

Evidence for catastrophic volcanic debris flows in Pemberton Valley, British Columbia

K.A. Simpson, M. Stasiuk, K. Shimamura, J.J. Clague, and P. Friele

Abstract: The Mount Meager volcanic complex in southern British Columbia is snow and ice covered and has steep glaciated and unstable slopes of hydrothermally altered volcanic deposits. Three large-volume ($>10^8$ m³) volcanic debris flow deposits derived from the Mount Meager volcanic complex have been identified. The volcanic debris flows travelled at least 30 km downstream from the volcanic complex and inundated now populated areas of Pemberton Valley. Clay content and mineralogy of the deposits indicate that the volcanic debris flows were clay-rich (5%–7% clay in the matrix) and derived from hydrothermally altered volcanic material. The youngest volcanic debris flow deposit is interpreted to be associated with the last known volcanic eruption, ~2360 calendar (cal) years BP. The other two debris flows may not have been directly associated with eruptions. Volcanic debris flow hazard inundation maps have been produced using the Geographic Information System (GIS)-based modelling program, LAHARZ. The maps provide estimates of the areas that would be inundated by future moderate to large-magnitude events. Given the available data, the probability of a volcanic debris flow reaching populated areas in Pemberton Valley is ~1 in 2400 years. Additional mapping in the source regions is necessary to determine if sufficient material remains on the volcanic edifice to generate future large-magnitude, clay-rich volcanic debris flows.

Résumé : Le complexe volcanique du mont Meager dans le sud de la Colombie-Britannique est recouvert de neige et de glace; ses pentes, abruptes, glacées et instables, sont recouvertes de dépôts volcaniques, qui ont subi une altération hydrothermale. Trois importants dépôts ($>10^8$ m³) de coulées de débris volcaniques provenant du complexe volcanique du mont Meager ont été identifiés. Les coulées de débris volcaniques ont voyagé au moins 30 km en aval du complexe volcanique et ont recouvert des secteurs maintenant habités de la vallée de Pemberton. La teneur en argile et la minéralogie des dépôts indiquent que les coulées de débris volcaniques étaient riches en argile (5 à 7 % argile dans la matrice) et provenaient de matériel volcanique ayant subi une altération hydrothermale. Les plus jeunes coulées de débris volcaniques seraient associées à la dernière éruption volcanique connue, ~2360 années avant le présent. Les deux autres coulées de débris ne sont peut-être pas associées directement avec des éruptions. Des cartes de risque de recouvrement par des coulées de débris volcaniques ont été produites en utilisant le programme de modélisation LAHARZ, lequel est basé sur un système d'information géographique. Les cartes estiment les secteurs qui seraient recouverts par des événements futurs de dimensions modérées à grandes. En se basant sur les données disponibles, la probabilité qu'une coulée de débris volcaniques atteigne les secteurs peuplés de la vallée de Pemberton est d'environ une fois dans 2400 ans. Il faudra de la cartographie supplémentaire dans les régions sources pour déterminer s'il reste suffisamment de matériel sur l'édifice volcanique pour générer, dans l'avenir, de grandes coulées de débris volcaniques riches en argile.

[Traduit par la Rédaction]

Introduction

Volcanic debris flows are a well documented and significant volcanic hazard. They can travel tens of kilometres from their source and have been responsible for great loss of life and property (e.g., 1985 eruption of Nevado del Ruiz, Colombia with more than 22 000 fatalities; Herd et al. 1986). A Canadian volcano where this hazard exists is the Mount Meager volcanic complex (MMVC), a snow- and ice-capped Quaternary volcano at the head of Pemberton Valley in the

Coast Mountains of southwestern British Columbia (Figs. 1, 2). It is characterized by steep, unstable, glaciated slopes dominated by poorly consolidated, highly fractured and, locally, hydrothermally altered volcanic deposits. These characteristics, in addition to its location in a region of high precipitation, make the MMVC prone to syn- and non-eruptive volcanic debris flows.

All streams flowing off the MMVC drain into Lillooet River (Figs. 3, 4), which occupies the Pemberton Valley. Areas on the immediate flanks of the MMVC are uninhabited,

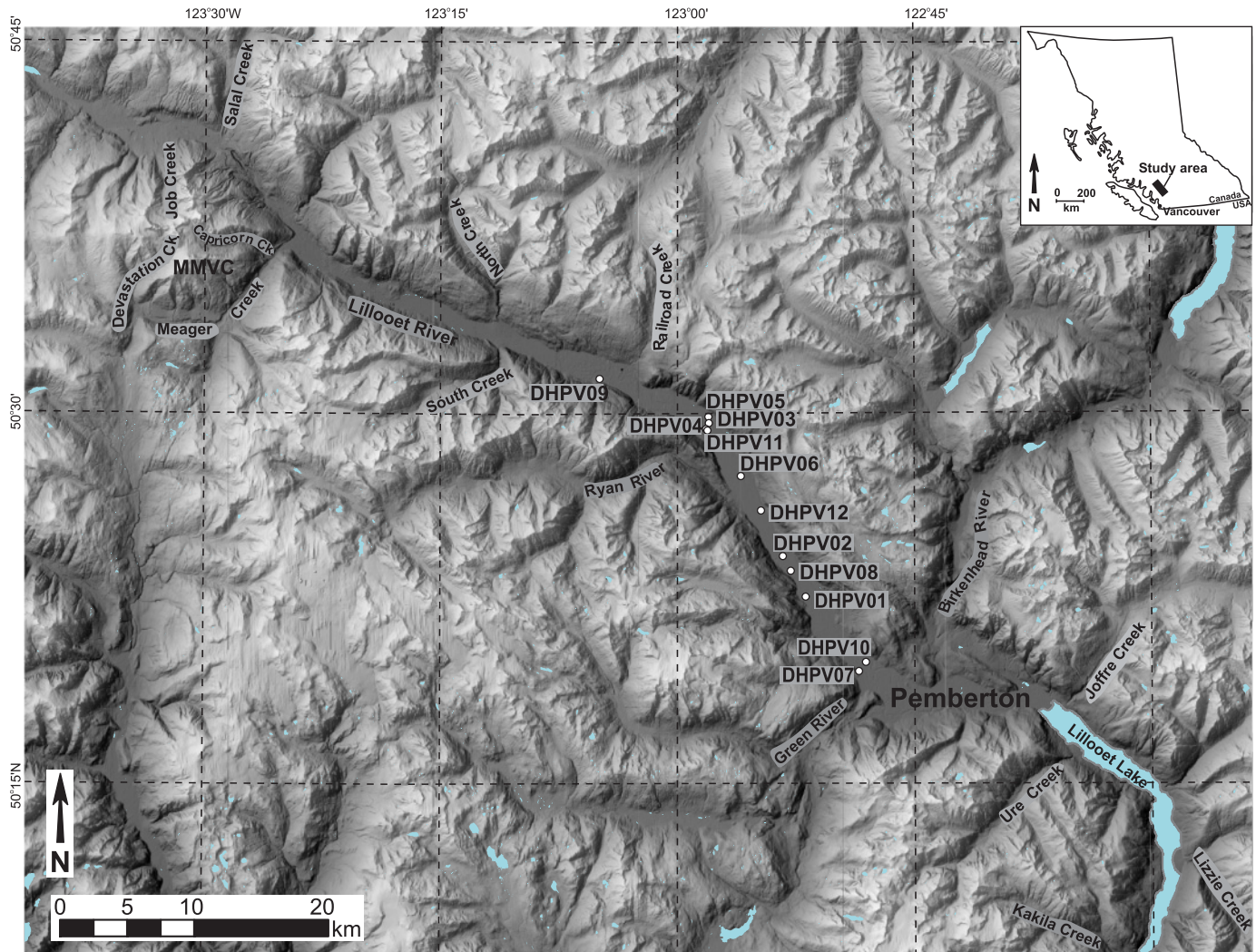
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Fig. 1. Map of study area showing the location of drill holes in relation to the Mount Meager volcanic complex (modified after Friele et al. 2005).



but the town of Pemberton is ~60 km downstream and farms are located within 30 km of the volcano. In addition, upstream areas closer to the volcano are used for forestry, mining, geothermal exploration, and recreation.

Previous studies at the MMVC have documented proximal landslide deposits (Friele and Clague 2004), small debris flows (e.g., Evans 1987; Jordan 1987; McNeely and McCuaig 1991; Jordan 1994; Bovis and Jakob 2000), and deposits of an outburst flood (Stasiuk et al. 1994). Downstream distal facies, however, have not been identified. Recent drilling in Pemberton Valley has provided information on the valley's sedimentary facies architecture, as well as distal eruptive products and evidence for other catastrophic events. Friele et al. (2005) present a facies architecture model of the valley fill, and estimate floodplain aggradation and delta-front progradation rates.

This paper documents and interprets three widespread and voluminous volcanic debris flow deposits that were identified during the drilling program. Debris flow source areas and triggering mechanisms are discussed, as is the potential hazard of future volcanic debris flows to Pemberton Valley.

Terminology

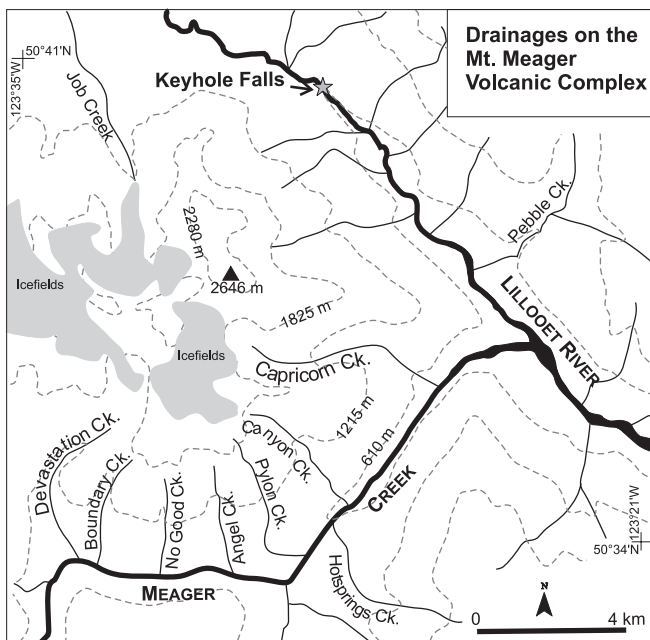
The term debris flow is used here to describe a flowing mixture of water and sediment with sediment concentrations >60% by volume or >80% by weight (Vallance and Scott 1997). We preface the term debris flow with "volcanic" to indicate that the debris flow is directly associated with a volcano and that the dominant clastic component is volcanic in origin. The term "lahar" is avoided owing to inconsistencies in its use in the literature.

Volcanic debris flows can be subdivided into two types based on clay content: (1) clay-rich volcanic debris flows, containing >3%–5% clay-size sediment, and (2) clay-poor volcanic debris flows, containing <3%–5% clay-size sediment (Scott 1988; Scott et al. 1995; Vallance and Scott 1997). Clay-poor debris flows commonly initiate as water floods and transform into debris flows by incorporating sediment (bulking) from the substrate. They can subsequently transform downstream to more dilute flows through dilution and debulking (Pierson and Scott 1985; Scott et al. 1995; Scott et al. 2001). Clay-poor debris flows can be generated by

Fig. 2. View to the west of the Mount Meager volcanic complex. Major peaks are labelled.



Fig. 3. Map of the Mount Meager volcanic complex area. Streams that drain the flanks of the volcano flow into Lillooet River. Lillooet River has a single channel above its confluence with Meager Creek, but is braided below (modified after Bovis and Jakob 2000).



eruption-induced meltwater surges, lake breakouts that entrain unconsolidated volcanoclastic detritus (Scott et al. 2001), eruptions through crater lakes, and intense rainfall. In contrast, clay-rich debris flows begin as water-saturated debris avalanches that rapidly transform into debris flows; they remain debris flows to their termini (Scott et al. 1995). Clay-rich debris flows typically form by collapse of water-saturated, hydrothermally altered volcanic deposits (Crandell 1971; Scott 1988; Vallance and Scott 1997; Scott et al. 2001). Both clay-rich and clay-poor volcanic debris flows can occur during eruptions or during periods without volcanic activity (e.g., seismogenically induced or rain-induced debris flows).

Geological setting

The MMVC is a potentially active volcano in the Garibaldi volcanic belt, which is the northern extension of the Cascade Range. The volcanoes of the Cascade Range and Garibaldi volcanic belt form the Cascade magmatic arc, and they are related to subduction of the Juan de Fuca plate beneath the North America plate.

The MMVC was erupted onto a mountainous, glaciated topography underlain by plutonic rocks of the Coast plutonic complex. The volcanic complex has been deeply eroded by glaciers and rivers, and, as a result, only the more resistant coherent units remain as peaks, spires, and ridge tops (Fig. 2). It consists of seven main volcanic assemblages: the Devastator, Pylon, Job, Capricorn, Plinth, Mosaic, and Pebble Creek formations (Read 1977, 1979; Hickson et al. 1999). Radiometric age determinations for deposits of the MMVC range from 2.2 million years to 2360 cal years BP (Read 1977, 1979; Evans 1992; Clague et al. 1995; Leonard 1995).

In general terms, the volcanic complex consists of mafic, intermediate, and felsic rocks, which includes lavas and domes and associated volcanoclastic rocks, and pyroclastic flow and fall deposits (Anderson 1975; Read 1977, 1979; Stasiuk and Russell 1989, 1990; Stasiuk et al. 1996; Hickson et al. 1999; Stewart et al. 2001, 2002). The local occurrence of finely, chaotically jointed coherent units, some of which are associated with monomictic volcanoclastic deposits, suggests that at least some eruptions took place beneath or in contact with ice. Eruptions in association with ice, as well as subsequent erosion by glaciers and mass wasting, may explain the limited extent and relatively small volume of volcanic deposits preserved at the MMVC.

Only the most recent eruption of the MMVC (2360 cal years BP; Clague et al. 1995; Leonard 1995) is well documented (Stasiuk et al. 1996; Stasiuk and Russell 1989, 1990; Hickson et al. 1999; Stewart et al. 2001, 2002). Activity consisted of both explosive and effusive eruptions of dacitic magma. Ash from the eruption travelled up to 530 km from the vent, which would be as far as present-day Alberta (Stevenson 1947; Nasmith et al. 1967; Westgate and Dreimanis 1967). Welded block-and-ash flow deposits blocked Lillooet River, creating a temporary lake upstream. Subsequent failure

Fig. 4. View to the southeast down Pemberton Valley from Mount Meager.



of the dam released the lake water as a catastrophic outburst flood.

Hydrothermal activity continues at the MMVC, with hot-springs located on the south side of the volcano in Meager Creek and on the east side in Lillooet River. There is a strong sulfur odour on the northern side of the complex, in the Job Creek area, but no hydrothermal vents have been found there to date. The MMVC shows no increased signs of activity at this time, but it is regarded as a potentially active volcano that will erupt again.

Sedimentary facies architecture of Pemberton Valley Holocene fill

Previous studies (Evans 1987; Jordan 1987; McNeely and McCuaig 1991; Jordan 1994; Bovis and Jakob 2000; Friele and Clague 2004) identified volcanic debris flow deposits proximal to the MMVC, but they did not document the downstream extent of the deposits. Twelve vertical holes were drilled in Pemberton Valley to reconstruct the sedimentary architecture of its Holocene fill, which comprises about 13 km³ of sediment (Friele et al. 2005), and to determine if large debris flows with sources on the MMVC had reached downstream (Fig. 1). Drilling rationale and methods were described by Friele et al. (2005). Five main sedimentary facies were identified and interpreted from drill core (Simpson et al. 2003; Friele et al. 2005): (1) channel facies, (2) overbank facies, (3) hyperconcentrated flow facies, (4) debris flow facies, and (5) alluvial fan facies.

The focus of this paper is three widespread, polymictic,

volcanic-clast dominated, unconsolidated breccia deposits that were intersected in drill core (Friele et al. 2005).

Deposit characteristics

Three distinct unconsolidated, volcanic-clast dominated, polymictic breccia deposits were intersected during drilling, referred to herein as the upper unit, middle unit, and lower unit. The upper unit was intersected in seven drill holes (DHPV03, DHPV04, DHPV05, DHPV06, DHPV09, DHPV11, DHPV12; Table 1; Fig.1) and ranges in thickness from 2.0 to 4.4 m (Table 1). The middle and lower units were intersected only in drill hole DHPV09 (Table 1; Fig. 1), which is the deepest and closest hole to the volcanic complex. The thickness of the middle unit could not be determined because of poor core recovery over the interval of intersection. The lower unit is 7.94 m thick in DHPV09.

All three units are grey, massive, polymictic, matrix-supported, very poorly sorted, and contain dominantly angular to subangular clasts. Clasts range from 0.5 to 11 cm across but most are <2 cm across. Lithology counts on sieved samples indicate that most clasts are volcanic lithologies (82%–95%). They are dominantly non-vesicular to poorly vesicular, variably coloured, and feldspar ± quartz ± biotite ± amphibole-phyric. Hydrothermally altered volcanic clasts and aphanitic, vesicular basalt clasts occur in the upper and lower units. Some altered volcanic clasts have completely degraded to clay-sized particles; their former clast boundaries are only distinguishable from the matrix because of their distinct pink, yellow, or orange colours. One sample (S041) from the upper unit in DHPV04 contains rounded, light grey–brown porphyritic pumice clasts

Table 1. Depth and thickness of volcanic debris deposits intercepted in drill holes.

Drill hole	Distance from MMVC (km)	Depth of hole (m) ^a	Unit	Depth of unit below surface (m)	Unit thickness (m)
DHPV03	42	24.4	upper	6.6–8.9	2.3
DHPV04	42	22.9	upper	7.9–11.1	3.2
DHPV05	42	11.0	upper	6.9–10.8	3.9
DHPV06	46	19.8	upper	8.9–11.1	2.2
DHPV11	42	33.3	upper	8.8–11.5	2.7
DHPV12	50	14.6	upper	8.7–13.0	4.3
DHPV09	34	38.7	upper	11.1–13.1	2.0
DHPV09	34	38.7	middle	22.9–23.5	>0.6 ^b
DHPV09	34	38.7	lower	28.4–36.3	7.9

Note: MMVC, Mount Meager volcanic complex.

^aCores did not intersect the entire unconsolidated Holocene fill sequence.

^bPoor core recovery; thickness is a minimum.

(28% of clasts) up to 1 cm across. Wood fragments are common within the deposits.

The matrix of the deposits is grey and consists of sand, silt, and clay. Clay content as a percent of the matrix ((clay/(sand + silt + clay))*100) in the upper unit ranges from 4.9% to 6.5%, except for sample S041, which has a clay content of 0.35% (Table 2). One sample from the middle unit has a clay content of 6.9% and the two samples from the lower unit have clay contents of 7.1% and 7.0%. The clay-size fraction of all three deposits consists of quartz, plagioclase, chlorite, illite, and smectite (Table 2).

The upper unit was intersected in drill holes along an ~18 km length of Pemberton Valley (Fig. 1) and at sites laterally across the valley. No lateral or downstream facies variations were observed in this unit. The middle and lower units were intersected in only one drill hole, thus any variability they might have remains unknown.

Bounding strata

Sediments encountered in Pemberton Valley drill holes are dominantly fluvial channel and overbank deposits consistent with deposition in a braided or meandering river system (Friele et al. 2005). Minor beds of peat were also intersected in the drill holes.

The upper unit is underlain by channel (DHPV09, DHPV05) and overbank (DHPV03, DHPV04, DHPV11, DHPV12; Friele et al. 2005) deposits. Sediments directly overlying the upper unit are atypical in that they contain <1%–100% light grey–brown, porphyritic pumice. The pumice-bearing strata range from poorly sorted, pebble to cobble gravel with rare rounded pumice clasts to well-sorted, clast-supported pebble and cobble gravel beds consisting entirely of rounded to angular pumice. The characteristics of sediments bounding the middle unit could not be determined because of poor core recovery. The lower unit is underlain and overlain by channel deposits, and lacks the distinctive pumiceous facies that overlies the upper unit.

Deposit interpretation

The three massive, volcanic-clast-dominated, polymictic breccia deposits are distinct from the fluvial deposits that dominate the Pemberton Valley fill. The distribution of the deposits, their internal structure (poorly sorted, matrix-supported,

and massive), angular clasts, and significant thickness are consistent with rapid deposition from debris flows. Furthermore, the volcanic clast-dominated assemblages and significant clay contents (>3%–5% of matrix) indicate that the upper, middle, and lower units were deposited from clay-rich volcanic debris flows.

The dominance of volcanic clasts constrains the source region to the MMVC, the only significant source of volcanic detritus upstream of the drill holes. The abundance of chlorite, illite, and smectite minerals in the clay-size fraction is consistent with formation under moderate-temperature (100–200 °C) hydrothermal alteration. This clay mineral assemblage suggests that the source area is dominated by hydrothermally altered volcanic rocks, which are abundant in the MMVC. The clay-rich volcanic debris flow deposits are thus interpreted to have been generated by collapse of hydrothermally altered volcanic deposits from the MMVC (cf. Crandell 1971; Scott 1988; Vallance and Scott 1997; Scott et al. 2001).

Bounding strata help to constrain the depositional environments of the debris flow deposits. The upper unit is underlain by both channel and overbank deposits and thus was not confined to the channel of Lillooet River. This inference is supported by the lateral distribution of drill-hole intercepts that show that the upper unit occurs across the full width of Pemberton Valley (DHPV03, DHPV04, DHPV05, DHPV11). Pumice in the sediments overlying the upper unit are compositionally and texturally similar to pumice derived from the explosive phase of the 2360 cal years BP eruption. We interpret the pumice to be resedimented airfall deposits of this eruption.

The upper, middle, and lower clay-rich volcanic debris flow deposits were intersected at distances between 32 and 50 km downstream of the MMVC and are interpreted to be distal facies. Evidence for equivalent proximal facies and temporal relations with respect to known volcanic activity at the MMVC is evaluated in the following sections.

Chronology

Nine samples of wood, peat, and charcoal (Table 3) from seven drill holes were radiocarbon dated. Dated samples are from the upper and lower debris flow deposits, and from peat layers below and above the upper debris flow deposit (Table 3). Ages of wood fragments and charcoal within the

Table 2. Granulometry and qualitative mineralogy of the <2 μm fraction of volcanic debris flow deposits.

Drill hole	Unit	Sample no.	Depth (m)	Weight % sand-silt-clay			Clay mineralogy				
				% sand (>63 μm)	% silt (63–4 μm)	% clay (<4 μm)	Qtz	Pl	Chl	Ill	Sm
DHPV03	upper	S030	7.0–7.2	65.7	28.8	5.5	m	A	m	m	A-m
DHPV03	upper	S031	7.8–8.0	65.9	28.7	5.4	m	A	m	m	A
DHPV03	upper	S033	8.6–8.9	66.4	28.6	4.9	m	A	m	m	A
DHPV04	upper	S041	8.1–8.3	95.9	3.8	0.3	—	—	—	—	—
DHPV04	upper	S042	8.5–8.7	64.4	29.7	5.9	m	A	m	m	A-m
DHPV05	upper	S061	8.7–9.0	64.6	29.7	5.6	m	A	m	m	A-m
DHPV05	upper	S155	7.1–7.5	65.6	28.6	5.8	m	A	m	m	A
DHPV05	upper	S156	8.4	61.8	32.4	5.8	—	—	—	—	—
DHPV05	upper	S157	10.3–10.6	65.9	28.2	5.8	m	A	m	m	A
DHPV06	upper	S066	10.0–10.3	64.4	29.8	5.8	m	A	m	m-tr	A
DHPV06	upper	S159	10.7–11.1	64.4	29.5	6.1	m	A	m	m	A
DHPV09	middle	S092	22.9–23.1	67.7	25.4	6.9	m	A	m	m	A-m
DHPV09	lower	S096	28.5–29.3	61.4	31.4	7.1	m	A	m	m	A
DHPV09	lower	S100	31.0–32.0	62.4	30.5	7.0	m	A	m	m	A
DHPV12	upper	S143	10.8–11.2	63.7	29.8	6.5	m	A	m	m-tr	A
DHPV12	upper	S151	12.9–13.0	65.5	29.0	5.5	m	A	m	m	A

Note: Qtz, quartz; Pl, plagioclase; Chl, chlorite; Ill, illite; Sm, smectite. Mineralogy determined by X-ray diffraction analysis using JADE® software. A, abundant; m, minor; tr, trace.

upper volcanic debris flow deposit range from 2570 ± 40 to 3970 ± 40 ^{14}C years BP (Table 3). The 3970 ± 40 ^{14}C years BP age is anomalously old and may represent incorporation of significantly older wood into the debris flow. Detrital wood can be older than the deposits in which it occurs; therefore, these ages are maxima for the true age of the upper volcanic debris flow deposit. The middle volcanic debris flow deposit was not dated but an age of between 4304 and 4530 cal years BP was inferred using the long-term, average aggradation rate of 4.4 ± 1.3 mm a^{-1} (Friele et al. 2005). Two radiocarbon ages on samples of detrital wood collected from the lower volcanic debris flow unit are 6250 ± 30 and 6370 ± 35 ^{14}C years BP (Table 3).

Proximal facies

Proximal volcanic debris flow deposits have been identified in Meager Creek (McNeely and McCuaig 1991; Friele and Clague 2004) and in the upper Lillooet River valley above Keyhole Falls (Evans 1992; this paper). Distinctive proximal outburst flood deposits have also been identified in Lillooet River valley (Stasiuk et al. 1994). They are interpreted to have been formed catastrophic failure of a welded block-and-ash flow deposit that temporarily dammed Lillooet River during the 2360 cal years BP eruptive cycle.

Proximal volcanic debris flow deposits upstream of Keyhole Falls resemble the volcanic debris flow deposits identified in drill core; they have similar textures, similar clay abundance (6.4%), and the same clay mineralogy (illite, smectite, chlorite, quartz, and plagioclase). One of the proximal volcanic debris flow deposits above Keyhole Falls has yielded a radiocarbon age of 2650 ± 60 ^{14}C years BP (GSC-6696), which overlaps the age of the upper distal debris flow deposit intersected in drill core.

Source regions and triggering mechanisms

The three volcanic debris flow deposits are dominated by volcanic lithologies and contain illite, smectite, and chlorite, which is consistent with a hydrothermally altered, volcanic source region. Possible sources on the MMVC include the Devastation Creek, Angel Creek, and Job Creek basins (Fig. 3).

Upper unit

The upper volcanic debris flow deposit is probably derived from Job Creek basin, based on clay mineralogy and the similarity in the age of the deposit to that of proximal facies above Keyhole Falls. Radiocarbon ages on the upper volcanic debris flow deposit (Table 3) also overlap the age of the last eruption of the MMVC (2360 cal years BP; Clague et al. 1995). The widespread and abundant pumice deposits above the upper debris flow deposit record syn-eruptively resedimented pyroclastic deposits of the initial plinian phase of the 2360 cal years BP eruption cycle. The absence of a significant sedimentary break between the upper debris flow deposit and the pumice unit supports a close temporal relation between these deposits. We, therefore, infer that the debris flow triggering mechanism was syn-volcanic and that the upper clay-rich volcanic debris flow was generated prior to the main explosive event. Potential triggering mechanisms include (1) volcanic seismicity, (2) over-saturation of hydrothermally altered volcanic deposits owing 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.

Middle unit

Friele and Clague (2004) identified a proximal landslide deposit derived from Angel Creek basin that they tentatively correlated with the middle volcanic debris flow described in

Table 3. Radiocarbon ages from drill core samples.

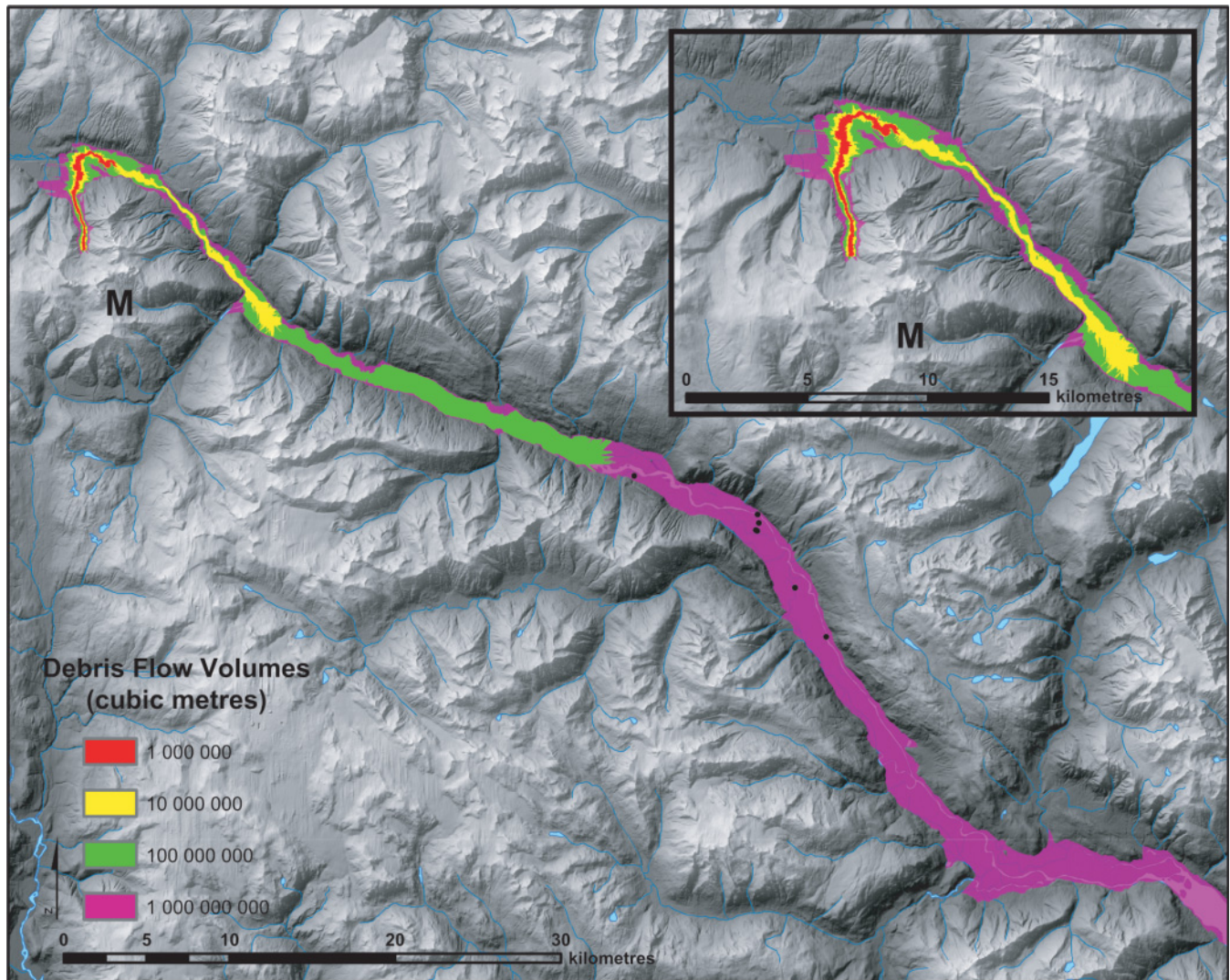
Drill hole	Laboratory no. ^a	Depth (m)	Stratigraphic position	Sample description	Technique ^b	Radiocarbon age (¹⁴ C years BP) ^c	Calendric age range (cal years BP) ^c
DHPV05	Beta-166052	5.43–5.45	Above upper unit	Interlaminated peat and silt ~1.39 m above upper volcanic debris flow deposit	CONV	1780±60	1540–1830
DHPV06	Beta-166166	8.84–8.86	Directly overlying upper unit	Fibrous mat of plant matter within coarse silt directly overlying upper volcanic debris flow deposit	AMS	2480±40	2360–2720
DHPV05	Beta-166059	6.84–6.85	upper unit	Charcoal within upper volcanic debris flow deposit	AMS	2570±40	2480–2650, 2700–2770
DHPV03	Beta-166057	7.92	upper unit	Wood fragment from within upper volcanic debris flow deposit	AMS	2690±50	2740–2880
DHPV12	GSC-6648	11.08	upper unit	Wood fragment from within upper volcanic debris flow deposit	CONV	2720±80	2750–2880
DHPV11	GSC-6647	16.16–16.20	Below upper unit	Interbedded silt and peat 4.67 m below the base of the upper volcanic debris flow deposit	CONV	2950±50	2990–3210
DHPV04	Beta-166058	10.39	upper unit	Wood fragment from within upper volcanic debris flow deposit	AMS	3970±40	4280–4530
DHPV09	OS-36556	31.00–32.00	lower unit	Wood fragment from within lower volcanic debris flow deposit	AMS	6250±30	7020–7130, 7150–7220
DHPV09	OS-36552	29.15–29.25	lower unit	Wood fragment from within lower volcanic debris flow deposit	AMS	6370±35	7200–7330, 7350–7380

^aLaboratories: Beta, Beta Analytic Inc, Miami, Florida; GSC, Geological Survey of Canada, Radiocarbon Laboratory, Ottawa, Ontario; OS, National Ocean Sciences Accelerator Mass Spectrometer Facility, Woods Hole Oceanographic Institute, USA.

^bAMS, accelerator mass spectrometry; CONV, conventional radiocarbon dating (β decay).

^cReference datum is A.D. 1950. Calibrated age ranges determined from the decadal data of Stuiver et al. (1998) using the probability distribution method within the program CALIB 4.4 (Stuiver and Reimer 1993). Ranges are $\pm 2\sigma$ calculated with an error multiplier of 1.0.

Fig. 5. Hazard inundation zones for a volcanic debris flow from the Job Creek basin. Black dots indicate the drill holes that intersected the upper debris flow deposit. Inset map shows details of the proximal inundation zones. M, Mount Meager volcanic complex.



this paper. The clay mineralogy of the middle debris flow unit is consistent with the clay mineralogy presented by Friele and Clague (2004). Furthermore, the middle debris flow unit has an inferred age of between 4304 and 4530 cal years BP, which is close to the 4400 cal years BP age of the proximal landslide deposit of Friele and Clague (2004). No eruptive deposits of this age have been identified, therefore the middle volcanic debris flow may have been triggered by a non-volcanic process.

Lower unit

No proximal volcanic debris flow deposits have been identified that can be correlated with the lower volcanic debris flow deposit; therefore, the source of the lower unit is unknown. Additionally, no eruptive deposits of similar age are known, therefore the lower unit was either not associated with an eruption or its eruptive deposits have yet to be identified.

Debris flow inundation zones

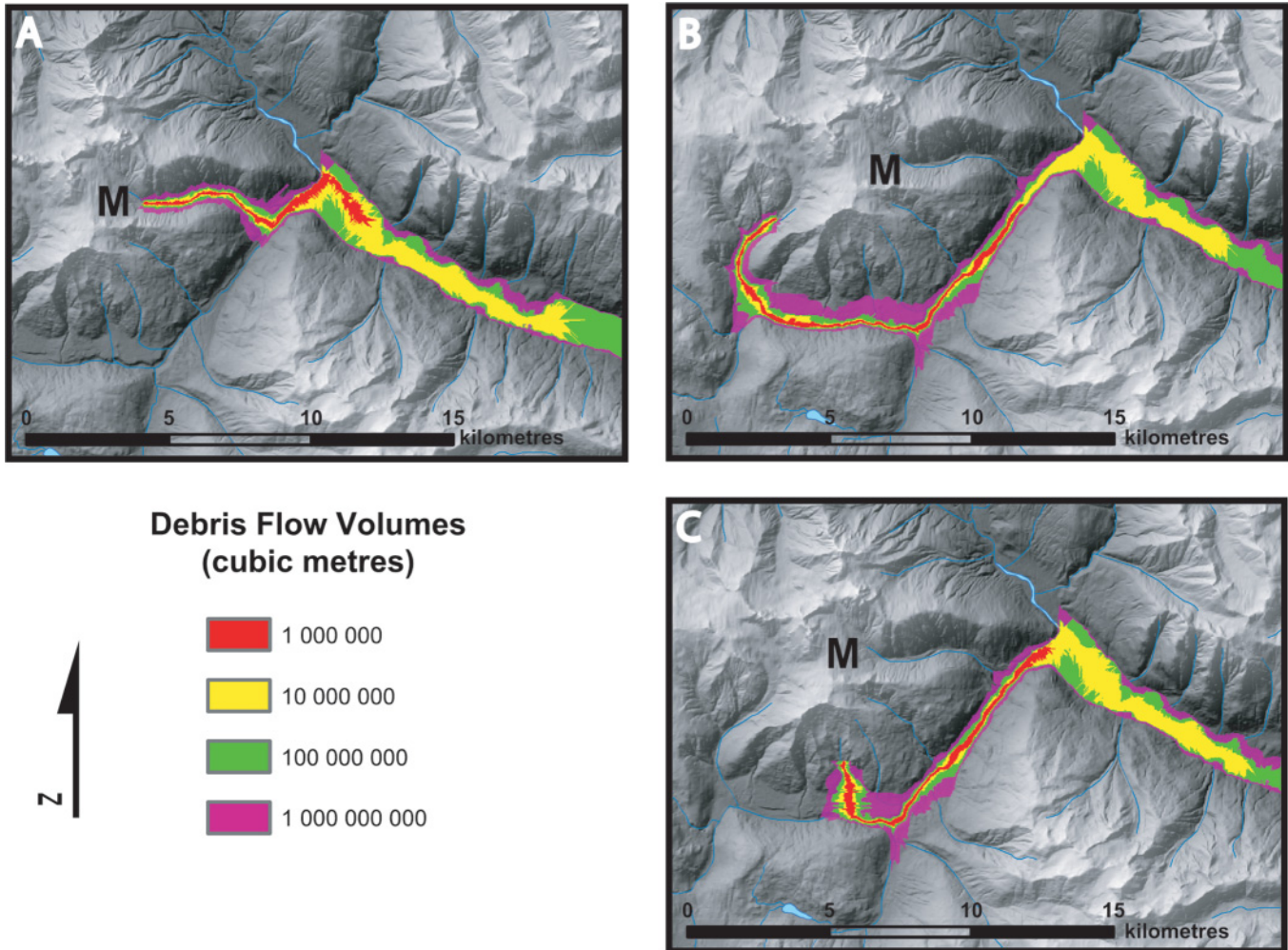
The GIS-based semiempirical modelling software LAHARZ

(Iverson et al. 1998; Schilling 1998) was used to estimate potential areas of debris flow inundation downstream from the MMVC. This software predicts the valley cross-sectional area and the planimetric area inundated by lahars for given volumes. The LAHARZ model was calibrated using 27 lahar paths from nine volcanoes (Iverson et al. 1998). The automated mapping process provides a rapid, reproducible, effective tool for forecasting aerial limits of lahar inundation, and it has been used at volcanoes in the United States, Mexico, and Central and South America (e.g., Iverson et al. 1998; Major et al. 2003; Vallance et al. 2001).

Nested inundation zones were determined for debris flows with initial volumes ranging from 10^6 to 10^9 m³ and originating from Job, Capricorn, Devastation, and Angel creek basins (Figs. 5, 6). For all basins, debris flows with volumes $>10^8$ m³ inundated populated areas of Pemberton Valley. At volumes of 10^9 m³, debris flows reached Lillooet Lake, where the model was stopped.

Although the topography today is not the same as 2500 years ago, the volume of the upper debris flow unit can be estimated from the inundation model (Fig. 5), and the

Fig. 6. Proximal hazard inundation zones for volcanic debris flows derived from the (A) Capricorn Creek (B) Devastation Creek and (C) Angel Creek basins. Distal inundation zones are similar to those shown in Fig. 5 for Job Creek basin. M, Mount Meager volcanic complex.



deposit's inferred distribution based on drill hole data. The estimated volume is 10^8 – 10^9 m³. The semicircular scarp that defines the head of Job Creek basin is interpreted to be the limit of a major flank collapse that generated the upper debris flow deposit. Rough volume calculations of the material that might have failed in the basin are consistent with the modelled 10^8 – 10^9 m³ volume estimate for the upper debris flow deposit.

Factors such as debris flow triggering mechanisms, material properties, flow paths, and volumes may affect the specific inundation patterns and extents of future debris flows. However, the modelling results, drilling results, and the presence of hydrothermally altered material on the edifice suggest that future large-magnitude debris flows could reach inhabited areas in Pemberton Valley.

Hazard implications

Volcanic debris flows are a common hazard at volcanoes with steep unstable slopes, especially those that are snow and ice capped and located in areas of high precipitation. Some of the best-studied volcanic debris flow deposits are

those associated with volcanoes in the Cascade Range (Mt. Baker, Mt. Rainier, and Mt. St. Helens). The deposits of the 5600 years BP Osceola Mudflow at Mt. Rainier have been mapped at distances in excess of 120 km from the volcano and have a volume of 3.8×10^9 m³ (Crandell 1971; Vallance and Scott 1997). Future debris flows from Mt. Rainier pose a significant hazard to several hundred thousand people who live in areas that have been inundated by volcanic debris flows in the past. The United States Geological Survey is conducting a comprehensive campaign to educate people who live and work in the areas at risk, and a debris flow warning system has been installed to provide advance warning.

Although the MMVC is located in a semi-wilderness area of British Columbia, the hazard from future volcanic debris flows is significant. The closest town, Pemberton, has a population of about 1600 people. It experienced a 91% growth in population between 1996 and 2001, making it one of the fastest growing communities in Canada (Statistics Canada 2001). Hotsprings in Meager Creek valley attract thousands of visitors annually, and hikers and climbers use the area for recreation. There are also two pumice mines, active logging operations, and geothermal power exploration activities around

the MMVC. Presently, most of Pemberton Valley is protected under the Agricultural Land Reserve, thus blocking urban growth of Pemberton from spreading toward the MMVC.

Historically, landslides 10^5 – 10^7 m³ in size have occurred at the MMVC without associated volcanic activity approximately every 10 years, making it one of the most geomorphically active areas in the Canadian Cordillera (Carter 1932; Mokievsky-Zubok 1977; Croft 1983; Evans 1984, 1987; Jordan and Slaymaker 1991; Jakob 1996; Bovis and Jakob 2000). The steep mountainous topography, coupled with a wet climate and large volumes of unconsolidated, altered volcanic deposits, are responsible for the significant landslide activity and hazard. In 1975, a landslide (27 – 30×10^6 m³) derived from the Devastation basin killed four geologists at the confluence of Devastation and Meager creeks (Mokievsky-Zubok 1977). In 1998, a debris flow (1.2×10^6 m³) from the Capricorn basin destroyed part of a logging road and impounded Meager Creek, creating a landslide-dammed lake (Bovis and Jakob 2000). The MMVC landslides have had significant local economic impact and have increased the sediment load to Lillooet River, with far-reaching downstream effects (e.g., aggradation of the river channel, with an attendant increase in overbank flows).

The results of this and previous studies (McNeely and McCuaig 1991; Jordan 1994; Friele and Clague 2004) show that prehistoric landslides included large-magnitude events (10^8 – 10^9 m³) without historical precedent. Large-magnitude debris flows inundated now-populated areas of the Pemberton valley at least three times in the past 7300 years. Based on the available data, the probability of such an event is ~1 in 2400 years.

Large-magnitude, clay-rich volcanic debris flows from the MMVC may be associated with volcanic activity, in which case sufficient warning of such an event is possible. However, at this time only one of the large-magnitude, clay-rich volcanic debris flows can be confidently correlated with an eruption. It must be assumed that volcanic debris flows from the MMVC can occur without associated volcanic activity and there may be little to no advanced warning of such an event. If people living or working in debris flow hazard zones are informed of the hazard, they may choose to move to higher ground when conditions favour the generation of a debris flow (i.e., after a felt earthquake). This reasoning is the premise of Education for Self Warning and Evacuation, as described by Scott et al. (1995) and Scott and Driedger (1998) for the Mt. Rainier area.

If the middle and lower clay-rich volcanic debris flows were caused by volcanic activity that has not yet been identified, the eruption frequency of the MMVC is significantly greater than presently thought. It is important that further work be undertaken to establish if unrecognized volcanic events have occurred at the MMVC and, if so, whether they can be correlated with the middle and lower volcanic debris flow deposits.

Conclusions

Deposits of three, large-magnitude ($>10^8$ m³), clay-rich volcanic debris flows have been identified in drill core from Pemberton Valley. Clay contents (4.9%–7.1%) and clay mineralogy (chlorite, illite, and smectite) indicate that the debris

flows were generated by collapse of hydrothermally altered parts of the volcanic edifice. Each debris flow travelled more than 30 km downstream and inundated now-populated areas of Pemberton Valley to depths of up to 8 m. Inundation may have been valley-wide, based on the sedimentary facies architecture of the valley-fill deposits. Run-out modelling indicates that debris flows with initial volumes $>10^8$ m³ would inundate populated areas of Pemberton Valley. With available data, the probability of such an event is ~1 in 2400 years. More mapping is necessary to identify unstable parts of the edifice and to determine if sufficient material remains on the volcanic edifice to generate future large-magnitude volcanic debris flows.

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References

- Anderson, R.G. 1975. The geology of the volcanics in the Meager Creek map-area, Southwestern British Columbia. B.Sc. thesis, The University of British Columbia, Vancouver, B.C.
- Bovis, M.J., and Jakob, M. 2000. The July 29, 1988, debris flow and landslide dam at Capricorn Creek, Mount Meager volcanic complex, Southern Coast Mountains, 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.
- Clague, J.J., Evans, S.G., Rampton, V.N., and Woodsworth, G.J. 1995. Improved age estimates for White River and Bridge River tephra, Western Canada. *Canadian Journal of Earth Sciences*, **32**: 1172–1179.
- Crandell, D.R. 1971. Postglacial lahars from Mount Rainier volcano, Washington. US Geological Survey, Professional Paper 677.
- Croft, S.A.S. 1983. Stability assessment of the Capricorn Creek valley, British Columbia. B.Sc. thesis, The University of British Columbia, Vancouver, B.C.
- Evans, S.G. 1984. The landslide response of tectonic assemblages in the southern Canadian Cordillera. In *Proceedings of the IV International Symposium on Landslides*, Toronto, Ont., 16–21 September 1984, Vol.1. pp. 495–503.
- Evans, S.G. 1987. A rock avalanche from the peak of Mount Meager, British Columbia. In *Current research, part A*. Geological Survey of Canada, Paper 87-1A. pp. 929–934.
- Evans, S.G. 1992. Landslide and river damming events associated with the Plinth Peak volcanic eruption, southwestern British Columbia. In *Proceedings of the 1st Canadian Symposium on Geotechnical and Natural Hazards*, Vancouver, B.C. BiTech Publishing, Vancouver, B.C., pp. 405–412.

- Friele, P.A., and Clague, J.J. 2004. Large prehistoric landslides from Pylon Peak, Meager Creek volcanic complex, southwestern British Columbia. *Canadian Journal of Earth Sciences*, **41**: 165–182.
- 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.
- Herd, D.G., and the Comité de Estudios Vulcanológicos. 1986. The 1985 Ruiz volcano disaster. EOS, *Transactions of the American Geophysical Union*, **67**: 457–460.
- Hickson, C.J., Russell, J.K., and Stasiuk, M.V. 1999. Volcanology of the 2350 B.P. eruption of Mount Meager volcanic complex, British Columbia, Canada: implications for hazards from eruptions in topographically complex terrain. *Bulletin of Volcanology*, **60**: 489–507.
- Iverson, R.M., Schilling, S.P., and Vallance, J.W. 1998. Objective delineation of lahar-inundation hazard zones. *Geological Society of America Bulletin*, **110**: 972–984.
- Jakob, M. 1996. Morphometric and geotechnical controls of debris flow frequency and magnitude. Ph.D. thesis, University of British Columbia, Vancouver, B.C.
- Jordan, P. 1987. Impacts of mass movement events on rivers in the southern Coast Mountains, British Columbia: summary report. Environment Canada, Inland Waters Directorate, Sediment Survey IWD-HQ-WRB-SS-87-3.
- Jordan, P. 1994. Debris flows in the southern Coast Mountains, British Columbia: dynamic behavior and physical properties. Ph.D. thesis, University of British Columbia, Vancouver, B.C.
- 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.
- Leonard, E.M. 1995. A varve-based calibration of the Bridge River tephra fall. *Canadian Journal of Earth Sciences*, **32**: 2098–2102.
- Major, J.J., Schilling, S.P., and Pullinger, C.R. 2003. Volcanic debris flows in developing countries—the extreme need for public education and awareness of debris-flow hazards. *In Debris-flow hazards mitigation: mechanics, prediction, and assessment. Edited by D. Rickenmann and C. Chen. Millpress, Rotterdam, The Netherlands*, pp. 1185–1196.
- McNeely, R., and McCuaig, S. 1991. Geological Survey of Canada radiocarbon dates XXIX. Geological Survey of Canada, Paper 89-7, 134 p.
- Mokievsky-Zubok, O. 1977. Glacier caused slide near Pylon Peak, British Columbia. *Canadian Journal of Earth Sciences*, **15**: 2657–2662.
- Nasmith, H., Mathews, W.H., and Rouse, G.E. 1967. Bridge River Ash and some other recent ash beds in British Columbia. *Canadian Journal of Earth Sciences*, **4**: 163–170.
- Pierson, T.C., and Scott, K.M. 1985. Downstream dilution of a lahar: transition from debris flow to hyperconcentrated streamflow. *Water Resources Research*, **21**: 1511–1524.
- Read, P.B. 1977. Meager Creek volcanic complex, southwestern British Columbia. *In Report of activities, part A. Geological Survey of Canada, Paper 77-1A*, pp. 277–281.
- Read, P.B. 1979. Geology of Meager Creek geothermal area, British Columbia. Geological Survey of Canada, Open File Report 603.
- Schilling, S.P. 1998. LAHARZ: GIS programs for automated delineation of lahar hazard zones. US Geological Survey, Open File Report 98-638.
- Scott, K.M. 1988. Origins, behavior, and sedimentology of lahars and lahar-runout flows in the Toutle-Cowlitz River system. US Geological Survey, Professional Paper 1447-A.
- Scott, K.M., and Driedger, C.L. 1998. Education for self warning and evacuation (ESWEV)—saving lives from catastrophic lahars and nonvolcanic debris flows. *In Proceedings of the International Meeting, Cities on Volcanoes. International Association of Volcanology and Chemistry of the Earth's Interior, Abstract with Programs*, p. 124.
- Scott, K.M., Vallance J.W., and Pringle P.T. 1995. Sedimentology, behavior, and hazards of debris flows at Mount Rainier, Washington. US Geological Survey, Professional Paper 1547.
- Scott, K.M., Macias, J.L., Naranjo, J.A., Rodriguez, S., and McGeehin, J.P. 2001. Catastrophic debris flows transformed from landslide in volcanic terrains: mobility, hazard assessment, and mitigation strategies. US Geological Survey, Professional Paper 1630.
- Simpson, K.A., Stasiuk, M.V., Clague, J.J., Evans, S.G., and Friele, P. 2003. Preliminary drilling results from the Pemberton Valley, British Columbia. Geological Survey of Canada, Current Research 2003-A5.
- Stasiuk, M.V., and Russell, J.K. 1989. Petrography and chemistry of the Meager Mountain volcanic complex, southwestern British Columbia. *In Current research, part E. Geological Survey of Canada, Paper 89-1E*, pp. 189–196.
- Stasiuk, M.V., and Russell, J.K. 1990. The Bridge River Assemblage in the Meager Mountain volcanic complex, Southwestern British Columbia. *In Current research, part E. Geological Survey of Canada, Paper 90-01E*, pp. 227–233.
- Stasiuk, M.V., Russell, J.K., and Hickson, C.J. 1994. Influence of magma chemistry on eruption behaviour from the distribution and nature of the 2400 BP eruption products of Mount Meager, British Columbia. Geological Survey of Canada, Open File Report 2843.
- 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.
- Stevenson, L.S. 1947. Pumice from Haylmore, Bridge River, British Columbia. *American Mineralogist*, **32**: 547–552.
- Stewart, M.L., Russell, J.K., and Hickson, C.J. 2001. Discrimination of hot versus cold avalanche deposits: implications for hazards assessment at Mount Meager, British Columbia. Geological Survey of Canada, Current Research 2001-A10.
- Stewart, M.L., Russell, J.K., and Hickson, C.J. 2002. Revised stratigraphy of the Pebble Creek Formation, British Columbia; evidence for interplay between volcanism and mountainous terrain. Geological Survey of Canada, Current Research 2002-E3.
- Stuiver, M., and Reimer, P.J. 1993. Extended ¹⁴C database and revised CALIB radiocarbon calibration program. *Radiocarbon*, **35**: 215–230.
- Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A. et al. 1998. INTCAL98 radiocarbon age calibration, 24 000 – 0 cal BP. *Radiocarbon*, **40**: 1041–1083.
- 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.
- Vallance, J.W., Schilling, S.P., and Devoli, G. 2001. Lahar hazard at Mombacho Volcano, Nicaragua. US Geological Survey, Open-File Report 01-455.
- Westgate, J.A., and Dreimanis, A. 1967. Volcanic ash layers of Recent age at Banff National Park, Alberta, Canada. *Canadian Journal of Earth Sciences*, **4**: 155–161.