshwan Glacier rock avalanche

Some time between the autumn of 1992 and the spring of 1993, a rock avalanche slid onto and traveled across Kshwan Glacier (NTS 103P/13; 55° 46.27' N, 129° 40.45' W), approximately 26 km southeast of Stewart in the Coast Mountains of British Columbia (Mauthner, 1995, 1996; Fig. 3). Kshwan Glacier is located at the southern margin of the Cambria Icefield. close to areas of active mineral exploration and potential mine development. The landslide involved granodiorite of the Kshwan Glacier Pluton, and initial sliding appears to have taken place on steeply dipping, stress-relief sheeting joints (Fig. 3) .

Pre- and post- event topographic maps show that the failed rock mass formed the upper part of a glacially oversteepened slope that was partly debuttressed as a result of the thinning of a tributary glacier between 1987 and 1994 (Fig. 3). This confirms Mauthner's (1996) suggestion that glacial debutressing was a key factor in the failure. Large-scale post-event topographic maps based on 1994 photography indicate that the top of the detachment zone is at 1750 m.a.s.l. and the distal tip of the debris is at 960 m.a.s.l. (H = 790 m). The total length (L) of the travel path is 2250 m, yielding a fahrböschung ($\tan^{-1}$ H/L) of 19° . The debris sheet on the glacier surface is about 1.4 km

Fig. 3. Vertical aerial photograph of the Kshwan Glacier rock avalanche which occurred in the northern Coast Mountains between the autumn of 1992 and the spring of 1993. Photograph taken on August 17, 1994 (Province of British Columbia 30BCB94050-063). Scale bar is approximate.



long, with a maximum width of 675 m (Fig. 3). Photogrammetric measurements on 1994 air photographs indicate an average debris thickness of approximately 5 m. It is noted that the margins of the debris sheet are sharply defined (Fig. 3). Comparison of pre- and post-event DEMs

Fig. 4. Perspective view to the southeast of the 1997 Mount Munday rock avalanche on Ice Valley Glacier, Waddington Range, southern Coast Mountains. This digital image was prepared from aerial photographs flown on August 20, 1997, and consists of a DEM with an orthophoto drape. Note flow lines in the debris. The elevation of the top of the source area is 3000 m.a.s.l. and the lower tip of the debris is at 2100 m.a.s.l. The length of the rock avalanche path is 4.7 km.

yield a source volume of 3.17 M m^3, larger than Mauthner's (1996) estimate of 1 - 3 M m^3.

Mount Munday rock avalanche

Sometime between May 25 and July 10, 1997, a large rock avalanche occurred on the southern flank of Mount Munday (3367 m.a.s.l.; NTS 92N/6; 51° 19.9' N, 125° 12.8' W) in the Waddington Range of British Columbia's Coast Mountains, 280 km northwest of Vancouver (Fig. 1; Evans and Clague, 1998). The site is 6.5 km southeast of Mount Waddington (4019 m.a.s.l.), British Columbia's highest peak. The debris flowed across and down Ice Valley Glacier, forming a spectacular tongue-shaped deposit on the glacier surface (Fig. 4). The landslide involved highly resistant gneissic rocks of the Coast Plutonic Complex which form a number of jagged peaks in the Waddington Range.

The detachment zone is located on the west shoulder of Mount Munday which rises steeply from the surface of Ice Valley Glacier. The source area rock is hornblende-rich, dioritic, granitoid gneiss of the Central Gneiss Complex (Roddick, 1985; Evans and Clague, 1998) which is coarsely foliated with foliation dipping steeply to the SSW.

Field examination of the detachment zone in 1997 and 1998 suggests that the mechanics of initial sliding are complex. Failure appears to have been controlled by the foliation and by a steeply dipping planar fault surface that has a more southerly strike and cuts across the foliation at a lower dip angle. This discontinuity geometry gives rise to multiple wedges, some of which detached completely whilst others slid a limited distance. A substantial mass of disturbed rock remains on the failed slope; although this mass slid some distance, it did not detach from the mountain side. Toppling of the steeply dipping foliation also appears to have contributed to the failure.

The detached rock mass first travelled in a southwest direction across Ice Valley Glacier (Fig. 4). It ran up the opposing slope to a height of about 100 m above the glacier surface and was deflected about 90° downglacier in a northwest direction, in a manner similar to a bobsled. Below the bobsled bend, the debris travelled up to 2.6 km over the snow-covered glacier surface on a slope of only 6°. Ridges of snow were pushed up at the margins of the debris (Fig. 5). At the distal limit of the debris, a lobe approximately half the width of the main debris sheet moved a distance of 900 m on a slope of 5° between 2195 and 2120 m.a.s.l. (Fig. 4).

The geometry of the rock avalanche path below the bobsled bend indicates a coefficient of kinetic friction of approximately 0.11 (6°) for the interface between the debris and snow. This is similar to the direct estimate of kinetic friction of rock debris sliding on ice at the 1991 Mount Cook rock avalanche in the New Zealand Alps (McSaveney et al., 1992) and corresponds to the equivalent coefficient of kinetic friction calculated for the movement of debris over ice and snow in the Sherman Glacier rock avalanche (McSaveney, 1978).

Fig. 5. Ground view of the distal limit of debris, Mount Munday rock avalanche, 4.7 km from the source. Person is standing on a pressure ridge, consisting of snow pushed up ahead of the sliding debris. Note the sharp boundary of the debris

The debris on Ice Valley Glacier was inspected on August 31, 1997, within two months of the event. It ranges from silt to boulder size (Fig. 6). Locally, silt- to sand-size accumulations of pulverised rock were noted and wet black dust covered many large boulders. As is common in rock avalanche debris, huge blocks of bedrock are present (Fig. 5 and 6), and clearly defined, overlapping flow lines are evident in the debris (Fig. 4). In places along the travel path, debris is thin or absent, exposing the glacier surface beneath.

Fig. 6. View to the northwest of debris of the Mount Munday rock avalanche. The person is standing on a huge gneissic block approximately 20 m in longest dimension.

The highest point of failed rock in the source area is approximately 3000 m.a.s.l and the distal tip of the debris is at 2100 m.a.s. l. (H = 900 m). The total distance of travel (L) is 4.7 km ; thus the fahrböschung is about 11° .

Comparison of DEMs obtained from pre-slide (1987) and post-slide (1997) photography indicates that the volume of rock that detached from Mount Munday is 3.2 M m^3. Based on vertical aerial photographs taken on August 20, 1997, we estimate that the debris covers an area of about 220 ha. The average thickness of the debris is thus only 1.5 m. In comparison, the average thickness of the Sherman Glacier rock avalanche debris was 1.65 m (McSaveney, 1978).

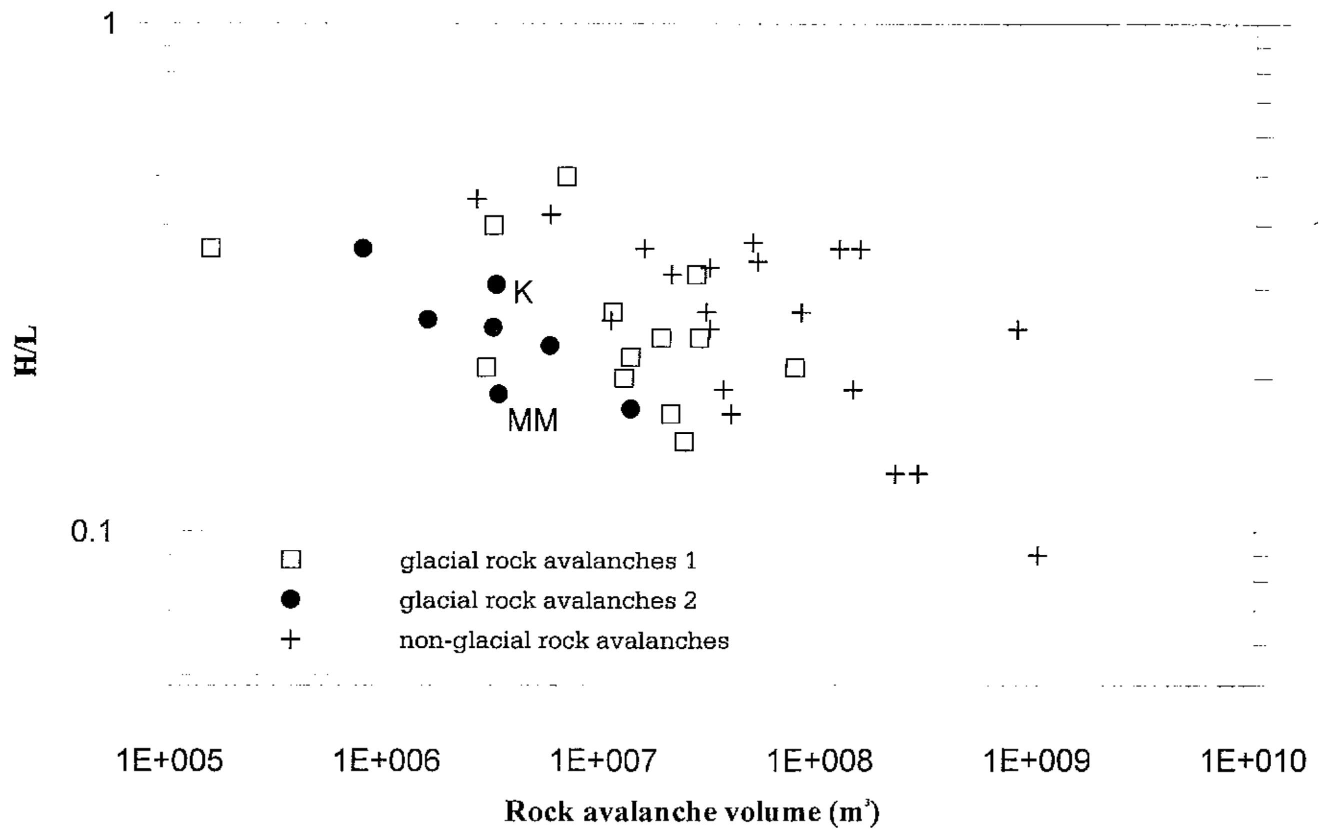
Glaciers in the Mount Waddington area have thinned and retreated due to twentieth century climate warming, and glacier ice loss was likely a factor in the Mount Munday event. The immediate trigger of the failure at Mount Munday may be related to the exceptional precipitation in southwest British Columbia during the first half of 1997 and a pronounced period of warming immediately prior to the rock avalanche.

Mobility

Evans and Clague (1988) suggested that rock avalanche travel distances over glacier surfaces are enhanced due to the low friction at the debris-glacier interface. Friction may be further reduced through the formation of water films and the development of pore pressures at the base of the debris due to frictional heating or the presence of compressible snow on the ice surface. With additional data reported here, the plot of mobility (H/L) vs. source volume in Fig. 7 qualitatively supports this thesis.

However, in this paper it has been shown that rock avalanches of similar volume may exhibit contrasting mobility in the glacial environment and that not all rock avalanches on glaciers are highly mobile. In the Mount Munday case, the fahrböschung is 11° for a volume of 3.2 M m^3. This value is well below the fahrböschung that would be predicted for non-glacial rock avalanches of similar volume. In contrast, the fahrböschung of the Kshwan Glacier rock avalanche (19°) plots in the non-glacial field (Fig. 7). It is evident that the Kshwan landslide retained a thicker debris sheet during

Fig. 7. Mobility plot of rock avalanches in glacial and non-glacial environments. H is vertical height of path and L is total horizontal distance of travel. Data for glacial rock avalanches 1 are for non-Canadian examples (from Table 2 in Evans and Clague, 1988); data for glacial rock avalanches 2 are British Columbia examples from Table 1 in this paper; and data for non-glacial rock avalanches are from Table 1 in Scheidegger (1973). K = Kshwan Glacier rock avalanche; MM = Mount Munday rock avalanche.



emplacement, whereas the debris in the Mount Munday rock avalanche ran out further to form a thinner sheet. The geometry of the debris sheets thus suggests lower friction travel for the Mount Munday event. This is also reflected in the debris morphology. Dramatic cross-overs and the multi-lobate form of the Mount Munday debris contrasts with the more-or-less homogeneous Kshwan debris sheet. It is also noteworthy that in the Mount Munday case, a higher degree of fragmentation of the source rock mass resulted in a higher percentage of finer particles in the debris and the creation of large amounts of dust that covered the surrounding snow. This greater fragmentation may have enhanced the mobility of the Mount Munday rock avalanche.

Conclusions

Rock slopes adjacent to glaciers are particularly susceptible to catastrophic failure. There is evidence to suggest that this is partly due to the dramatic twentieth century ice loss in mountain regions of the world due to climate warming. In the period 1899-1999, rock avalanches on glaciers occurrred with a frequency of about one event in six years in the Coast and St. Elias Mountains of British Columbia. Since 1955 the frequency has been one event in 3.5 years. The record of rock avalanches is undoubtedly incomplete, thus the actual frequencies would be higher. In the St. Elias Mountains some rock avalanches have been triggered by major earthquakes, but in most of the cases examined debutressing due to glacier thinning is considered to be a major factor in rock slope failure.

Debris spreads out on a glacier in a well defined sheet which is rapidly transformed by glacier movement. Rock avalanches of a given volume tend to travel further on glaciers than on non-glacial surfaces. On glaciers, however, differential mobility of rock avalanches appears to be related to debris sheet thickness; thinner sheets are characteristic of more mobile rock avalanches. On glaciers, contrasting mobility may also relate to the degree of fragmentation of the debris. The occurrence of rock avalanches in a glacial environment is an important geotechnical response to recent climate warming.

Although the rock avalanches discussed in this paper occur in remote parts of the Cordillera, activities such as mining exploration and development, recreation, and eco-tourism may be impacted by future events.

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