VOLCANIC LANDSLIDE HAZARDS AT MOUNT MEAGER, BRITISH COLUMBIA

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ABSTRACT
Landslides are frequent on the unstable slopes of the Mount Meager volcanic massif in the southern Coast Mountains of British Columbia. We compile data on historic and prehistoric landslides to determine the risk to people involved in recreation, geothermal power development, and forestry in valleys proximal to Mount Meager, and also to residents in the Lillooet River valley at distances up to 75 km from the volcano. Landslides 10^6-10^7 m^3 in size will have direct impacts in Meager Creek and upper Lillooet River valleys and indirect impacts, including channel aggradation and flooding, at more distant locations. Landslides larger than 10^7 m^3, although relatively rare, may trigger volcanic debris flows that will reach populated areas in the Lillooet River valley, 32-75 km downstream from the source. Without advance warning, the loss of life from such an event could be high.

RESUME
Les glissements de terrain sont fréquents sur les pentes volcaniques du massif du mont Meager sur la côte sud de la Colombie-Britannique. Nous compilons de l'information sur les éboulements historiques et préhistoriques afin de déterminer le risque vis-à-vis les personnes impliquées dans le domaine de la récréation, des développements géothermiques et de l'industrie forestière tout au long de la vallée de Lillooet jusqu'à une distance de 75 km du volcan. Les glissements de terrain classé 106-107 m3, auront un impact direct dans la région du ruisseau Meager et de la partie supérieure de la vallée de la rivière Lillooet et un impact indirect, sur les inondations et la dégradation des sols en avale. Les glissement de terrain supérieurs à 107 m3, quoique rares, peuvent occasionner le déplacement des débris volcaniques pouvant rejoindre les endroits peuplés de la rivière Lillooet, à une distance de 32 à 75 km à partir de la source. Sans avertissement au préalable, les pertes de vie pourraient s'élever considérablement.

1. INTRODUCTION

Stewart (2002) pointed out the danger that Mount Meager volcano presents to residents of Pemberton and Mount Currie in the Lillooet River valley, British Columbia: “The Mount Meager volcanic complex poses a risk to people in the Lillooet valley, both near the mountain and further downstream in Pemberton, B.C. It is essential to properly describe hazards that pose a risk to people in preparing strategies to deal with the occurrence of such an event” (p. 72).

The Mount Meager volcanic complex (MMVC, Figure 1) is the most unstable mountain massif in Canada (Read 1990). It poses a threat to people involved in activities in proximal valleys, including recreational use of Meager Creek and other hotsprings, geothermal exploitation, and forestry. The volcano also presents a more remote risk to settled areas downstream along the Lillooet River valley at Pemberton.

This paper summarizes the landslide hazard associated with the Mount Meager volcanic complex based on previous geological studies. An early attempt to characterize the landslide impacts to rivers in the region was made by Jordan (1987), but little was known about the frequency, magnitude, and travel distances of large landslides at MMVC, resulting in an underestimation of the contribution of landslides to the sediment budget of Lillooet River (Jordan and Slaymaker 1991). Since that time, considerable progress has been made in documenting large volcanic landslides at Mount Meager (Stasiuk et al. 1996; Stewart 2002; Friele and Clague 2004; Friele et al. 2005; Simpson et al., in press), allowing for a much more accurate hazard characterization.

2. SETTING

The Mount Meager volcanic complex is located about 150 km north of Vancouver, at the head of Lillooet River (Figure 1). The west side of the massif is drained by Meager Creek and the east side by upper Lillooet River. MMVC is the largest of the volcanic centres in the Garibaldi volcanic belt, with 20 km^3 of dacitic and rhyolitic eruptive rocks dating back to the Pliocene (Hickson 1994). The last eruption occurred ca. 2360 years ago (Clague et al. 1995). The principal volcanic hazards are edifice collapse, large rock avalanches and debris flows, associated river damming, and floods and hyperconcentrated flows produced by outbursts from landslide-dammed lakes.

The villages of Pemberton and Mount Currie, and associated rural settlement, are situated along the Lillooet River valley 32-75 km downstream from Mount Meager. In 2006, about 5000 people live in the Lillooet

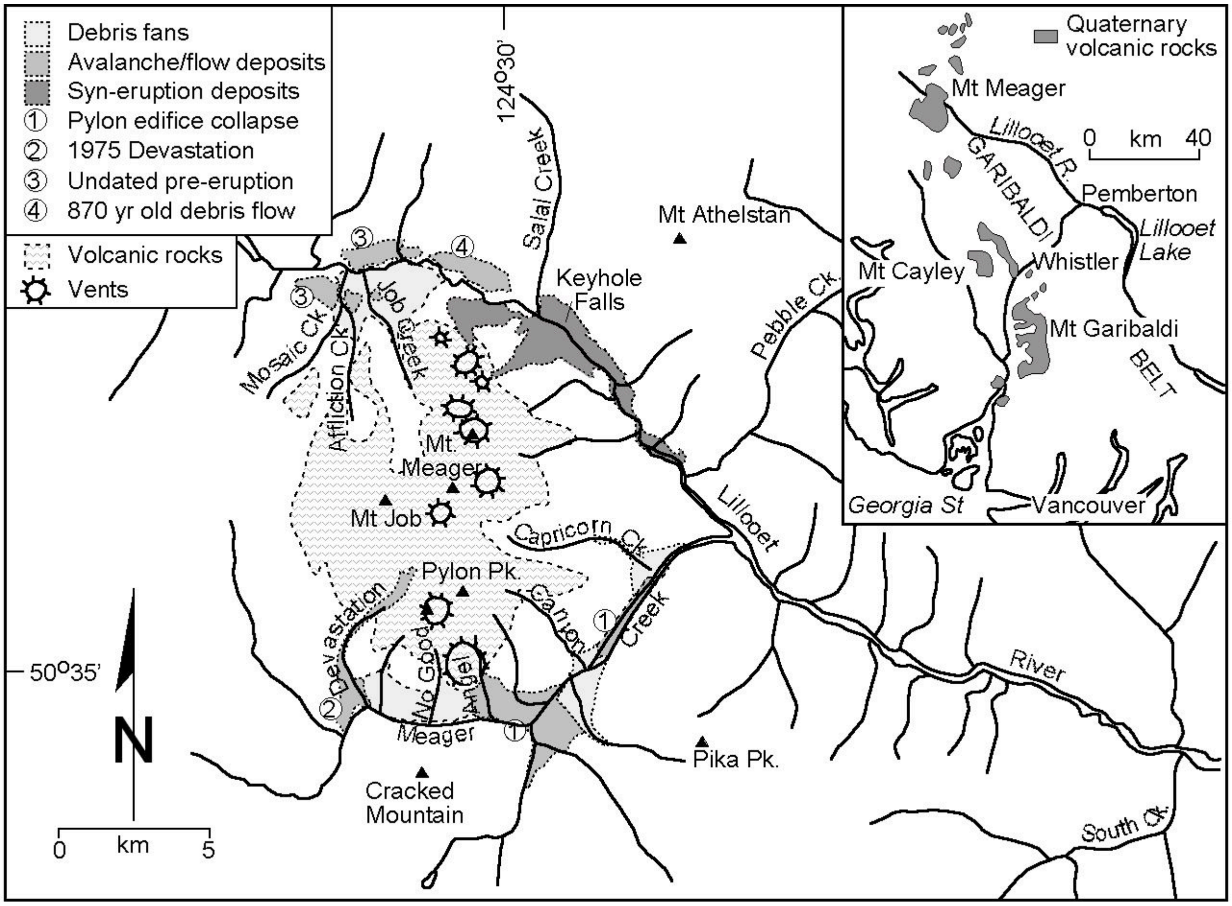

Figure 1. Map of the Mount Meager volcanic complex showing the major proximal landslide deposits in upper Lillooet River and Meager Creek.

River valley: 200 people nearest (32-55 km) the volcano; 700 people 55-58 km from the volcano; 2500 people in Pemberton Municipality; 600 people 58-65 km from the volcano, and about 1000 people in Mount Currie Indian Reserve, 65-75 km from the volcano (K. Creary, Squamish-Lillooet Regional District, personal communication, 2006). Large volcanic debris flows can have long run-outs (e.g., Vallance and Scott 1997) and such events pose a threat to life and property throughout the Lillooet River valley.

3. KNOWN EVENTS

3.1 Meager Creek

Prehistoric and historic landslide activity in Meager Creek valley has been well documented by Friele and Clague (2004; and references therein) and is summarized in Table 1. The reader is referred to their paper for additional detail.

A large (~10^6-10^7 m^3) rock avalanche deposit is exposed in a 20-m-high road cut 800 m south of the mouth of Capricorn Creek (Figure 1). The deposit has yielded radiocarbon ages of 5250±70 ^{14}C yr BP (GSC-5454) and 5310±60 ^{14}C yr BP (GSC-5456). A much younger debris flow, dated at 150±60 ^{14}C yr BP (GSC-5464), likely dammed Meager Creek in the same area. This event was similar to a 1.2x10^6 m^3 debris flow that dammed Meager Creek at the mouth of Capricorn Creek in 1998, producing a 1-km-long lake (Bovis and Jakob 2000).

The south flank of Pylon Peak collapsed twice, once about 7900 years ago and a second time about 4400 years ago. These events involved an estimated 4.5x10^8 m^3 and 2x10^8 m^3 of rock, respectively, and comprised both rock avalanche and debris flow phases (Friele and Clague 2004). Poorly preserved landslide deposits (~10^5-10^6 m^3) just downstream of Angel Creek (Figure 1) have been dated at 1920±50 ^{14}C yr BP (GSC-3733) and 210±50 ^{14}C yr BP (GSC-3811).

A rock avalanche deposit at No Good Creek (Figure 1) has yielded radiocarbon ages of 460±50 ^{14}C yr BP (GSC-3736), 480±50 ^{14}C yr BP (GSC-3750), and 370±50 ^{14}C yr BP (GSC3509). Based on the deposit's aerial extent of ~0.75 km^2 and an estimated average thickness of 10 m, it likely had an original volume of 10^6-10^7 m^3. It overlies a debris flow deposit of similar thickness, and probably similar size, dated at 900±60

^{14}C yr BP (GSC-4223), 990±70 ^{14}C yr BP (GSC-4239), and 800±70 ^{14}C yr BP (GSC-4264).

A landslide deposit at the mouth of Devastation Creek (Figure 1) yielded a radiocarbon age of 2170±60 ^{14}C yr BP (GSC-4302). It may have been similar in size to a 1.2×10^7 m^3 debris flow that killed four people at the mouth of Devastation Creek in 1975 (Mokievsky-Zubok 1977; Evans 2001). Two other large historic events occurred in the Devastation Creek watershed: (1) a 3×10^6 m^3 debris flow in 1931 (Carter 1932; Jordan 1994) traveled down Devastation Creek, then Meager Creek to its mouth, and raised the flow of Lillooet River at least 15 km downstream (Decker et al. 1977); (2) a ~10^5-10^6 m^3 rock avalanche in 1947 remained confined to the valley of Devastation Creek (Read 1978).

3.2 Upper Lillooet River

The surface deposits of the upper Lillooet River valley consist primarily of units related to the 2360-year-old eruption and subsequent instability, although one pre-eruption unit has also been documented (Table 1).

3.2.1 Syn-eruptive Deposits

The deposits of the last eruption of Mount Meager (Figure 1) have been studied and mapped by Stasiuk et al. (1996) and Stewart (2002). The initial blast, directed to the east, buried the landscape near the volcano with many metres of pumiceous tephra. Radiocarbon ages on charred trees in growth position date the event (Clague et al. 1995). The blast was followed by pyroclastic flows that left a dense ash-flow tuff up to many tens of metres thick in adjacent Lillooet River valley below Keyhole Falls (Figure 1). The ash-flow tuff dammed Lillooet River and impounded a lake that soon overtopped the dam, producing an outburst flood in the valley below. The total volume of pyroclastic material produced during the eruption is estimated to be about 4.4×10^8 m^3 (Stewart 2002).

The impoundment upstream of Keyhole Falls is marked by a delta at the mouth of Salal Creek (Figure 1). Wood fragments recovered from foreset beds of the delta yielded radiocarbon ages of 2350±60 ^{14}C yr BP (Beta-209559), and 2210±40 ^{14}C yr BP (Beta-209558). A lacustrine sand unit, 2.2 km upstream of the mouth of Salal Creek, gave an age of 2360±60 ^{14}C yr BP (Beta-209551).

At least two outburst flood events are recorded by deposits exposed about 8 km downstream from Keyhole Falls: a pumiceous debris flow unit (2460±60 ^{14}C yr BP, GSC-5403), and a pyroclastic debris flow (2490±80 ^{14}C yr BP, GSC-5433). The volume of material eroded and transported by the outburst floods is estimated to be 2×10^8 m^3 (Stewart 2002). Later, a large rock avalanche (ca. 4.4×10^7 m^3) crossed Lillooet valley, ran about 300 m up the opposing valley wall, and traveled about 4 km down the valley (Stewart 2002). It has not been directly dated, but stratigraphic and geomorphic relations demonstrate that it is younger than the main phase of the eruption. A small lava flow was erupted from the volcanic crater after this landslide.

3.3 Post-eruptive Deposits

Terraces underlain by lacustrine, fluvial, and debris flow sediments extend over an area about 6 km long and 1.5 km wide upstream of the syn-eruptive deposits between Salal and Mosaic creeks (Figure 1). The deposits are remnants of a complex valley fill that accumulated in the valley following the eruption 2360 years ago.

These deposits are exposed in a 20-m-high bank along Lillooet River at the northeast margin of the Job Creek fan. A basal volcanic debris flow deposit dated at 2240±60 ^{14}C yr BP (Beta-200717) is overlain by at least eight upward-coarsening, silt to sandy gravel units deposited over a 600-year period (unpublished data). The upward-coarsening units are interpreted to be backwater deposits associated with successive landslides. One of these events is directly dated: landslide debris near this section yielded a radiocarbon age of 1860±50 ^{14}C yr BP (GSC-5278), and a thin debris flow unit downstream, at Keyhole Falls, overlies pumiceous gravel dated at 1990±40 ^{14}C yr BP (Beta-200715). Periodic temporary damming appears to have extended almost to the present, as shown by ages of 1100±50 ^{14}C yr BP (GSC-5370) and 280±70 ^{14}C yr BP (GSC-5401) from lacustrine sands at two other sites. Thus, landslide damming appears to be a characteristic feature of the upper Lillooet River valley over the past 2400 years since the last eruption of Mount Meager.

A large level terrace (ca. 210 ha) on the valley bottom upstream of Salal Creek (4 in Figure 1) is underlain by one or more thick volcanic debris flow units capped by peat. Many radiocarbon ages have been obtained from an exposure at the downstream end of the terrace by different researchers. Wood fragments from the diamicton have yielded ages of 870±50 ^{14}C yr BP (GSC-3215), 900±60 ^{14}C yr BP (GSC-3498), and 890±80 ^{14}C yr BP (GSC-4290) (Jordan 1994). Wood samples from another exposure gave ages of 1680±60 ^{14}C yr BP (Beta-209556) and 1100±50 ^{14}C yr BP (Beta-209557), and samples from the peat have been dated at 890±60 ^{14}C yr BP (GSC-5441), 1000±50 ^{14}C yr BP (GSC-5448), 830±30 ^{14}C yr BP (GSC-5451), 360±60 ^{14}C yr BP (GSC-5452), and 270±60 yr BP (Beta-209555). Recently, near the upstream end of the terrace, peat within a sequence of interbedded silt and sand overlying a debris flow deposit yielded an age of 2650±60 (GSC-6696). Previously, the diamicton underlying the terrace was assumed to represent one debris flow. Now, with additional radiocarbon ages from different sites, it appears that the diamicton may be a composite unit including a remnant of the precursor landslide to the 2360-year-old eruption (Simpson et al. in press) and a large debris flow about 870±50 ^{14}C yr BP. The estimated volume of the 870 yr BP deposit is about 8-10×10^6 m^3 (Jordan 1994).

Remnants of another large volcanic debris flow cover an area of about 200 ha at the northwest margin of the Job Creek fan (Figure 1). These deposits have yielded ages of 630±40 ^{14}C yr BP (Beta-209553), 630±60 ^{14}C yr BP (Beta-209561), and 670±50 ^{14}C yr BP (Beta-209554). The deposit contains metre-size rip-up clasts of lacustrine silt, indicating that upper Lillooet Valley was

Table 1. Large mass movements at the Mount Meager Volcanic Complex.

Event	Source	[1]Age	[3]Volume (m^3)	Reference
Prehistoric events (Age BP)				
Rock avalanche / debris flow	Pylon Pk.	7900	4.5×10^8	Friele and Clague 2004
Debris flow	Unknown	[2]6250	10^8-10^9	Friele et al. 2005
Rock avalanche / debris flow	Capricorn Ck.	5150	10^6 - 10^7	McNeely and McCuaig 1991
Rock avalanche / debris flow/ hyperconcentrated flow	Pylon Pk	4400	2×10^8	Friele and Clague 2004; Friele et al. 2005.
Rock avalanche / debris flow	Syn-eruptive	2600	10^8-10^9	Friele et al. 2005; Simpson et al. in press
Pyroclastic flow	Syn-eruptive	2400	4.4×10^8	Stasiuk et al. 1996; Stewart 2002
Rock avalanche / outburst flood /debris flow/ hyperconcentrated flow	Syn-eruptive	2400	2×10^8	Stasiuk et al. 1996; Stewart 2002
Rock avalanche	Syn- to post-eruptive	2400	4.4×10^7	Stasiuk et al. 1996; Stewart 2002
Debris flow	Devastation Ck.	2170	1.2×10^7	McNeely and McCuaig 1991
Debris flow	Job Ck.	2240	10^6	This paper
Debris flow	Angel Ck.	1920	10^5 - 10^6	McNeely and McCuaig 1991
Debris flow	Job Ck.	1860	10^6	McNeely and McCuaig 1991
Debris flow	Job Ck.??	870	8×10^6 - 10^7	Jordan 1994
Debris flow	No Good Ck.	800	10^5	McNeely and McCuaig 1991
Debris flow	Job Ck.	670	1×10^6	This paper.
Debris flow	No Good Ck.	370	10^6 - 10^7	McNeely and McCuaig 1991
Debris flow	Angel Ck.	210	10^5	McNeely and McCuaig 1991
Debris flow	Capricorn Ck.	150	1.2×10^6	McNeely and McCuaig 1991
Historic events (Age AD)				
Debris flow / hyperconcentrated flow	Devastation Ck.	1931	3×10^6	Carter 1932; Decker et al. 1977; Jordan 1994
Rock avalanche	Capricorn Ck.	<100 yrs	10^5 - 10^6	Croft 1983
Rock avalanche	Devastation Ck.	1947	10^5	Read 1978
Debris flow	Capricorn Ck.	1972	2×10^5	Jordan 1994
Debris flow	Devastation Ck.	1975	1.2×10^7	Mokievsky-Zubok 1977; Evans 2001
Debris flow	Affliction Ck.	1984	2×10^5	Jordan 1994
Rock avalanche	Mt Meager	1986	10^5 - 10^6	Evans 1987
Debris flow	Capricorn Ck.	1998	1.2×10^6	Bovis and Jakob 2000

1. Age given is the youngest constraining age for the event.
2. The 6250 yr BP deposit from core is tentatively correlated with the undated deposit in upper Lillooet River valley.
3. Volumes are likely minima because of erosion and burial.

Table 2. Magnitude-frequency analysis for non-eruptive landslides at the Mount Meager Volcanic Complex.

Volume (m^3)	Event ages (AD; BP)	Total no.	Record (yrs)	Annual frequency	[1]Qualitative frequency
10^5-10^6	<100, 1947, 1972, 1984, 1986; 210, 670, 800, 1920, 2240	5 historic 10 total	75 2240	Historic 1:15 Total 1:225	Very high Moderate
10^6-10^7	1931, 1998; 150, 370, 870, 1860, 5150	2 historic 7 total	75 5150	Historic 1:40 Total 1:735	High Low
10^7-10^8	1975; 2170	1 Historic 2 Total	2170	Historic 1:75 Total 1:1100	High Low
10^8-10^9	4400, 6250, 7900	3	7900	1:2600	Very Low
$>10^9$	--	--	10,000	<1:10,000	Negligible

1. Very high, >1/20; High, 1/100-1/20; Moderate, 1/500-1/100; Low, 1/2500-1/500; Very low, <1/2500.

dammed at or before the time. Based on its present extent, the debris flow probably had a volume of about $1x10^6$ m^3.

3.3.1 Undated Pre-eruption Rock Avalanche

Massive to weakly stratified, volcanic rock avalanche debris up to 100 m thick is exposed in a river bluff at the north and west margins of the Job Creek fan (Figure 1). The deposit is lithologically zoned, a characteristic of large rock avalanches. Grey and maroon units within the deposit suggest derivation from rocks in the headwaters of Job Creek. This rock avalanche is undated, but because volcanic ash overlies the deposit, it must be older than the 2360 cal yr BP eruption. We tentatively correlate this undated rock avalanche deposit with the 6250 yr BP debris flow deposit in drill core in Lillooet River valley 32 km downstream from Mount Meager (section 3.4.1). The rock avalanche deposit extends an unknown distance below present river level at the section mentioned above. The four erosional remnants of the deposit have a total area of about $3.5x10^6$ m^2; we estimate its original extent to have been $1x10^7$ m^2. If we assume an average thickness of 35-100 m, the rock avalanche may have had a volume of $3.5x10^8$ m^3 to $1x10^9$ m^3.

3.4 Distal Deposits in Lillooet Valley

Recent drilling in Lillooet River valley 32-65 km downstream from Mount Meager has revealed three volcanic debris flow units and at least three significant hyperconcentrated flow units in the upper part of the valley fill (Friele et al. 2005; Simpson et al. in press).

3.4.1 Debris Flows

Deposits of the three debris flows have been identified in one drill hole 32 km from the volcano. The older of the three deposits at this site is at least 8 m thick and has yielded ages of 6370±35 ^{14}C yr BP (OS-36552) and 6250±30 ^{14}C yr BP (OS-36556). No proximal landslide deposits in the valleys of Meager Creek or upper Lillooet River have yielded a similar age. However, based on its enormous size, the undated rock avalanche deposit described in section 3.3.1 is tentatively correlated with the lower debris flow deposit in the drill core (Table 1).

The middle debris flow unit in the drill hole is bracketed by radiocarbon ages to the period 4300-4530 cal yr BP (Friele et al. 2005) and likely is the debris flow phase of the 4400 cal yr BP flank collapse of Pylon Peak into the valley of Meager Creek (Friele and Clague 2004).

The uppermost of the three debris flow units has been found in drill holes 32-50 km downstream from Mount Meager. It is 2-4 m thick and is has a valley-wide (1.5-2 km) distribution. A thin peat bed lying directly on the diamicton yielded a radiocarbon age of 2570±40 ^{14}C yr BP (Beta-166059), and a wood fragment from the diamicton gave an age of 2690±50 ^{14}C yr BP (Beta-166057). The two ages suggest that the event preceded the Mount Meager eruption by a few hundred years. Simpson et al. (in press) suggested four possible triggering mechanisms: (1) volcanic seismicity; (2) oversaturation of hydrothermally altered volcanic rocks due to increased melting of snow and ice as magma rose within the volcano; (3) inflation of the volcano and destabilization of already steep unstable slopes; and (4) minor explosive eruptions.

The proximal deposit of this event has not been identified, but it may include diamicton underlying peat dated to 2650±60 (GSC-6696) at a site 3.3 km upstream of Salal Creek.

3.4.2 Hyperconcentrated Flows

A hyperconcentrated flow unit 2-6 m thick was found in two cores 42 km downstream from the volcano (Friele et al 2005). It is bracketed by radiocarbon ages to the period 3300-5500 cal yr BP. The unit may represent the lahar runout facies (Pierson and Scott 1985) of the 4400 cal yr BP collapse of Pylon Peak.

A pumiceous hyperconcentrated flow unit 0.5-3 m thick caps a thin peat bed, which in turn overlies the uppermost debris flow unit in cores 42-47 km downstream from the volcano. Similar pumiceous wash was also found in deltaic sediments 65 km downstream from the volcano (Friele et al. 2005). These sediments are likely the downstream facies of the syn-eruptive outburst flood and ensuing pumiceous debris flow identified in the proximal zone in Lillooet River valley below Keyhole Falls.

A third hyperconcentrated flow unit was recovered in drill core 47 km downstream from the volcano. It is tentatively correlated with the 900-yr-old debris flow identified in upper Lillooet River valley (Friele et al. 2005). A thick layer of lacustrine sediment, recorded by strong acoustic reflectors and dating to this time, has been found in Lillooet Lake (Desloges and Gilbert 1994).

The 1931 debris flow from Devastation Creek traveled down Devastation Creek and along Meager Creek to its mouth. It caused Lillooet River to surge with sediment and coarse woody debris, almost killing a trapper at his cabin at South Creek (Figure 1), 16 km downstream from the mouth of Meager Creek (Decker et al. 1977).

4. A FREQUENCY-MAGNITUDE MODEL

4.1 Frequency-Magnitude

A sound frequency-magnitude (F-M) model is an essential step in assessing landslide risk. To produce a model for MMVC, we separated documented landslides into syn-eruptive and non-eruptive events (Table 1). We considered only the latter (Table 2) in our analysis (Figure 2). Apparent landslide frequencies for both historic and prehistoric landslides are plotted in Figure 2, with uncertainties shown as vertical bars. No uncertainty bar is shown for the 10^8-10^9 m^3 category because no historic events of this size have occurred. The $>10^9$ m^3 category is excluded because no landslides of this volume are considered to be possible at Mount Meager. Landslide frequency for the smallest category is based on the work of Jakob (1996). Debris flows of less than 10^5 m^3 in the three subbasins of the Meager Creek watershed that Jakob studied have return intervals of 1-10 years. To represent his finding, we plotted the smallest class with a return interval of 5 years. A best-fit line connecting the data points of the smallest and largest volume categories lies within the uncertainty bars of the intermediate categories, suggesting that our model is reasonable.

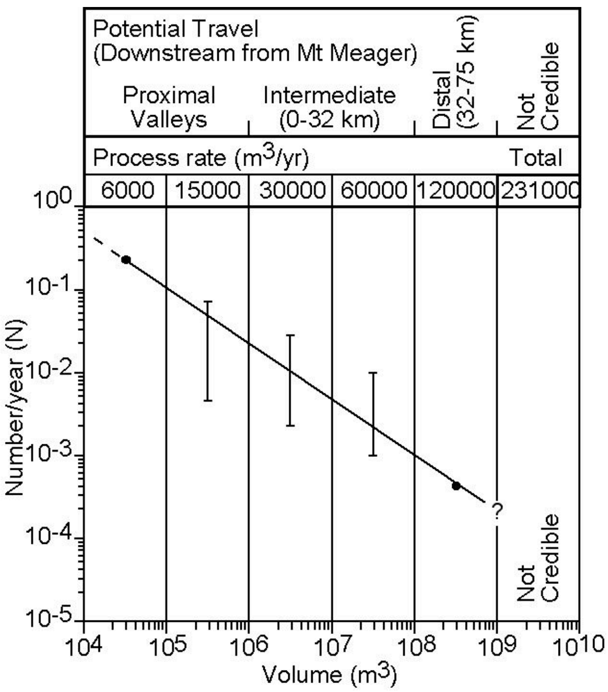

Figure 2. Frequency-magnitude plot for non-eruptive volcanic landslides derived from the Mount Meager volcanic complex. Potential travel distances are based on observed deposits and are supported by debris flow run-out modeling.

4.2 Consequence/Travel

As landslide volume increases, the area and amount of potential damage also increase (Jakob 2005). The distance and area of inundation of volcanic debris flows in Lillooet River valley have been modeled by Simpson et al. (in press) (Figure 3). Debris flows less than 10^6 m^3 will remain confined to proximal valleys. Debris flows with volumes between 10^6 and 10^8 m^3 will reach presently uninhabited portions of Lillooet River valley, and may have indirect impacts (outburst flood, hyperconcentrated flow, and channel aggradation) farther downstream. Of greatest concern are debris flows larger than 10^8 m^3 (Siebert 2002). Debris flows of this volume will directly impact settled areas of Lillooet River valley, 32-75 km downstream from Mount Meager (Simpson et al. in press).

4.3 Landslide Process Rate

Integration of the area below the best-fit line in Figure 2 provides the volcanic landslide process rate for MMVC (Moon et al 2005). Summed across categories, the total annual production of debris is 231,000 m^3 a^{-1}. The volcanic complex has an area of about 76 km^2, thus the denudation rate is about 3000 m^3 a^{-1} km^{-2}, or 3 mm a^{-1} over the entire area. This rate is 53 times higher than the average for hyper-maritime areas of British Columbia (Martin et al. 2002; Guthrie and Evans 2004), three times higher than the average reported for forested basins in California (Kelsey 1982; Madej 1987), but comparable to rates in the New Zealand Alps (Hovius et al. 1997).

Debris produced by landslides at MMVC is stored in both the proximal and distal zones, and is reworked into the fluvial system, contributing to floodplain aggradation and progradation of the Lillooet River delta. The high rate of sediment production is responsible for the strong bias of volcanic lithologies in Lillooet River gravels (Friele et al. 2005). This result contradicts the conclusion made by Desloges and Gilbert (1994) that paraglacial activity is responsible for high sedimentation rates in Lillooet Lake.

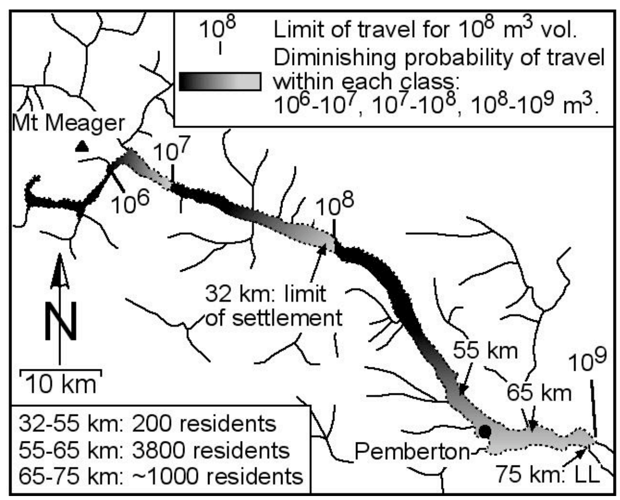

Figure 3. Travel distances of volcanic debris flows from Devastation Creek as a function of volume (after Simpson et al. in press). LL, Lillooet Lake. Population estimates from Squamish-Lillooet Regional District.

5. POTENTIAL INSTABILITY

Researchers have pointed out the potential for catastrophic slope failures in mountainous terrain due to thinning and retreat of alpine glaciers during the twentieth century (Evans and Clague 1994). This phenomenon has been studied in detail at Meager Mountain (Holm et al. 2004), who concluded "The bedrock landslide response to glacial retreat varies appreciably according to rock type and the extent of glacial scour below Little Ice Age trimlines. Valleys carved in weak Quaternary volcanics show significant erosional oversteepening and contain deep-seated slope movement features, active rock fall, rock slides, and rock avalanches near glacial trimlines … Significant spatial association was also observed between recent catastrophic failures, gravitational slope deformation, and slopes that were oversteepened then debuttressed by glacial erosion. Eight out of nine catastrophic rock slope failures occurred just above glacial trimlines and all occurred in areas with a previous history of deep-seated gravitational slope movement, implying that this type of deformation is a precursor to catastrophic detachment."

Thus, at least for landslides smaller than 10^7 m^3, we might expect that failure rate in the future will be similar to those of the recent past. However, landslides larger than 10^7 m^3 remove huge volumes of unstable debris (Siebert 2002), and one might question whether the potential for future events has been reduced by those of the past. Poorly lithified pyroclastic rocks and hydrothermally altered rock associated with vents create the potential for edifice collapse at volcanoes (Finn et al. 2001; Siebert 2002). The sources of the major edifice collapses at MMVC are coincident with vent areas in the Angel and Job Creek basins (Figure 1). A large mass of unstable volcanic rock with sufficient relief to generate edifice collapse still exists at MMVC. The most likely sites of future edifice collapse are the east side of Devastation Creek, including the flanks of the Devastator and Pylon Peaks; and the east slope of Job Creek, including flank of Mount Meager.

Of particular note is an area of several square kilometres on the east side of Devastation Creek that is underlain by hydrothermally altered rock of the Devastator Assemblage. This area shows settlement rates of 1-2 cm/year based on InSAR measurements (van der Kooj and Lambert 2002). The potential source area (Read 1978) is 10 times the size of the 1975 rock avalanche ($1.2x10^7$ m^3), thus if catastrophic failure were to occur, the maximum volume would be of the order of 10^8 m^3. Volumes of 10^6-10^8 m^3 are likely for partial collapse.

6. CONCLUSIONS

Non-eruptive volcanic landslides at Mount Meager are a hazard to proximal valleys and distal reaches of Lillooet River. Landslides with volumes of 10^5-10^7 m^3 are a risk to recreation, geothermal, and forestry activities in the valleys of Meager Creek and upper Lillooet River close to the volcano. They can also have indirect, distal impacts through the processes of river damming, outburst floods, and hyper-concentrated flows, which create challenges in dealing with channel aggradation and consequent flooding. These issues need to be taken into account in floodplain management and flood protection.

Landslides larger than 10^7 m^3 have occurred at Meager Mountain in the past, and future events of this size are likely. Landslides at the upper end of this size range would generate debris flows that would have catastrophic consequences, with total destruction along the settled reaches of Lillooet River valley and, if not preceded by warnings, the loss of hundreds to thousands of lives.

The following comment of Siebert (2002, p. 231) on volcanic edifice failure seems particularly apropos in the context of the Lillooet River valley: "The high mobility of volcanic debris avalanches places large areas of dense population within risk. However, the low recurrence rate of avalanches at individual volcanoes often effectively precludes hazard zoning that restricts occupancy of potentially affected areas. The difficulty of anticipating whether edifice failure will occur during a given eruption (or in the absence of an eruption) can produce severe political and economic problems, even for shorter term hazard mitigation efforts."

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