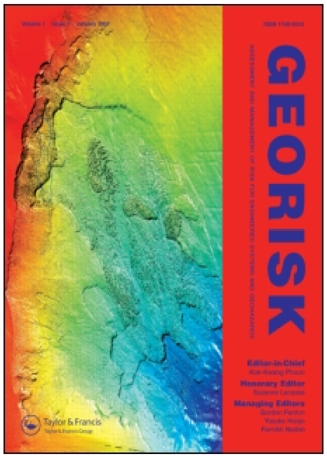


Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards

Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t744347545

Hazard and risk from large landslides from Mount Meager volcano, British Columbia, Canada

Pierre Friele [a]; Matthias Jakob [b]; John Clague [c]
[a] Cordilleran Geoscience, Squamish, BC, Canada
[b] BGC Engineering Inc., Vancouver, BC, Canada
[c] Centre for Natural Hazard Research, Simon Fraser University, Burnaby, BC, Canada

To cite this Article: Friele, Pierre, Jakob, Matthias and Clague, John (2008) 'Hazard and risk from large landslides from Mount Meager volcano, British Columbia, Canada', Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards, 2:1, 48 - 64
To link to this article: DOI: 10.1080/17499510801958711
URL: http://dx.doi.org/10.1080/17499510801958711

Georisk
Vol. 2, No. 1, March 2008, 48–64

Taylor & Francis
Taylor & Francis Group

Hazard and risk from large landslides from Mount Meager volcano, British Columbia, Canada

Pierre Friele[a]*, Matthias Jakob[b] and John Clague[c]

[a]*Cordilleran Geoscience, Squamish, BC, Canada;* [b]*BGC Engineering Inc., Vancouver, BC, Canada;* [c]*Centre for Natural Hazard Research, Simon Fraser University, Burnaby, BC, Canada*

During the past 8000 years, large volcanic debris flows from Mount Meager, a Quaternary volcano in southwest British Columbia, have reached several tens of kilometres downstream in Lillooet River valley, with flow velocities of many metres per second and flow depths of several metres. These debris flows inundated areas that have become settled in the past 100 years and are now experiencing rapid urban growth. Notably, Pemberton, 65 km from Mount Meager, has doubled in size in the past five years. Approval of subdivision and building permits in Pemberton and adjacent areas requires assessment and mitigation of flood hazards, but large, rare debris flows from Mount Meager are not considered in the permitting process. Unlike floods, some volcanic debris flows occur without warning. We quantify the risk to residents in Lillooet River valley from non-eruption triggered volcanic debris flows based on Holocene landslide activity at Mount Meager. The calculated risk exceeds, by orders of magnitude, risk tolerance thresholds developed in Hong Kong, Australia, England, and in one jurisdiction in Canada. This finding poses a challenge for local governments responsible for public safety.

Keywords: Quaternary volcano; Mount Meager; landslide hazard and risk; quantitative risk assessment; debris flow; volcanism

Western Canada is subject to a variety of hazardous and high-risk geomorphic and hydrologic processes. One of the most destructive of these processes is landsliding. Risk to life and property from landslides originates from specific sources that, with sufficient study, can be identified, assessed, and managed. Some landslides, however, can cause damage far from their sources (Vallance and Scott 1997). In such cases, the risk is rarely recognised or, at best, is poorly understood and, consequently, is neither quantified nor incorporated into planning or mitigation. The failure to recognise and adequately quantify long-runout landslides has led to several disasters in British Columbia (Evans 1997) and around the world (Evans and de Graff 2005).

Risk associated with landslides can be quantified by (1) developing an inventory of landslide hazards, (2) quantifying the probability and consequence of landslide occurrence, and (3) determining whether or not stakeholders find the estimated risk acceptable. This approach, termed 'quantitative risk assessment', is systematic, transparent, and reproducible, and is the basis for Canadian and international protocols for risk management.

The Association of Professional Engineers and Geoscientists of British Columbia released 'Guidelines for Legislated Landslide Assessments for Proposed Residential Development in British Columbia' in March 2006, in order to standardise landslide risk assessment methodology. The guidelines propose standards against which present and future professional practice will be measured. In this paper, we apply appropriate methods, based on these guidelines, to compare existing and acceptable risk from landslide hazards in the Lillooet River valley of southwest British Columbia. Specifically, we summarise the hazards and risk posed by large volcanic debris flows originating at the Mount Meager volcanic complex (MMVC) in the upper Lillooet River watershed, 150 km north of Vancouver (Figure 1). The administrative jurisdiction of our study area is the Squamish-Lillooet Regional District, which currently has no standards or guidelines for acceptable risk. For this reason, we use international standards as a metric for assessing the existing risk. Our focus is risk to residents in Lillooet River valley, although the risk to resource workers, hotsprings users, hikers, skiers, and snowmobilers close to the volcano could be considered.

We chose the Mount Meager volcanic complex for this study because of the large body of research that has been carried out on it since geothermal exploration began in the 1970s. Read (1978, 1990) argued that Mount Meager is the most unstable mountain massif in Canada. Later, Jordan (1994) and Jakob (1996) conducted research on the mechanics

---

*Corresponding author. Email: friele@telus.net

ISSN 1749-9518 print/ISSN 1749-9526 online

DOI: 10.1080/17499510801958711
http://www.informaworld.com

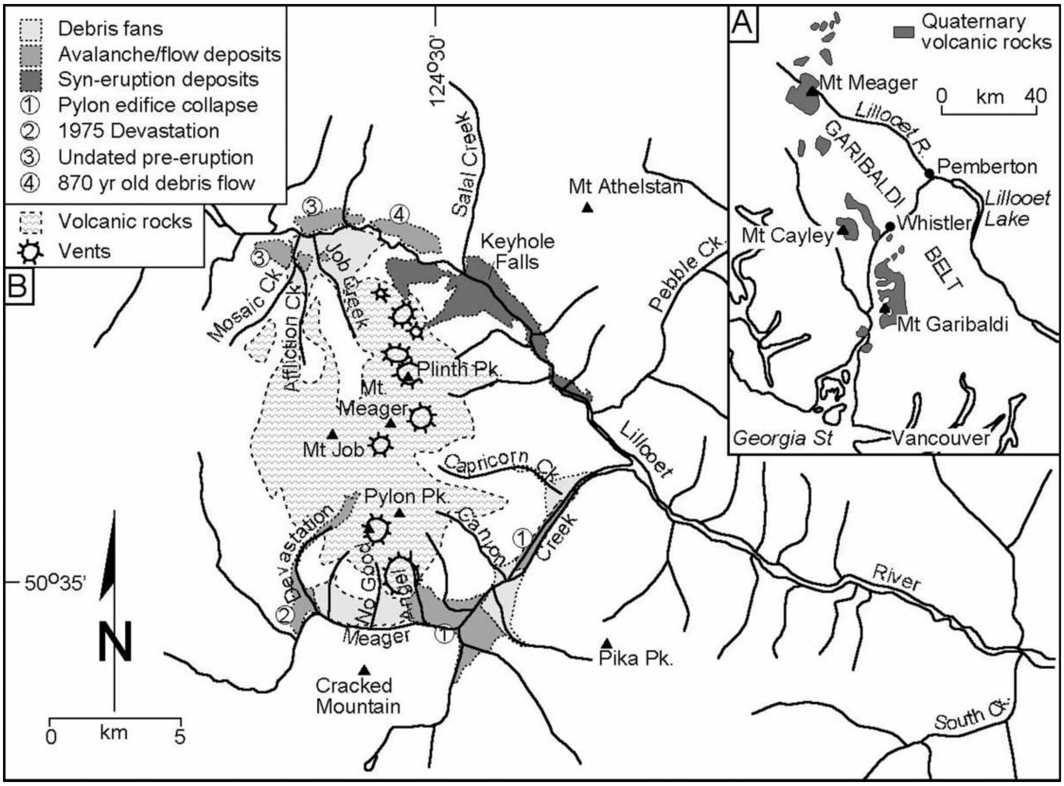


Figure 1. (A) Map of southwestern British Columbia showing the distribution of Quaternary volcanic rocks, including the Mount Meager volcanic complex. (B) Landslide deposits derived from the Mount Meager massif in the watersheds of upper Lillooet River and Meager Creek.

and frequency-magnitude relations of mostly small (classes 3, 4, 5, and 6; Jakob 2005) debris flows. Large syn-eruptive and non-eruptive landslides (classes 7, 8, and 9; Jakob 2005) were documented by Stasiuk *et al.* (1996), Stewart (2002), and Friele and Clague (2004). Several researchers have suggested that Lillooet valley and the village of Pemberton, 65 km downstream, are susceptible to volcanic debris flows from Mount Meager (Jordan and Slaymaker 1991, Stewart 2002, Friele and Clague 2004). Subsurface stratigraphic investigations in Lillooet valley have confirmed this supposition (Friele *et al.* 2005, Simpson *et al.* 2006).

In recognition of this risk at Mount Meager, Stewart (2002, p. 72) stated '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'. Accelerated growth in and around Pemberton since Stewart's study provided the impetus for our study. In this paper, we use previously published and new data on large debris flows from MMVC to quantitatively assess the risk to residents of Lillooet valley. The previous lack of such a study contrasts sharply with the extensive research performed on flood hazards and risk in the valley (Nesbitt-Porter 1985, Kerr Wood Leidal Associates 2001). We conclude with a discussion of risk management policies in British Columbia.

Setting

The Mount Meager volcanic complex consists of about 20 km^3 of dacitic and rhyolitic eruptive rocks dating back to the Pliocene; it is the largest volcanic centre in the Garibaldi volcanic belt (Hickson 1994). The massif has been deeply dissected by streams and glaciers, and its upper slopes are covered by snow and ice. The last eruption occurred about 2360 years ago, based on radiocarbon ages on charred trees in growth position (Clague *et al.* 1995). It spread ash as far east as western Alberta. The principal volcanic hazards are edifice collapse, large rock avalanches and debris flows, associated river damming, and floods and hyperconcentrated flows produced by outbursts of landslide-dammed lakes (Hickson 1994). The village of Pemberton and associated rural settlement are located on the floor of Lillooet valley, 32–75 km downstream from Mount Meager.

Table 1. Compilation of volcanic landslide hazards at Mount Meager.

Event	Source	Age[1] (BP)	Volume[3] (m^3)	Reference
Prehistoric				
Rock avalanche/debris flow	Pylon Pk.	7900	4.5×10^8	Friele and Clague (2004)
Rock avalanche/debris flow	Job Ck.	6250[2]	10^8–10^9	Friele *et al.* (2005)
Rock avalanche/debris flow	Capricorn Ck.	5250	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	Job Ck., eruption precursor	2600	10^8–10^9	Friele *et al.* (2005); Simpson *et al.* (2006)
Pyroclastic flow	Syneruptive	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.	630	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	10^5–10^6	McNeely and McCuaig (1991)
Historic (age AD)				
Debris flow	Devastation Ck.	1931	3×10^6	Carter (1932); Decker *et al.* (1977); Jordan (1994)
Rock avalanche	Capricorn Ck.	<100 years	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)
Rock avalanche	Devastation Ck.	1975	1.2×10^7	Mokievsky-Zubot (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] Radiocarbon age in ^{14}C year BP. The cited ages are those that most closely constrain the age of the event.

[2] The 6250 yr BP deposit from core is tentatively correlated with the undated rock avalanche in upper Lillooet valley.

[3] Volumes of prehistoric landslides are likely minima because of erosion and burial.

Hazard characterisation

Data on large landslides derived from the Meager massif are briefly discussed (see Friele and Clague (2006) for additional details). Although all known events are compiled (Table 1), only non-eruptive triggered landslides (Table 2) are considered in the risk analysis because syn-eruptive events may be predicted and thus pose significantly less risk to public safety. The data in Table 2 are then used to generate a frequency-magnitude (F-M) plot (Moon *et al.* 2005) for MMVC.

Deposits in Meager Creek valley

Remnants of a large ($\sim 10^6$–10^7 m^3) rock avalanche deposit are exposed in a 20-m high road cut 800 m south of the mouth of Capricorn Creek (Figure 1). The deposit has yielded two radiocarbon ages, the younger of which, and presumably closest to the time of the landslide (i.e. the youngest maximum age), is 5250 ± 70 ^{14}C yr BP (GSC-5454). A much younger debris flow, dated at 150 ± 60 ^{14}C yr BP (GSC-5464), likely dammed Meager Creek in the same area. The latter event was similar to a 1.2×10^6 m^3 debris flow that dammed Meager Creek at the mouth of Capricorn Creek in 1998 (Bovis and Jakob 2000), producing a 1-km long lake.

The south flank of Pylon Peak collapsed twice in the Holocene, once about 7900 years ago (4.5×10^8 m^3) and a second time about 4400 years ago (2×10^8 m^3) (Friele and Clague 2004). Each landslide consisted of rock avalanche and debris flow phases.

Table 2. Magnitude-frequency analysis for non-eruptive debris flows and rock avalanches at Mount Meager.

Volume (m^3)	Event ages (AD, BP)	No. of events	Record (years)	Annual frequency	Future likelihood[1]
10^5–10^6	1947, 1972, 1984, 1986; <100, 150, 210, 630, 800, 1920, 2240	4 historic; 11 total	77; 2240	Historic 1:19; total 1:200	Certain
10^6–10^7	1931, 1998; 370, 870, 1860, 5150	2 historic; 6 total	77; 5150	Historic 1:38; total 1:860	Certain
10^7–10^8	1975; 2170	1 historic; 2 total	77; 2170	Historic 1:77; total 1:1100	Likely
10^8–10^9	2600, 4400, 6250, 7900	4	8000	1:2000	Possible
$>10^9$	–	–	12,000	<1:12,000	Not credible

[1] Ratings after Fell *et al.* (2005). Ratings are based on consideration of apparent annual frequency, distribution of susceptible rock types and active sackung, and glacial debuttressing.

Two poorly preserved landslide deposits ($\sim 10^5$–10^6 m^3) just downstream of Angel Creek (Figure 1) have been radiocarbon 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 three radiocarbon ages, with a youngest maximum age of 370 ± 50 ^{14}C yr BP (GSC-3509). Based on the deposit's areal extent (~ 0.75 km^2) and an estimated average thickness of 10 m, it likely had a volume of 10^6–10^7 m^3. The rock avalanche debris overlies a debris flow deposit of similar size that has yielded three radiocarbon ages, the youngest of which is 800 ± 70 ^{14}C yr BP (GSC-4264).

A landslide deposit at the mouth of Devastation Creek (Figure 1), dated to 2170 ± 60 ^{14}C yr BP (GSC-4302), records an event 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 debris flows have occurred in the watershed of Devastation Creek in the twentieth century: (1) a 3×10^6 m^3 debris flow in 1931 that travelled the full length of Meager Creek and entered Lillooet River (Carter 1932, Decker *et al.* 1977, Jordan 1994); and (2) a $\sim 10^5$–10^6 m^3 rock avalanche in 1947 that was confined to the valley of Devastation Creek (Read 1978).

Proximal deposits in upper Lillooet River valley

Much of the surface and near-surface fill in upper Lillooet valley is related to the 2360-year-old eruption and subsequent slope instability, although one pre-eruption unit has also been documented (Table 1). Syn-eruptive deposits are described by Stasiuk *et al.* (1996) and Stewart (2002), but detailed descriptions of non-eruptive landslide deposits have not been previously published.

Pre-eruption rock avalanche

Massive to weakly stratified, volcanic rock avalanche debris up to 100 m thick (Figure 2) is exposed in a river bluff at the north and west margins of the Job Creek fan (Figure 1). Grey and maroon units within the deposit indicate derivation from volcanic rocks in the headwaters of Job Creek. The rock avalanche is undated, but Bridge River tephra overlies the deposit, thus it must be older than the 2360 cal yr BP eruption. Erosional remnants of the rock avalanche deposit have a total area of about 3.5×10^6 m^2, and we estimate its original extent to have been 1×10^7 m^2. Assuming an average thickness of 35–100 m, the rock avalanche had a volume of 3.5×10^8 to 1×10^9 m^3.

Syn-eruptive deposits

The vent of the 2360-year-old eruption is located near Plinth Peak (Figure 1). The initial blast buried the landscape near the volcano with many metres of pumiceous tephra. The blast was followed by one or more pyroclastic flows that left a welded ash-flow tuff up to many tens of metres thick in Lillooet valley below Keyhole Falls (Figure 1). The ash-flow tuff blocked Lillooet River and impounded a lake that eventually overtopped the dam, causing 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).

A delta at the mouth of Salal Creek, upstream of Keyhole Falls, was built into the reservoir impounded by the ash-flow tuff (Figure 1). Wood fragments recovered from the forest 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). Wood in lacustrine sand 2.2 km upstream of the mouth of Salal Creek gave an age of 2360 ± 60 ^{14}C yr BP (Beta-209551). These ages suggest that the reservoir persisted for at least 100 years.

Two large landslides are recorded by deposits exposed about 8 km downstream from Keyhole Falls: a pumiceous debris flow dated at 2460 ± 60 ^{14}C yr BP (GSC-5403); and a pyroclastic flow of similar age (2490 ± 80 ^{14}C yr BP, GSC-5433). Stewart (2002)

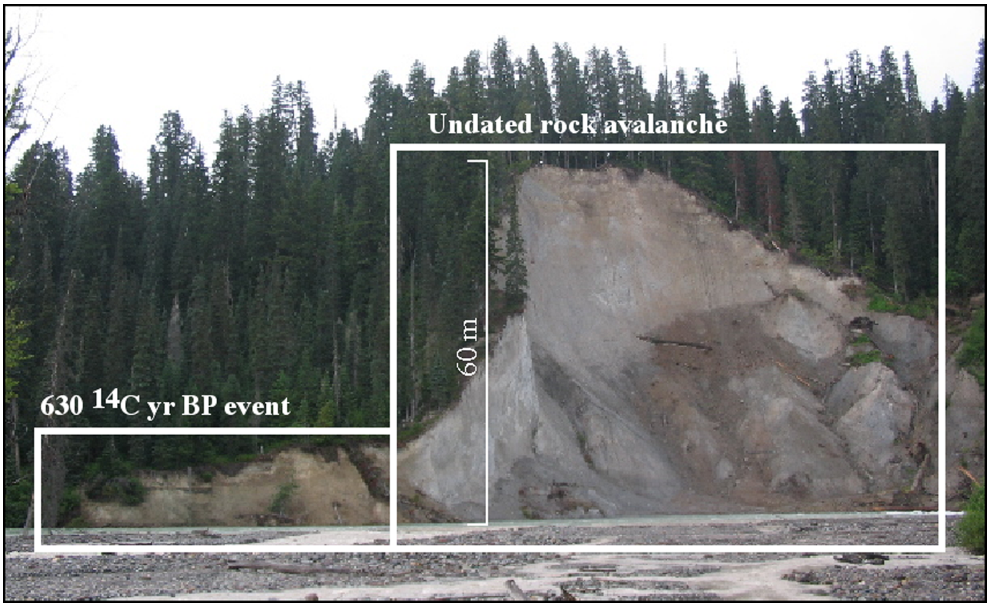


Figure 2. Section opposite the mouth of Job Creek (Figure 1), showing an undated, pre-eruption rock avalanche deposit and a debris flow unit about 630 ^{14}C years old.

estimated the total volume of material transported by these events to be 2×10^8 m^3. Later, a large rock mass (ca. 4.4×10^7 m^3) fell from the flank of Plinth Peak, fragmented as it crossed Lillooet valley, ran 300 m up the opposing valley wall, and travelled about 4 km down the valley (Stewart 2002). The rock avalanche 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 erupted from the vent after this landslide.

Post-eruptive deposits

Terraces underlain by lacustrine, fluvial, and debris flow deposits occur over an area about 6 km long and 1.5 km wide between Salal and Mosaic creeks (Figure 1). The deposits are remnants of a complex valley fill that accumulated in the valley following the Plinth Peak eruption.

A 20-m high bank along Lillooet River (Figure 3) at the northeast margin of the Job Creek fan (Figure 1) exposes a basal volcanic debris flow unit dated at 2240 ± 60 ^{14}C yr BP (Beta-200717) and, above it, at least 11 upward-coarsening, silt to sandy gravel units, eight of which were deposited over a 600-year period. The upward-coarsening units are interpreted to be backwater deposits associated with successive landslides that blocked the canyon at the upstream end of Keyhole Falls (Figure 1). One of the upward-coarsening units (Figure 3) is bracketed by ages of 1820 ± 40 ^{14}C yr BP (Beta-200719) and 1980 ± 50 ^{14}C yr BP (Beta-200718). Landslide debris near this section has yielded a maximum limiting radiocarbon age of 1860 ± 50 ^{14}C yr BP (GSC-5278), and a thin debris flow unit at Keyhole Falls overlies pumiceous gravel dated at 1990 ± 40 ^{14}C yr BP (Beta-200715). Thus, in the post-eruptive period the upper Lillooet River has been frequently blocked by landslides.

A large (ca. 210 ha) terrace on the Lillooet valley bottom upstream of Salal Creek (site 4 in Figure 1) is underlain by 4–5 m of debris flow sediments unit capped by peat. Ten radiocarbon ages obtained from wood within the debris and from the overlying peat indicate that the debris flow occurred 870 ± 50 ^{14}C yr BP (GSC-3215). Jordan (1994) estimated the volume of the deposit to be 8–10 $\times 10^6$ m^3.

Remnant deposits of another large volcanic debris flow (Figure 2) cover an area of about 50 ha at the northwest margin of the Job Creek fan (Figure 1). The deposits have yielded three radiocarbon ages, the youngest of which is 630 ± 40 ^{14}C yr BP (Beta-209553). They contain metre-size rip-up clasts of lacustrine silt, indicating that upper Lillooet Valley was dammed at or before the time of the debris flow. Based on the extent and thickness of the remnant deposits, we estimate that the debris flow had a volume of about 1×10^6 m^3.

Distal deposits in Lillooet River valley

Drilling in Lillooet 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.* 2006).

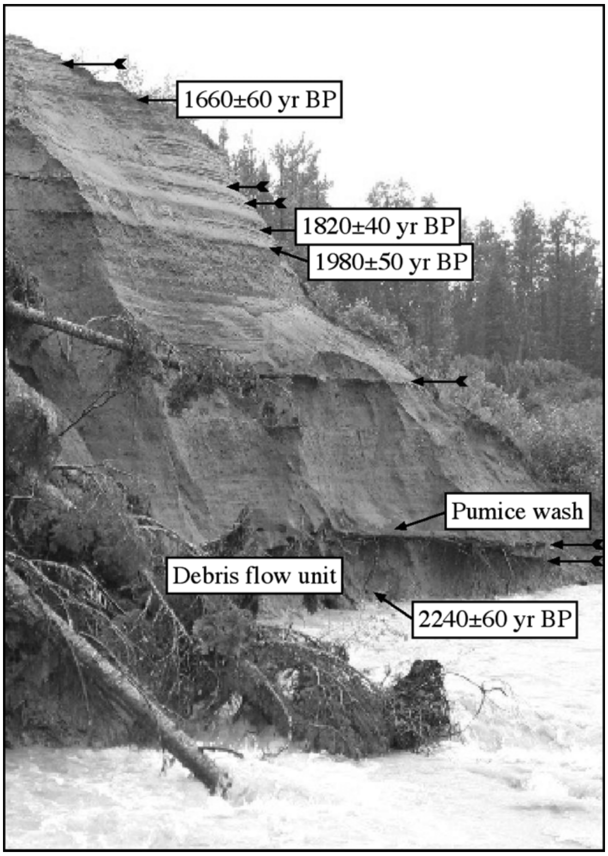


Figure 3. Section at the downstream end of the Job Creek fan exposing a sequence of eight normally graded sediment units overlying a basal debris flow diamicton that yielded a radiocarbon age of about 2200 ^{14}C yr BP. Peat beds (arrows) separate the graded units. Radiocarbon ages on the peat beds are enclosed in boxes.

Debris flows

The oldest of the three debris flow deposits is at least 8 m thick at a drill hole 32 km from Mount Meager. It has yielded two radiocarbon ages, the younger of which is 6250 ± 30 ^{14}C yr BP (OS-36556). No proximal landslide deposit of this age has been positively identified near the volcano. However, the large, rock avalanche deposit in upper Lillooet valley is tentatively correlated with the 6250 ^{14}C year-old debris flow deposit in the drill hole (Table 1).

Based on average aggradation rates, Friele *et al.* (2005) correlated the middle debris flow unit in the drill hole at 32 km from Mount Meager with the 4400-year-old flank collapse of Pylon Peak into the valley of Meager Creek (Friele and Clague 2004).

The youngest of the three debris flow units has been found in drill holes 32–50 km downstream from Mount Meager. It is a 2- to 4-m thick diamicton, which extends across the full 1.5–2 km width of the valley. A thin peat bed lying directly on the deposit yielded a radiocarbon age of 2570 ± 40 ^{14}C yr BP (Beta-166059), and a wood fragment recovered from the diamicton gave an age of 2690 ± 50 ^{14}C yr BP (Beta-166057). The two ages suggest that the debris flow preceded the Mount Meager eruption by as much as a few hundred years, and although likely related to magmatic activity or minor explosions (Simpson *et al.* 2006), it is not strictly syn-eruptive. The proximal deposit of the debris flow has not yet been identified, but it may include diamicton underlying peat that gave an age of 2650 ± 60 ^{14}C yr BP (GSC-6696) at a site 3.3 km upstream of Salal Creek.

Hyperconcentrated flows

A hyperconcentrated flow unit up to 6 m thick was found in two cores 42 km downstream from Mount Meager (Friele *et al.* 2005). It is bracketed by radiocarbon ages of 3230 ± 70 ^{14}C yr BP (Beta-166051) and 4550 ± 90 ^{14}C yr BP (GSC-6645). The unit may be the debris flow runout faces (Pierson and Scott 1985) of the 4400-year-old rock avalanche/debris flow at Pylon Peak (Friele and Clague 2004).

A pumiceous hyperconcentrated flow unit up to 3 m thick caps a thin peat bed, which in turn overlies the uppermost debris flow unit in drill cores 42–47 km downstream from Mount Meager. Similar pumiceous wash is present in deltaic sediments 65 km downstream from the volcano (Friele *et al.* 2005). These sediments are likely the distal deposits of the syn-eruptive outburst flood and ensuing debris flow below Keyhole Falls described by Stasiuk *et al.* (1996).

A third hyperconcentrated flow unit, which is <1 m thick, is present in core collected at a site 47 km downstream from the volcano. We tentatively assign it to the 870-year-old debris flow in upper Lillooet valley (Friele *et al.* 2005). An anomalously thick layer of lacustrine sediment, marked by a strong acoustic reflector and estimated to be of about 900 years old, is present in Lillooet Lake (Desloges and Gilbert 1994).

Frequency-magnitude model

A frequency-magnitude model is required to quantitatively assess landslide risk (Moon *et al.* 2005). Geologic data, however, are generally incomplete, limiting frequency-magnitude analyses. Records based on historic observations or tree damage over several centuries may yield good estimates of magnitude and frequency for small debris flows. Similarly, the frequency of large landslides, whose scars and deposits persist in the landscape (Guthrie and Evans 2007), may also be reasonably estimated. In contrast, deposits of medium-size landslides are easily eroded or buried, and their frequency is commonly underestimated. As records of past events are inevitably incomplete, formulation and use of frequency-magnitude plots must involve expert judgment.

With these issues in mind and for the purpose of risk assessment, we use the apparent frequencies of historic and prehistoric, non-eruptive landslides (Table 2) as a first order estimate of the bounds on the actual frequencies (Figure 4). Detailed assessment of fans in the study area indicates debris flows $<10^5$ m^3 in volume have return intervals of 1–10 years (Jordan 1994; Jakob 1996). Four 10^8–10^9 m^3 (class 9) events have been documented in an 8000-year period. We assume that 4–6 events may have occurred in 10,000 years. A best-fit line connecting the smallest and largest categories lies within the uncertainty bars of the intermediate-size categories, suggesting that our model is reasonable (Figure 4). Considering censoring, the grey band represents what we judge to be the most likely uncertainty bounds for the F-M model. Our risk assessment is limited to class 8 and 9 landslides, because only these size events reach distal, settled areas. Class 10 debris flows are excluded, because landslides of this volume are not considered possible at Mount Meager.

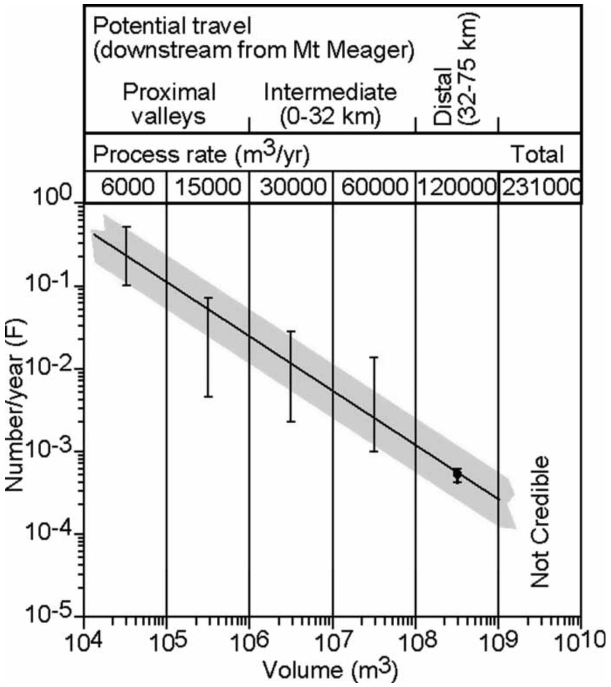


Figure 4. Composite frequency-magnitude diagram for non-eruption triggered volcanic landslides at Meager massif. Apparent uncertainty limits (black bars) for class 4–8 debris flows are derived from the historic record (upper bound) and geologic data (lower bound). In consideration of data censoring, the grey band represents what we judge to be the most likely uncertainty bounds for the F-M model. The total annual yield indicates that Meager massif is the most landslide prone region in Canada.

Integration of the area below the best-fit line in Figure 4 provides the volcanic landslide process rate (Moon *et al.* 2005) for MMVC. Summed across all size 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} averaged over the entire area of the massif. This rate is approximately 50 times higher than the average for hyper-maritime areas of British Columbia (Martin *et al.* 2002, Guthrie and Evans 2004) and three times higher than the average for forested basins in California (Kelsey 1982, Madej 1987). It is comparable to denudation rates in the Southern Alps of New Zealand (Hovius *et al.* 1997). Our analysis confirms Read's assessment that Mount Meager is the most landslide-prone mountain massif in Canada.

Potential instability

The potential for catastrophic slope failure in glacierised mountainous terrain increased during the past century due to thinning and retreat of alpine glaciers (Evans and Clague 1994). The phenomenon has been studied in detail at Mount Meager by Holm *et al.* (2004, p. 201), 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.

Furthermore, climate change scenarios for this region suggest warmer, wetter winters with more intense rainfall later during this century (Whitfield *et al.* 2002, 2003). Jakob and Lambert (2007) argue that increases in the amount and intensity of winter precipitation and a 3°C rise in mean temperature in southwestern British Columbia by 2100 will increase the frequency of landslides in the region.

For small and intermediate-size landslides ($<10^7$ m^3), we can expect the failure rate in the future will be similar to, or greater than, that 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 such events in the future has been reduced by those of the past. Poorly lithified and hydrothermally altered rocks create the potential for edifice collapse at volcanoes (Finn *et al.* 2001, Siebert 2002). The sources of the major edifice collapses at MMVC are hydrothermally altered rocks in the Angel, Devastation and Job Creek basins (Figure 1). Large masses of unstable volcanic rock with sufficient relief to generate edifice collapse still exist in these basins and elsewhere 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 Peak, and the east slope of the Job Creek basin, including the flank of Mount Meager. Of particular concern is an area of several square kilometres on the east side of Devastation Creek that is underlain by hydrothermally altered pyroclastic rocks and flows. This area shows settlement rates of 1–2 cm/year based on SAR interferometric measurements (van der Kooj and Lambert 2002). The potential source area (Read 1978) is ten times the size of the 1975 rock avalanche (1.2×10^7 m^3), thus if catastrophic failure were to occur, the maximum volume of the landslide would be of the order of 10^8 m^3. Volumes of 10^6–10^8 m^3 are likely for lesser, partial collapses. In summary, the potential for large (10^7–10^8 m^3) landslides at MMVC is likely to remain similar to that in the past. This risk is reinforced by frequent small earthquakes beneath the Meager massif (Figure 5), a sign of shallow magmatic activity and associated crustal adjustments.

Quantitative risk assessment

Methodology

The methodology we use to characterise landslide risk to residents of Lillooet valley follows Fell *et al.* (2005). We restrict our analysis to an assessment of loss of life. The variables used in quantitative risk analysis are:

P_{LOL}	annual probability of loss of life for an individual;
$P_{S:H}$	spatial probability that the event will reach the element at risk;
$P_{T:S}$	temporal probability of impact; i.e. the percentage of time the element at risk occupies the hazard area, defined as Lillooet valley between Mount Meager and Lillooet Lake;
V	likelihood of loss of life should the element at risk be affected by the hazard, which is a function of the intensity of the hazard at that location;
E	element of concern; in this paper, the number of lives potentially at risk.

Risk can be quantified for individuals or for groups. Risk to individuals customarily is related to the person most at risk, typically someone living closest to the hazard who is at or close to home for much of the time. This person could be an invalid or, in a rural area such as Pemberton, a farmer or homemaker. Individual risk is generally compared to some socially accepted or tolerable risk threshold. Annual risk of loss of life to an individual (P_{LOL}) can be formulated as:

$$P_{LOL} = P_H \times P_{S:H} \times P_{T:S} \times V. \qquad (1)$$

Society is more tolerant of individual loss of life than it is of the simultaneous death of a large number of people (Ale 2006). Group risk is estimated by plotting the annual frequency of one or more deaths from a particular hazard or suite of hazards against the expected number of fatalities on an *F*/*N* plot, where *F* is defined, according to Fell *et al.* (2005), as:

$$F = P_H \times P_{S:H} \times P_{T:S}, \qquad (2)$$

and *N* is the product of the number of elements at risk (*E*) and their vulnerability (*V*) to the hazard under consideration. On an *F*/*N* plot, the total risk is the sum of partial risks, for example, the risk accumulated from different hazards or, as in this paper, from different magnitude classes of the same hazard, each of which forms a separate hazard scenario.

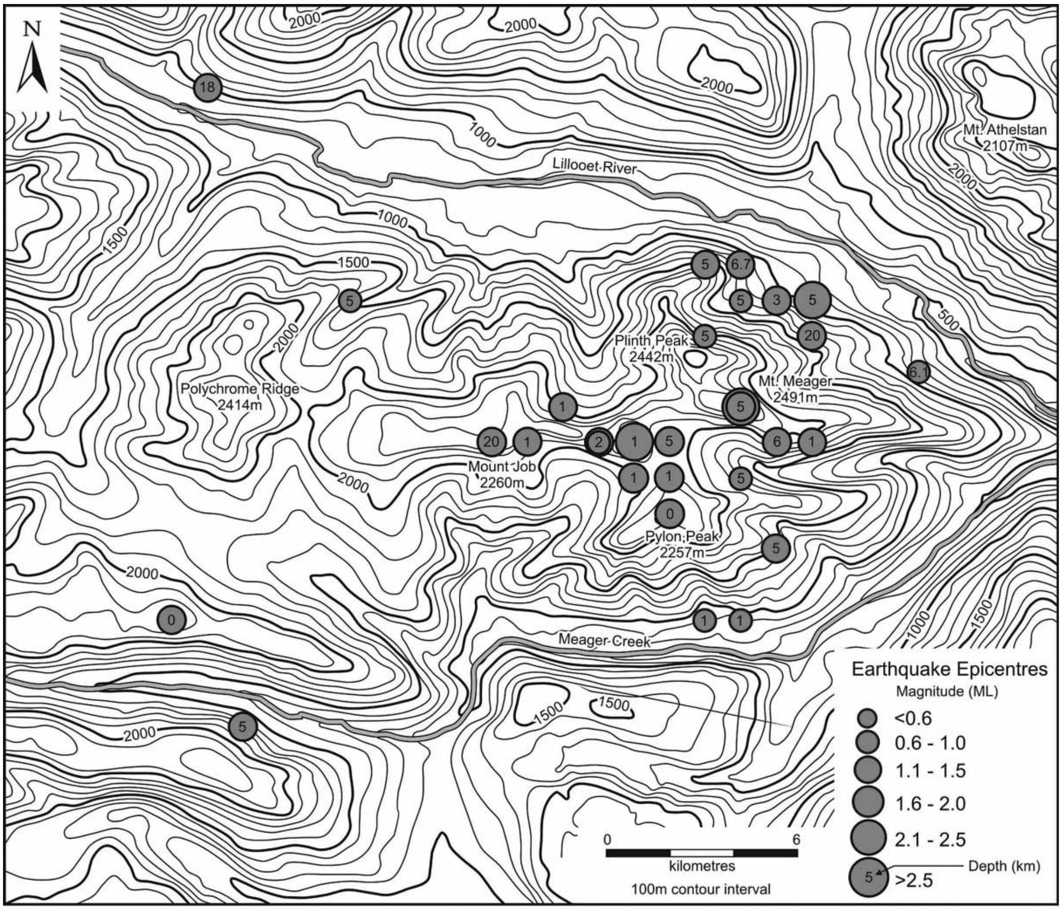
Parameterisation

Probability of the hazard (P_H)

In the following discussion, we distinguish 'event magnitude' from 'event class'; magnitude refers to the volume of an event, whereas class is a nominal magnitude category (Table 3), taken from Jakob (2005). Field evidence (Friele *et al.* 2005) and modeling (Simpson *et al.* 2006) show that only the largest debris flows (classes 8–9) reach settled areas of Lillooet valley (Table 3; Figure 6), thus the risk analysis refers to these event classes only. For class 8 events, $P_{H(min)}$ and $P_{H(max)}$ are taken as 0.001 and 0.005, respectively; for class 9 events, the corresponding values are, respectively, 0.0004 and 0.0006.

Spatial probability of impact ($P_{S:H}$)

Modeling of inundation areas and travel distances of debris flows of different volume (Simpson *et al.* 2006) (Table 3; Figure 6) were estimated using the LAHARZ model developed by Iverson *et al.* (1998). The results indicate that in the average case the 10^7 m^3 debris flow is unlikely to directly impact settled areas of Lillooet valley, but we assume that there is a remote chance of impact ($P_{S:H} = 0.01$). Modeling indicates that a 10^8 m^3 debris flow would just reach



clague/aug07/meager_epi.cdr

Figure 5. Seismic activity at Mount Meager between 1970 and 2005 (Natural Resources Canada, Pacific Geoscience Centre).

Pemberton Meadows, which we represent as low probability of impact ($P_{S:H} = 0.1$). A 10^9 m^3 debris flow would reach Lillooet Lake ($P_{S:H} = 1.0$). Thus, $P_{S:H}$ ranges from 0.01 to 0.1 for class 8 debris flows and 0.1 to 1.0 for class 9 debris flows (Table 4).

Temporal probability of impact ($P_{T:S}$)

In the case of class 8 debris flows, the temporal probability ($P_{T:S}$) is high for the inhabited part of the impacted area. This area is agricultural; the majority of the adult residents spend their time in the home or fields, while children commute daily to school in Pemberton. Thus, $P_{T:S}$ for class 8 debris flows is assigned a value of 0.9 for the person most at risk. Assuming a family of two adults and two children, with the children at school eight hours per day, $P_{T:S}$ for the average individual is 0.8. Class 9 debris flows travel farther, reaching areas occupied by farmers, first nation residents, and service sector workers, some of whom commute daily to Whistler. Lacking detailed occupational statistics, we assume 50% live and work/school locally, and 50% commute daily out of the valley and are absent 12 hours per day. $P_{T:S}$ for those staying in the valley is assumed to be 0.9 and for commuters is 0.5, the average value is 0.7 (Table 4).

Vulnerability

For this study, we define vulnerability as the likelihood of death should a building or site be impacted directly by a debris flow or debris flood. Any estimate of vulnerability has a large degree of uncertainty, because it is affected by parameters that are poorly known or highly variable, for example the location of individuals within a building, the intensity of impact, and the ability of a building to withstand impact without incurring structural damage that could lead to death.

Drilling in Lillooet valley has documented valley-wide debris sheets 2–8 m thick, 32–55 km downstream from Mount Meager volcano. Older homes in the valley were typically built directly on the floodplain, whereas new homes conform to the 200-year flood level, which is 1–2 m above the floodplain. A class 8

Table 3. Consequences of large volcanic debris flow along Lillooet River valley.

Debris flow class	Volume (m^3)	Peak discharge[1] (m^3/s)	Inundation area[1] (m^2)	Potential consequences[1]
6	10^5–10^6	3×10^3–3×10^4	2×10^6–3×10^7	Could obliterate valleys or fans up to several tens of km^2 in size and dam rivers. Modeling indicates events are confined to Meager and upper Lillooet valleys.[2]
7	10^6–10^7	3×10^4–3×10^5	3×10^7–3×10^8	Could obliterate valleys or fans up to several tens of km^2 in size, and dam large rivers with the potential for destructive outburst floods and hyperconcentrated flows. Modeling indicates debris flows travel up to 5 km downstream from the Meager-Lillooet river confluence.[2] The 1931 Devastation debris flow reached Lillooet River and caused muddy surges 15 km downstream.
8	10^7–10^8	3×10^5–3×10^6	3×10^8–3×10^9	Could inundate large valleys up to 100 km^2 in size, and dam large rivers with the potential for destructive outburst floods and hyperconcentrated flows. Modeling indicates debris flows may reach upstream limits of settlement.[2]
9	10^8–10^9	3×10^6–3×10^7	3×10^9–3×10^{10}	Vast and complete destruction over hundreds of km^2. Modeling indicates debris flows would inundate the entire Lillooet River valley, travelling 20–75 km downstream from Mount Meager to Lillooet Lake.[2] Field evidence documents deposits of three debris flow deposits 32–50 km downstream from the volcano.
10	$>10^9$	3×10^7–3×10^8	$>3 \times 10^{10}$	No known events.

[1] After Jakob (2005). Note that the inundation area is derived empirically from Iverson *et al.* (1998). At Lillooet River valley, the area inundated is smaller than quoted for the respective size volcanoes in Jakob (2005) due to the lateral constraint and the Lillooet Lake at the mouth, which define the maximum area that can be inundated in a single event.

[2] Modeling results after Simpson *et al.* (2006), based on Iverson *et al.* (1998).

or 9 debris flow would probably impact both old and new homes.

Hyperconcentrated flows from volcanoes have velocities of up to 4 m/s many tens of kilometres from their source. Much higher velocities, up to 12 m/s, have been inferred for snowmelt-generated debris flows and liquefied rock avalanche deposits on Mount St. Helens (Major *et al.* 2005). The events of concern in this paper can have velocities of 10–15 m/s in the upper Pemberton Meadows area and 3–6 m/s at Pemberton. A hyperconcentrated or debris flow with a specific gravity of 1.2–2.3, travelling at velocities of 3–15 m/s, would destroy most residential buildings in the valley. The impact forces would be increased by hundreds of thousands of trees uprooted and transported by the flow.

Under the scenarios outlined, buildings would collapse or fill with watery debris; occupants of buildings and people caught outside their homes would likely drown or be buried in debris. Some people might survive a class 8 debris flow by climbing into large standing trees or reaching higher ground in the valley, but death is more certain for class 9 events. Uncertainty is built into the vulnerability estimate by defining lower and upper bounds, $V_{\min}$ and $V_{\max}$. Allowing for some possibility of survival, $V_{\min}$ is assumed to be 0.5 for a class 8 debris flow and 0.9 for a class 9 debris flow. $V_{\max}$ is assigned a value of 1.0.

Element at risk value

The settled area of Lillooet valley can be divided into two zones with different population densities. Pemberton Meadows, 32–55 km downstream from the volcano, is primarily agricultural and has a population of about 200 people (average population density 5 persons/km^2) (Squamish-Lillooet Regional District, personal communication, 2006). Pemberton and Mount Currie, 55–75 km downstream, have about 3800 and 1000 residents, respectively (average population density of 125 persons/km^2).

Risk evaluation

Risk to individuals most at risk

The range of annual landslide risk to an individual residing in Lillooet valley is 5×10^{-6} to 5.0×10^{-4} deaths per year (Table 4). Governments in Australia, Hong Kong, and England have defined this tolerable risk level to be 10^{-4} annual probability for existing development and 10^{-5} annual probability of death for new development (Fell *et al.* 2005, Leroi *et al.* 2005). For Lillooet valley, individual risk is up to 5.4

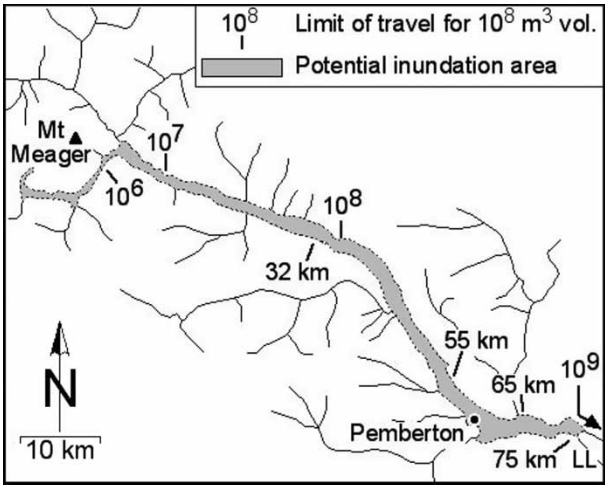


Figure 6. Travel distances of volcanic debris flows of different sizes, averaged from debris flows modelled from four different source areas (after Simpson *et al.* 2006). Modeling was carried out with LAHARZ software (Iverson *et al.* 1998) and is based on clay-rich, volcanic debris flows. The 10^9 m^3 event reaches Lillooet Lake (LL), terminating at the delta. Distances demarcate neighborhood boundaries: 32–55 km, Pemberton Meadows with 200 residents; 55–65 km, municipality of Pemberton and immediate fringe with 3800 residents; and 65–75 km, old Mount Currie with 1000 residents. Population estimates provided by Squamish-Lillooet Regional District.

times higher than acceptable levels for the jurisdictions cited above, and is up to 54 times higher than acceptable risk for individuals in the Netherlands (Ale 2005). In the Netherlands, however, the principle of 'as low as reasonably practical' does not apply, which is contrary to Anglo-Saxon common law. The latter encodes the principle of 'as low as reasonably practical', while encouraging additional risk reduction. For new development, the acceptable risk is one order of magnitude higher, and thus, without adequate mitigation, the risk values we have estimated are up to 36 times higher than acceptable levels.

Risk to groups

Societal risk (Table 4) was quantified for each debris flow class as f-N pairs on the F-N graph (Figure 7). Figure 7 shows evaluation criteria that are gaining acceptance in Australia, the United Kingdom, and recently in Canada (Fell *et al.* 2005; Porter *et al.* 2007). The F-N plot is subdivided into four zones: 'unacceptable' – risks are generally considered unacceptable by society and require mitigation; 'as low as reasonably practical' – the incremental risks from a hazard should, wherever possible, be reduced; 'broadly acceptable' – incremental risks from a hazard are within the range that society can tolerate; and 'intense scrutiny region' – the potential for large loss of life is low but careful consideration is required.

In this study, uncertainties in both hazards and consequence require that the risk for each class be plotted as a zone rather than a point on Figure 7. The plot shows that risk to groups in Lillooet valley is unacceptable for both class 8 and 9 debris flows based on international standards. Mitigation measures should therefore aim to reduce risk to the 'as low as reasonably practical' region of the F-N plot. Similarly, risk avoidance should be encouraged by restricting development to areas where risk can be reduced to the 'acceptable' level.

Discussion

General uncertainties

Not all uncertainties can be precisely quantified in landslide risk assessments, and herein they are captured by judgemental estimation of minimum and maximum values for each parameter, for risk to both individuals and groups (Table 4).

Uncertainty in the hazard level for class 8 and 9 debris flows appears reasonable, as these are large, formative events and their scars and deposits persist in the landscape (Guthrie and Evans 2007), and it is likely we have a developed a good census. Discovery of additional events would only increase hazard and risk. The precision and accuracy of spatial and temporal probabilities depend on an ability to accurately map debris flow deposits, on dating control, and on reliance on modeling results, which have some error that is not readily quantifiable. More detailed analyses could apply different models and/or confidence limits of runout estimates. Temporal probabilities could be improved by querying all households, although the improvement would only be temporary because occupancy of homes and other demographic factors change with time. Vulnerability is perhaps the most difficult variable to estimate due to scarcity of data for the effects of debris flows of different sizes on structures. Experience in British Columbia, however, has shown that direct impact by debris flows is generally fatal. An exception is a debris flow in North Vancouver, where a couple and their baby escaped severe injury because their house was located at the edge of the runout zone and was only partially damaged (Porter *et al.* 2007).

Global risk acceptance standards

Definitions of acceptable risk have been established for other fields of engineering and geoscience practice, such as dam safety (ANCOLD), flood hazards, and construction of hazardous installations

Table 4. Individual and group risk matrices for residents of Lillooet River valley. See text for details.

Individual most at risk

Volume (m^3)	$P_{H(Min)}$	$P_{H\ (max)}$	$P_{S:H\ (min)}$	$P_{S:H\ (max)}$	$P_{T:S}$	V_{min}	V_{max}	E	$R_{L(min)}$	$R_{L(max)}$	Factor* (min)	Factor (max)
10^7 to 10^8	0.001	0.005	0.01	0.1	0.9	0.5	1	1	0.000005	0.0005	0.05	4.5
10^8 to 10^9	0.0004	0.0006	0.1	1	0.9	0.9	1	1	0.000032	0.0005	0.32	5.4

Group risk

$F = P_H \times P_{S:H} \times P_{T:S}$

$N = V \times E$

Volume (m^3)	$P_{H\ (min)}$	$P_{H\ (max)}$	$P_{S:H\ (min)}$	$P_{S:H\ (max)}$	$P_{T:S}$	F (min)	F (max)	V_{min}	V_{max}	E_{min}	E_{max}	$N_{(min)}$	$N_{(max)}$
10^7 to 10^8	0.001	0.005	0.01	0.1	0.8	0.000008	0.000400	0.5	1	20	200	10	200
10^8 to 10^9	0.0004	0.0006	0.1	1	0.7	0.000028	0.000420	0.9	1	200	5000	180	5000

	min	max
F, $N > = 10^0$	0.000041	0.00127
F, $N > = 10^1$	0.000036	0.000820
F, $N > = 10^2$	0.000028	0.000420

"Factor" is the ratio of the minimum and maximum risk to the risk acceptance criterion of 10^{-4} for existing development. If the number exceeds 1.0, the risk is deemed unacceptable. Accordingly, only the upper range indicates that risk to individuals for class 8 and 9 debris flows is unacceptable.

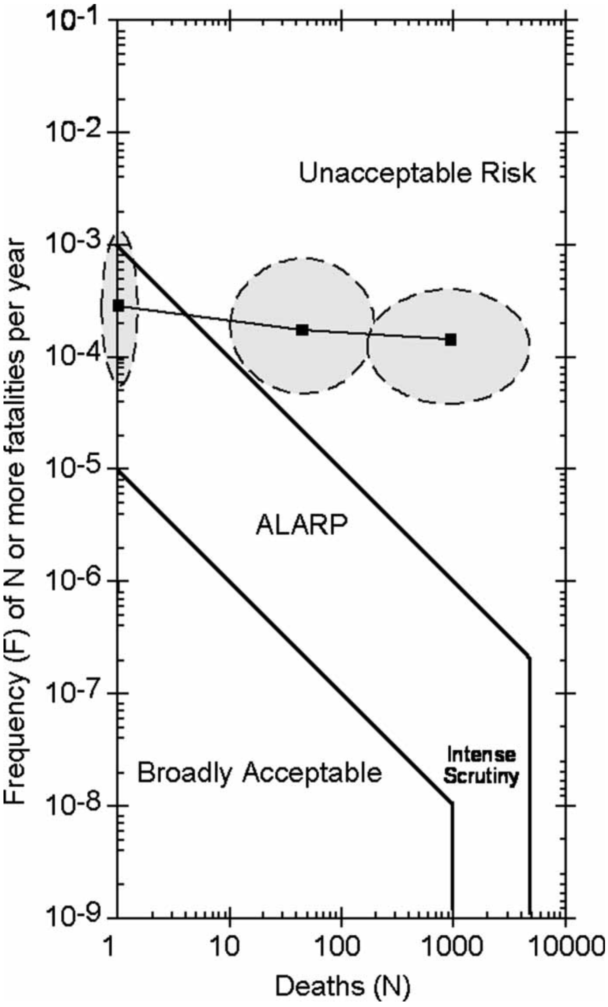


Figure 7. *F*/*N* plot for societal risk in Lillooet valley for class 8 and 9 debris flows from the Mount Meager massif. ALARP is 'as low as reasonably practical'. The results are plotted as shaded circles reflecting the uncertainties incorporated into the risk calculations, as discussed in the text. *F*/*N* threshold lines are shown for Hong Kong, the Netherlands (VROM criteria), Denmark, and Britain (HSE criteria). The last three lines separate the unacceptable zone from the ALARP zone.

such as nuclear power plants (Kendall *et al.* 1977). Insurance underwriters routinely calculate risk to provide adequate insurance coverage for their clients while earning a profit. However, only a few countries have established acceptable risk thresholds for naturally occurring hazards, and applications to residential developments are rare. With decreasing societal tolerance of risk to human safety and the environment, establishment and application of risk thresholds for natural hazards appears warranted.

Risk acceptance thresholds differ throughout the developed world, largely because risk tolerance differs from country to country. For example, risk tolerance in Denmark, the Netherlands (Ministry of Housing, Land Use Planning and Environment 1988), and Britain (Suddle 2003) differs by orders of magnitude. However, thresholds in all western European countries, as well as Australia and Hong Kong, are exceeded by the risk faced by residents of Lillooet valley from class 9 debris flows. The risk for class 8 debris flows would be acceptable only according to the British standard (Heath and Safety Executive 1989).

The Australian Geomechanics Society has specified a tolerable risk limit for loss of life of 10^{-4} per year for individuals most at risk on existing slopes or developments and 10^{-5} per annum for new developments. The Hong Kong Special Administrative Regional Government has adopted, on an interim basis, the same limits for landslides on natural slopes (Leroi *et al.* 2005). Britain's Health and Safety Executive (1988) defined acceptable risk in a document titled 'Tolerability of Risk' – annual probabilities of death of 10^{-4} and injury of 10^{-5}. In the Netherlands, the acceptable risk limit is 10^{-5} per annum for existing situations and 10^{-6} for new situations (Ale 2005).

Landslide hazard and risk policies in British Columbia

Quantitative risk criteria for landslides have not yet been defined for British Columbia in general or the Squamish-Lillooet Regional District specifically. Instead, land-use decisions in areas with recognised geologic hazards have been made by considering only hazard frequency (Berger 1973; Cave 1993). Development decisions have not been based on a consideration of risk, which includes both hazard (Table 2) and consequences (Table 3).

A recent a fatal landslide in North Vancouver set a precedent in landslide risk management in British Columbia. In that case, a recommendation by BGC Engineering (2006) that the thresholds for individual risk be set at an annual probability of 10^{-4} for existing development and 10^{-5} for new development was adopted on an interim basis by the District of North Vancouver (Porter *et al.* 2007). Societal risk or risk to groups is quantified from the relation between the frequency of deaths and the number of deaths as in Figure 7.

Residential development in British Columbia is governed by the Land Title Act, the Local Government Act, and the Community Charter. The Land Title Act contains provisions for refusing to approve a subdivision 'if the approving officer considers the land subject, or reasonably be expected to be subject to flooding, erosion, land slip or avalanche'. If the approving officer is in doubt, a report by a professional engineer or geoscientist experienced in geotechnical engineering is required to certify that 'the land may be used safely for the use intended'. The approving office may also stipulate one or more registered covenants restricting use of the land. Similarly vague statements appear in the Local Government Act (Section 919.1 and 920) and the BC Community Charter (Section 56). The Local Government Act (Section 910, Floodplain Bylaw Variances or Exemptions) states that, although development should be discouraged in areas prone to debris flows, 'consent to develop may be granted, with standard requirements as established for alluvial fan in Section 3.3 [of those guidelines], where there is no other land available, and where an assessment of the land by a suitably qualified professional indicates that development may occur safely'.

Three issues arise that cast doubt on the efficacy of these provisions. First, the approving officer needs to be sufficiently skilled to recognise that a report by a professional is needed. Second, there is no official designation of a 'geotechnical engineer', thus a variety of engineers or geoscientists can claim experience or expertise, even though their training may be inadequate for such assessment. Third, and most importantly, the word 'safe' is not defined and is therefore open to interpretation.

The failure to define 'safely' leaves all the quoted legal documents open to personal interpretation. We encourage that legislation be changed to replace the word 'safe' by a set of quantitative risk tolerance standards. Alternatively, if law makers are reluctant to amend their legal texts, practitioners can perform quantitative risk analyses and define 'safe' based on comparisons of existing risk with risk acceptance standards developed in those countries or jurisdictions that have successfully used those standards to manage landslide risk.

Conclusions

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.

Mount Meager has a well-documented history of instability and volcanism, and the supply of rock available for large landslides is by no means exhausted. A landslide as large as the largest that has occurred during the Holocene probably would generate a debris flow that would destroy much of the development in Lillooet valley and, if not preceded by warnings, would kill hundreds or possibly thousands of people. Using internationally developed and applied risk acceptance standards, and with reasonable uncertainties included in the analyses, we estimate that the existing risk to individuals and groups from volcanic debris flows in Lillooet valley is unacceptable.

Our paper is not intended to be a comprehensive risk analysis, because it focuses only on debris flows, which are only one of several hazards in Lillooet valley. The valley has a long history of floods that have overtopped river banks and levees, and caused significant damage. In addition, some steep slopes bordering the valley floor show signs of deep-seated movement (Bovis and Evans 1996), which although not necessarily a precursor of catastrophic failure, are also of concern.

Fell *et al.* (2005) have pointed out that a quantitative risk assessment is only one input into the decision process. Owners, society, and regulators will also consider political, social, and legal issues in their assessments and may consult the public affected by the hazard. In 2004, the BC provincial government freed itself of the responsibility to determine and enforce levels of acceptable hazard by transferring this responsibility to regional district and municipalities. These agencies commonly lack the technical expertise and resources to properly evaluate existing hazards and risk, and to implement effective mitigation strategies. Further, they may have a stake in promoting development because it increases the tax base used to enhance public services. Nevertheless, responsibility for informing residents of Pemberton Meadows, Pemberton, and Mount Currie of natural hazards and risk rests with policy makers in the Squamish-Lillooet Regional District, the Municipality of Pemberton, and the Department of Indian and Northern Affairs (responsible for the Mount Currie native reserve). As the population of the valley continues to increase, these agencies should develop a meaningful risk management policy that is acceptable to all stakeholders. The policy could include a spectrum of measures, ranging from restrictive covenants that regulate development in the valley, and specification of floodplain construction levels and types, to a debris flow warning system.

Unfortunately, the largest possible debris flow in Lillooet valley does not lend itself to active mitigation. A warning system may be the minimum requirement for responsible long-term hazard and risk management. Warning systems are widely used in British Columbia for a variety of other natural hazards, including include tsunami, heavy rainfall, severe winds, and avalanches. A warning system could include seismographs to record large landslides at Mount Meager and acoustic flow monitor (AFM) stations on the Lillooet River floodplain below the confluence of Meager Creek and Lillooet River. Each AFM station would consist of a geophone and a data logger that records the amplitude, frequency, and duration of ground vibrations. When vibrations exceed programmed thresholds, the data are radioed to a base-station computer. Data from all stations would then be transmitted by radio to duplicate base-station computers located at an emergency management centre in Pemberton, possibly adjacent to the continuously staffed fire hall. Special software would analyse the incoming data and trigger an automatic notice when a significant debris flow is detected. A similar system for detecting debris flows is operational at Mount Rainer (http://volcanoes.usgs.gov/About/Highlights/ RainierPilot/Pilot_highlight.html).

Approving authorities may expose themselves to significant liability if they ignore the now-quantified hazards and risks in Lillooet valley. The Supreme Court of Canada has established a framework for evaluating government liability for negligently performed regulatory duties. Quoting the law firm Singleton Urquhart (2007): ‘If in the exercise of their regulatory powers, whether the exercise of the power is discretionary or mandated by legislation, it is foreseeable that the negligent performance of those powers might cause harm of the nature complained of, and there is sufficient proximity between the government authority and the plaintiff, then the courts say a duty of care arises to exercise reasonable care in performance of the regulatory function’. In other words, government authorities could be held liable for losses that arise, because they took no action in the face of an identified hazard. For this reason, we encourage a dialogue between scientists and government bodies to establish and implement a reasonable debris flow risk management policy. Such a process is under way at the District of North Vancouver, where a task force of community members has been created to recommend risk tolerance criteria to the District Council. It would be desirable if other districts and governments adopted a similar strategy and learned from the District of North Vancouver’s experience.

Acknowledgements

We thank Stephen Black, John Vanloon, Niel Vanloon, Bruce Miller, Jack Ronayne, Bob Menzel, and John Beks for allowing us to drill on their properties and for clearing snow for the drill rigs. Drilling was carried out by Sonic Drilling Ltd. and Geotech Drilling Services Ltd. Many of the radiocarbon ages were provided by Roger McNeely (Geological Survey of Canada Radiocarbon Laboratory). The paper has benefited from careful review by Christophe Bonnard and an anonymous reviewer.

References

Ale, B.J.M., 2005. Tolerable or acceptable: a comparison of risk regulation in the United Kingdom and the Netherlands. *Risk Analysis*, 25 (2), 231–241.

Berger, T., 1973. The law and Mr. Planner: reasons for judgment. Supreme Court of British Columbia, Action No. X4042, 23 August 1973.

BGC Engineering, 2006. Berkley landslide risk management: phase 1 risk assessment. Report prepared by BGC Engineering Inc. for the District of North Vancouver, BC, Canada.

Bovis, M.J. and Evans, S.G., 1996. Extensive deformations of rock slopes in southern Coast Mountains, southwest British Columbia, Canada. *Engineering Geology*, 44, 163–182.

Bovis, M. and Jakob, M., 2000. The July 30, 1998 debris flow and landslide dam at Capricorn Creek, Mount Meager Volcanic Complex, British Columbia. *Canadian Journal of Earth Sciences*, 37, 1321–1334.

Carter, N.M., 1932. Exploration in the Lillooet River Watershed. *Canadian Alpine Journal*, 21, 8–18.

Cave, P., 1993. Hazard acceptability thresholds for development approvals by local government, British Columbia. British Columbia Geological Survey Branch, Open File 1992-15.

Clague, J.J., Evans, S.G., Rampton, V.N., and Woodsworth, G.J., 1995. Improved age estimates for the White River and Bridge River tephras, western Canada. *Canadian Journal of Earth Sciences*, 32, 1172–1179.

Croft, S.A.S., 1983. *Stability assessment of the Capricorn Creek Valley, British Columbia*. Thesis (BSc). University of British Columbia.

Decker, F., Fougberg, M., and Ronayne, M., 1977. *Pemberton: the history of a settlement*. Burnaby, BC: Hemlock Printing Ltd.

Desloges, J.R. and Gilbert, R., 1994. Sediment source and hydroclimatic inferences from glacial lake sediments: the postglacial sedimentary record of Lillooet Lake, British Columbia. *Journal of Hydrology*, 159, 375–393.

Evans, S.G., 1987. A rock avalanche from the peak of Mount Meager, British Columbia. *Geological Survey of Canada*, Paper 87-1A, 929–934.

Evans, S.G., 1997. Fatal landslides and landslide risk in Canada. *In*: R. Cruden and Fell, eds. *Landslide risk assessment*. Rotterdam: Balkema, 185–196.

Evans, S.G., 2001. Landslides. *In*: G.R. Brooks, ed. *A synthesis of geological hazards in Canada*. Geological Survey of Canada, Bulletin 548, 43–80.

Evans, S.G. and Clague, J.J., 1994. Recent climate change and catastrophic geomorphic processes in mountain environments. *Geomorphology*, 10, 107–128.

Evans, S.G. and De Graff, J.V., 2005. Preface. *In*: *Catastrophic landslides: effects, occurrence, and mechanics*. Boulder, CO: The Geological Society of America, vii–viii.

Fell, R., Ho, K.K.S., Lacasse, S., and Leroi, E., 2005. A framework for landslide risk assessment and management. *Proceedings of the International Conference on Landslide Risk Management*, Vancouver, BC, 3–25.

Finn, C.A., Sisson, T.W., and Deszcz-Pan, M., 2001. Aerogeophysical measurements of collapse-prone hydrothermally altered zones at Mount Rainier volcano. *Nature*, 409, 600–602.

Friele, P.A. and Clague, J.J., 2004. Large Holocene landslides from Pylon Peak, southwestern British Columbia. *Canadian Journal of Earth Sciences*, 41, 165–182.

Friele, P.A. and Clague, J.J., 2006. Volcanic landslide hazards at Mount Meager, British Columbia. *Proceedings of the 59th Annual Canadian Geotechnical Conference*, Vancouver, BC, 997–1004.

Friele, P.A., Clague, J.J., Simpson, K., and Stasiuk, M., 2005. Impact of a quaternary volcano on Holocene sedimentation in Lillooet River valley, British Columbia. *Sedimentary Geology*, 176, 305–322.

Guthrie, R.H. and Evans, S.G., 2004. Analysis of landslide frequencies and characteristics in a natural system, coastal British Columbia. *Earth Surface Processes and Landforms*, 29, 1321–1339.

Guthrie, R.H. and Evans, S.G., 2007. Work, persistence, and formative events: the geomorphic impact of landslides. *Geomorphology*, 88, 266–275.

Health and Safety Executive, 1988. *The tolerability of risk from nuclear power stations*. London: HM Stationery Office.

Health and Safety Executive, 1989. *Risk criteria for land-use planning in the vicinity of major industrial hazards*. London: HM Stationery Office.

Hickson, C.J., 1994. Character of volcanism, volcanic hazards, and risk, northern end of the Cascade magmatic arc, British Columbia and Washington State. *In*: J.W.H. Monger, ed. *Geology and geological hazards of the Vancouver region, Southwestern British Columbia*. Geological Survey of Canada, Bulletin 481, 231–250.

Holm, K., Bovis, M.J., and Jakob, M., 2004. The landslide response of alpine basins to post-Little Ice Age glacial thinning and retreat in southwestern British Columbia. *Geomorphology*, 57, 201–216.

Hovius, N., Stark, C.P., and Allen, P.A., 1997. Sediment flux from a mountain belt derived by landslide mapping. *Geology*, 25, 231–234.

Iverson, R.M., Schilling, S.P., and Vallance, J.W., 1998. Objective delineation of lahar-inundation hazard zones. *Geological Survey of America Bulletin*, 110, 972–984.

Jakob, M., 1996. *Morphometric and geotechnical controls on debris flow frequency and magnitude, southern coast mountains, British Columbia*. Thesis (PhD). University of British Columbia.

Jakob, M., 2005. A size classification for debris flows. *Engineering Geology*, 79, 151–161.

Jakob, M. and Lambert, S., 2007. Effects of climate change on the occurrence of landslides in coastal southwestern British Columbia. *Water Resources Research*. In review.

Jordan, P., 1994. *Debris flows in the southern coast mountains, British Columbia: dynamic behavior and physical properties*. Thesis (PhD). University of British Columbia.

Jordan, P. and Slaymaker, O., 1991. Holocene sediment production in Lillooet River basin, British Columbia: a sediment budget approach. *Géographie physique et Quaternaire*, 45, 45–57.

Kelsey, H.M., 1982. Hillslope evolution and sediment movement in a forested headwater basin, Van Duzen River, north coastal California. *In Sediment Budgets and Routing in Forested Drainage Basins*. US Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station General Technical Report, PNW-141, 86–96.

Kendall, H.W., Hubbard, R.B., Minor, G.C., and Bryan, W.M., 1977. *Union of concerned scientists, the risks of nuclear power reactors: a review of the NRC reactor safety study*. Cambridge, MA: The union for concerned Scientists.

Kerr Wood Leidal Associates Ltd., 2001. Engineering study for Lillooet River Corridor: hydrologic, geomorphic, and hydraulic investigations. Pemberton Valley Diking District, Mount Currie Indian Band, North Vancouver, BC.

Leroi, E., Bonnard,Ch., Fell, R., and McInnes, R., 2005. Risk assessment and management. *Proceedings of the International Conference on Landslide Risk Management*, Vancouver, BC, 159–198.

Madej, M.A., 1987. Residence times of channel stored sediment in Redwood Creek, northwestern California. *In*: R.L. Beschta *et al*., eds. *Proceedings of the International Symposium held at Oregon State University*, Corvallis, Oregon, 3–7 August 1987, International Association of Hydrological Sciences Publication, 429–438.

Major, J., Pierson, T.C., and Scott, K., 2005. Debris flows at Mount St. Helens, Washington, USA. *In*: M. Jakob and O. Hungr, eds. *Debris flow processes and related phenomena*. Heidelberg: Praxis-Springer, 685–731.

Martin, Y., Rood, K., Schwab, J.W., and Church, M., 2002. Sediment transfer by shallow landsliding in the Queen Charlotte Islands, British Columbia. *Canadian Journal of Earth Sciences*, 29, 189–205.

McNeely, R. and McCuaig, S., 1991. Geological survey of Canada Radiocarbon Dates XXIX. Geological Survey of Canada, Paper 89-9.

Mokievsky-Zubok, O., 1977. Glacier caused slide near Pylon Peak, British Columbia. *Canadian Journal of Earth Sciences*, 15, 1039–1052.

Moon, A.T., Wilson, R.A., and Flentje, P.N., 2005. Developing and using landslide frequency models. *Proceedings of the International Conference on Landslide Risk Management*, Vancouver, BC, 681–690.

Nesbitt-Porter, H.H., 1985. Pemberton Valley flood protection 1985 study. Unpublished report for Province of British Columbia, Ministry of Environment, Water Management Branch, Victoria, BC.

Pierson, T.C. and Scott, K.M., 1985. Downstream dilution of a debris flow: transition from debris flow to hyperconcentrated stream flow. *Water Resources Research*, 21, 1511–1524.

Porter, M., Jakob, M., Savigny, K.W., Fougere, S., and Morgenstern, N., 2007. Risk management for urban flow slides in North Vancouver, Canada. *Proceedings of the 60th Canadian Geotechnical Conference*, Ottawa, ON.

Read, P.B., 1978. *Geology, Meager Creek geothermal area, British Columbia*. Geological Survey of Canada, Open File 603.

Read, P.B., 1990. Mount Meager complex, Garibaldi Belt, southwestern British Columbia. *Geoscience Canada*, 17, 167–170.

Siebert, L., 2002. Landslides resulting from the structural failure of volcanoes. *In*: S.G. Evans and J.V. DeGraff, eds. *Geological Society of America, Reviews in Engineering Geology*, 209–235.

Simpson, K.A., Stasiuk, M., Shimamura, K., Clague, J.J., and Friele, P.A., 2006. Evidence for catastrophic volcanic debris flows in Pemberton Valley, British Columbia. *Canadian Journal of Earth Sciences*, 43, 679–689.

Singleton-Urquhart, 2007. Client alert. Responsibility for naturally unstable lands. Communication from a Law Firm to client: Singleton – Urquhart legal Council LLP. Vancouver, BC.

Stasiuk, M.V., Russell, J.K., and Hickson, C.J., 1996. Distribution, nature, and origins of the 2400 BP eruption products of Mount Meager, British Columbia; linkages between magma chemistry and eruption behaviour. Geological Survey of Canada, Bulletin 486.

Stewart, M. 2002. *Dacite block and ash avalanche hazards in mountainous terrain: 2360 yr BP eruption of Mount Meager, British Columbia*. Thesis (MSc). University of British Columbia.

Suddle, S.I., 2003. A logarithmic approach for individual risk: the safety index. *In*: T. Bedford and P.H.J.A.M.

van Gelder, eds. *Safety and reliability*. Lisse: Swets & Zeuitlinger, 1527–1534.

Vallance, J.W. and Scott, K.M., 1997. The Osceola mudflow from Mount Rainier: sedimentology and hazard implications of a huge clay-rich debris flow. *Geological Society of America Bulletin*, 109, 143–163.

van der Kooij, M. and Lambert, A., 2002. Results of processing and analysis of large volumes of repeat-pass InSAR data of Vancouver and Mount Meager, B.C. *Proceedings of the International Geoscience and Remote Sensing Symposium*, Vol. 2. New York: Institute of Electrical and Electronics Engineers, 1228–1230.

Whitfield, P.H., Reynolds, C.J., and Cannon, A.J., 2002. Modeling streamflow in present and future climates: examples from the Georgia Basin, British Columbia. *Canadian Water Resources Journal*, 27, 427–456.

Whitfield, P.H., Wang, J.Y., and Cannon, A.J., 2003. Modeling future streamflow extremes – floods and low flows in Georgia Basin, British Columbia. *Canadian Water Resources Journal*, 28, 633–656.