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C. J. Hickson · J. K. Russell · M. V. Stasiuk

Volcanology of the 2350 B.P. Eruption of Mount Meager Volcanic Complex, British Columbia, Canada: implications for Hazards from Eruptions in Topographically Complex Terrain[1]

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Abstract The Pebble Creek Formation (previously known as the Bridge River Assemblage) comprises the eruptive products of a 2350 calendar year B.P. eruption of the Mount Meager volcanic complex and two rock avalanche deposits. Volcanic rocks of the Pebble Creek Formation are the youngest known volcanic rocks of this complex. They are dacitic in composition and contain phenocrysts of plagioclase, orthopyroxene, amphibole, biotite and minor oxides in a glassy groundmass. The eruption was episodic, and the formation comprises fallout pumice (Bridge River tephra), pyroclastic flows, lahars and a lava flow. It also includes a unique form of welded block and ash breccia derived from collapsing fronts of the lava flow. This Merapi-type breccia dammed the Lillooet River. Collapse of the dam triggered a flood that flowed down the Lillooet Valley. The flood had an estimated total volume of 10^9 m^3 and inundated the Lillooet Valley to a depth of at least 30 m above the paleo-valley floor 5.5 km downstream of the blockage. Rock avalanches comprising mainly blocks of Plinth Assemblage volcanic rocks (an older formation making up part of the Mount Meager volcanic complex) underlie and overlie the primary volcanic units of the Formation. Both rock avalanches are unrelated to the 2350 B.P. eruption, although the post-eruption avalanche may have its origins in the oversteepened slopes created by the explosive phase of the eruption. Much of the stratigraphic complexity evident in the Pebble Creek Formation results from deposition in a narrow, steep-sided mountain valley containing a major river.

Key words Mount Meager · Volcanic stratigraphy · Pyroclastic flow · Lahar · Avalanche · Petrography · Geochemistry

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C. J. Hickson (✉)
Geological Survey of Canada, #101–605 Robson Street, Vancouver, British Columbia, V6B 5J3
E-mail: chickson@gsc.nrcan.gc.ca, Fax: (604) 666-7507

J. K. Russell
Department of Geological Sciences, University of British Columbia, 6339 Stores Road, Vancouver, B. C. V6T 1Z4

M. V. Stasiuk
Department of Geology, University of Lancaster, Great Britain

Introduction

Overview and purpose

The Mount Meager complex is the site of the most recent major explosive volcanic activity in British Columbia (Hickson 1994). This activity produced a diverse sequence of volcanic deposits, well exposed in the bluffs along the Lillooet River (Fig. 1), that are herein defined as the Pebble Creek Formation. The primary volcanic deposits are dacitic in composition and include dissected remnants of fallout pumice, pyroclastic flows, welded breccias, flood deposits (lahars) and a lava flow. The eruption was so energetic that thin, very fine-grained, distal deposits of tephra have been identified in Alberta, 530 km from the vent (Nasmith et al. 1967; Westgate and Dreimanis 1967). An unusual, thick apron of welded vitrophyric breccia may represent the explosive collapse of an early lava dome or lava flow front (e.g., Francis et al. 1974; Bardintzeff 1984; Nakada 1993).

This paper describes the physical aspects of these deposits: their distribution, relationships, nature and hazards. We summarize and review pertinent field, petrographic and chemical data (Nasmith et al. 1967; Anderson 1975; Read 1977a, b; Stasiuk and Russell 1989, 1990; Evans 1992; Ke 1992; Stasiuk et al. 1996), reconstruct the sequence of events that produced these volcanic deposits, and explain several enigmatic, if not unique, pyroclastic deposits. This complex volcanic assemblage provides an excellent example of the hazards resulting from cyclic deposition of Merapi-type deposits

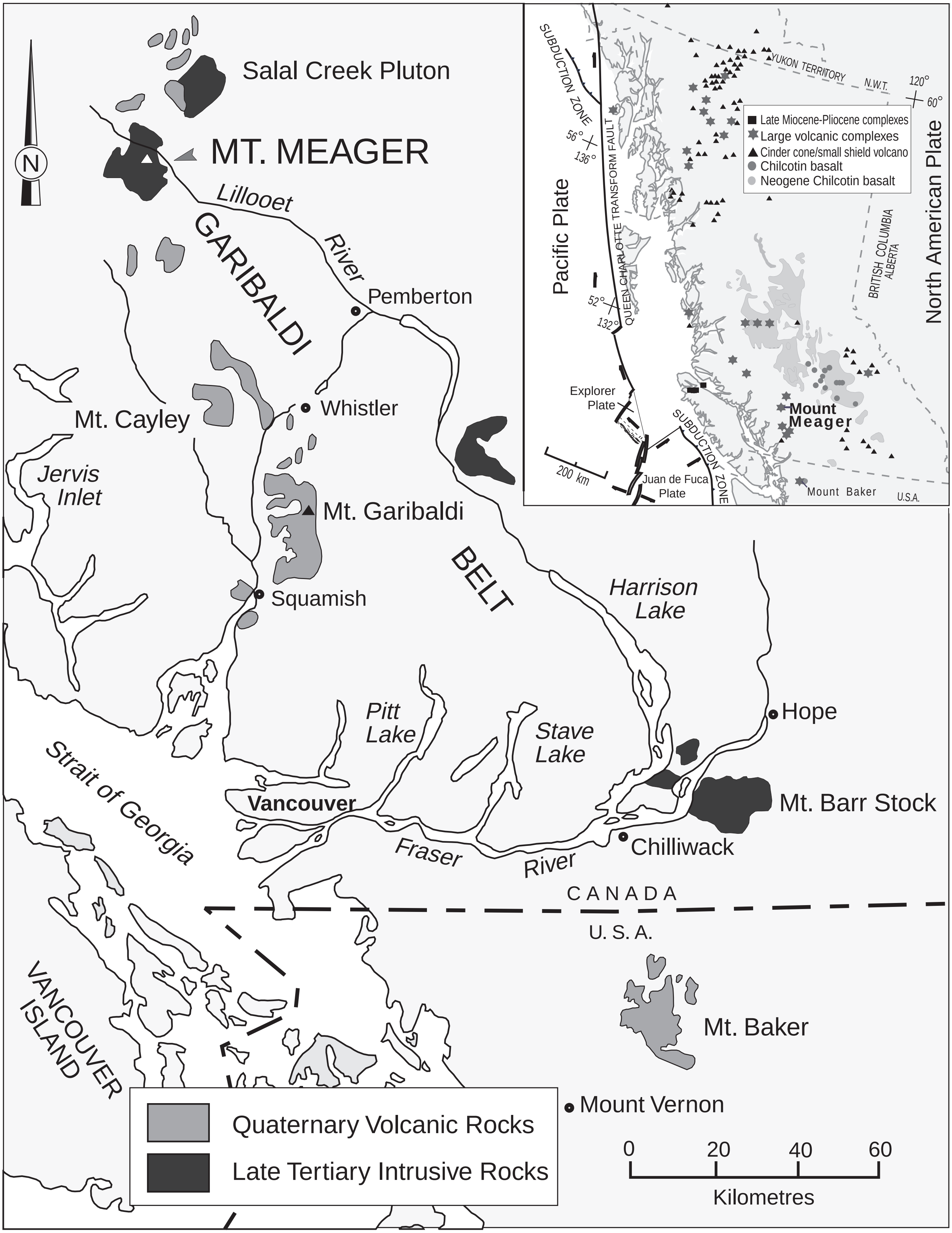

Fig. 1 Location of Mount Meager volcanic complex and the Garibaldi volcanic belt. Inset map shows Quaternary volcanoes in the Canadian Cordillera and adjacent areas of the United States (modified from Hickson 1994)

in rugged mountain valleys. Our work demonstrates that volcanic activity at Mount Meager blocked the Lillooet River, setting the stage for catastrophic failure of the upper part of the formation and resulted in an massive outburst flood.

Geological background

The Mount Meager complex is part of the Garibaldi volcanic belt (Fig. 1), the northernmost segment of the Cascade magmatic arc (Green et al. 1988; Guffanti and Weaver 1988; Read 1990; Sherrod and Smith 1990; Hickson 1994), which includes Mount Baker and Glacier Peak in Washington. Quaternary volcanism along the Cascade magmatic arc is related to subduction of the Juan de Fuca plate beneath North America (Fig. 1 inset; Green et al. 1988; Rohr et al. 1996).

The Mount Meager volcanic complex (2645 m asl) is 150 km north of Vancouver in the southern Coast Mountains, between the Lillooet River and Meager Creek (Fig. 2). The Quaternary volcanic complex overlies a basement of plutonic and metamorphic rocks. As originally mapped by Read (1977a, b), the Mount Meager volcanic complex includes peripheral coeval basaltic lava flows and pyroclastic deposits, central overlapping piles of andesite lava flows, dacite domes and flows, and pyroclastic units (Fig. 2). Read (1977a, b) subdivided the complex into a number of assemblages: the Devastator; Pylon; Job; Capricorn; Plinth; Mosaic; and the Bridge River Assemblage. Read (1977a, b) demonstrated that the most recent phase of volcanic activity was the eruption and deposition of the Bridge River Assemblage. The "Bridge River" designation was based on correlation with ash beds first described near Bridge River, British Columbia, and referred to as Bridge River tephra (e.g., Drysdale 1916; Stevenson 1947; Nasmith et al. 1967; Westgate and Dreimanis 1967). We have renamed this unit of postglacial volcanic deposits as the Pebble Creek Formation due to the prior usage of the term Bridge River Complex (Gabrielse and Yorath 1991) for Paleozoic rocks north of the volcanic complex.

Radiometric ages on volcanic rocks of the Mount Meager volcanic complex range from 2.2 Ma (K-Ar) to 2350 B.P. (radiocarbon) (Read 1977a, b; Evans 1992). The most recent dating by Clague et al. (1995) and Leonard (1995) indicates that the youngest eruption is about 2350 calendar years old. The vent for the most recent eruption is no longer exposed but was located by Read (1977a, b) on the amphitheatre-like northeastern shoulder of Plinth Peak at an elevation of about 1500 m, 1000 m above the floor of the Lillooet Valley (Fig. 3).

Petrographic characteristics

The vent of the 2350 B.P. eruption is in a col surrounded by steep cliffs comprising units of the Plinth

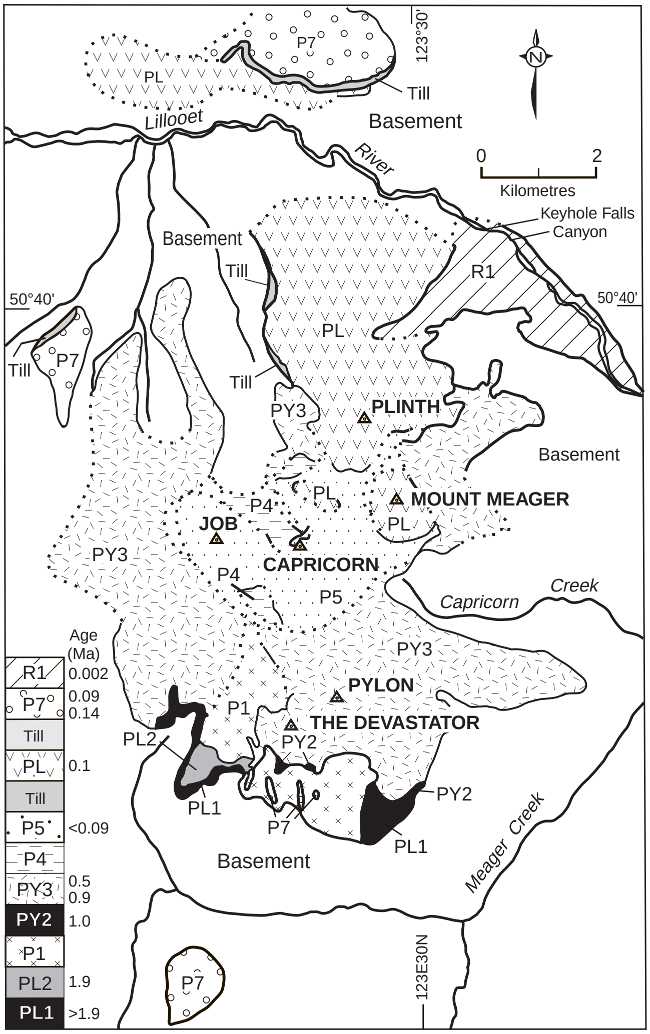

Fig. 2 Geological map showing the distribution and age of volcanic rocks of the Mount Meager volcanic complex (Read 1977b; modified from Read 1990): *PL1,* basal breccia; *PL2,* porphyritic dacite; *P1,* The Devastator Assemblage; *PY2* and *PY3,* Pylon Assemblage; *P4,* Job Assemblage; *P5,* Capricorn Assemblage; *PL,* Plinth Assemblage; *P7,* Mosaic Assemblage; *R1,* dacitic deposits of the Pebble Creek Formation

Assemblage (Plvd) (Fig. 2 unit PL; Fig. 3, unit Plvd; Read 1977a, b; Evans 1992). Although volcanic rocks of the Plinth and Pebble Creek Formations have a number of mineralogical and chemical similarities, they can be distinguished petrographically (Table 1). These petrologic differences are critical to sorting out the source and origin of some of the stratigraphic units.

In outcrop, rocks of the Plinth Assemblage are massive, dense, light to dark grey, and commonly red weathering. In thin section, the rocks are highly porphyritic; plagioclase dominates the phenocryst assemblage, but biotite and quartz are also abundant, and amphibole and clinopyroxene are also present. The groundmass is fine-grained, hyalocrystalline and microvesicular. Locally, the groundmass can be partly devitrified. The crystalline portion of the groundmass comprises crystals of plagioclase, amphibole, pyroxene and

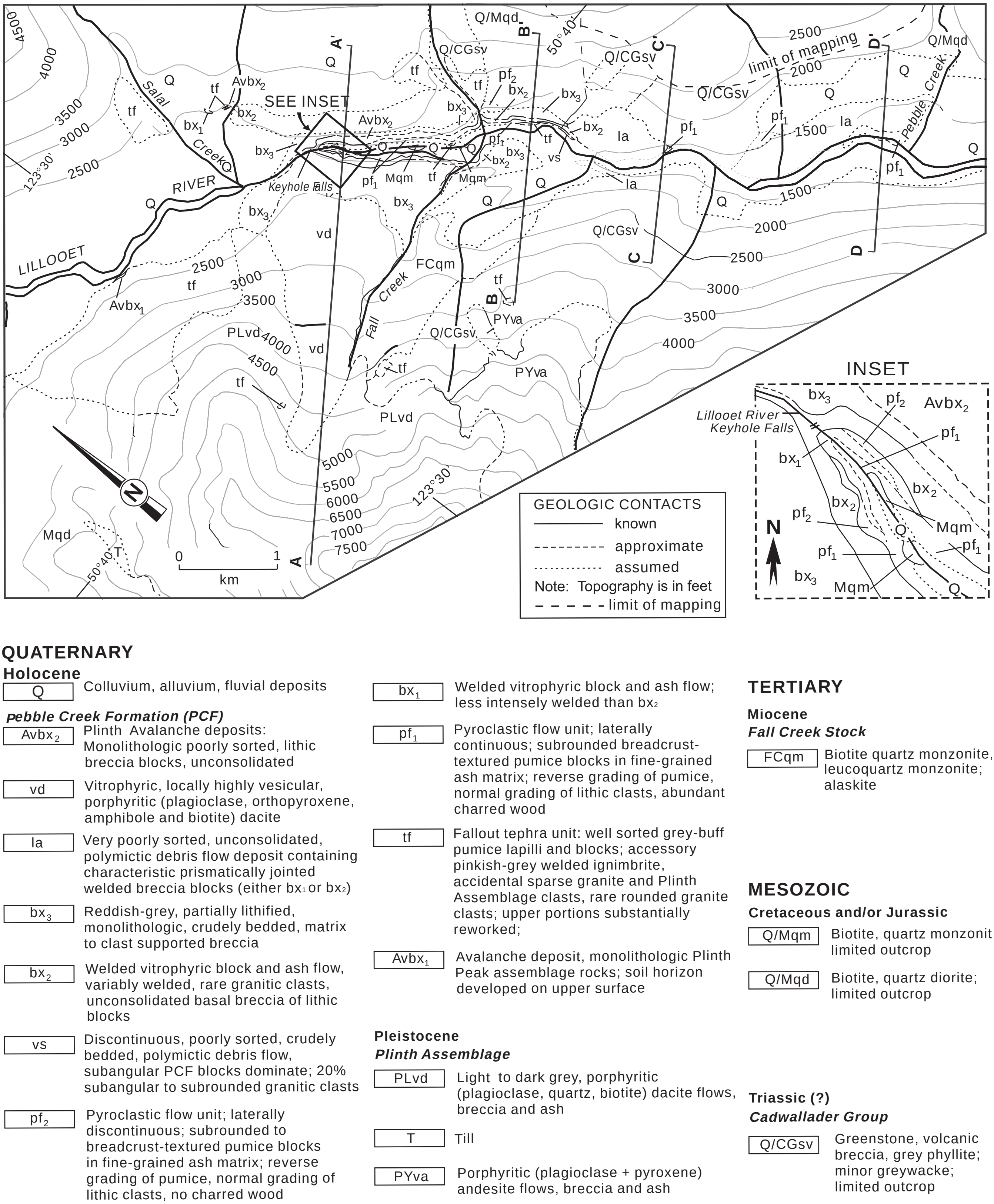

Fig. 3 Geological map showing areal distribution of Pebble Creek Formation including: a) fallout pumice deposits and reworked equivalents (unit *tf*), b) pyroclastic flow deposits (units $pf_{1\&2}$), c) "Merapi-type" welded block and ash deposit (units $bx_{1,2\&3}$), d) lava flow (unit *vd*), e) hot, jointed, block flood deposits (unit *la*), and f) Plinth-dominated rock avalanche deposits (units $Avbx_{p1\&2}$) (modified from Stasiuk et al. 1996 and Read 1977b). Locations of cross-sections shown in Fig. 7 are indicated. Contours in feet: 1 foot = 0.3048 m

Table 1 Petrographic characteristics of Pebble Creek and Plinth Formation rocks

Petrography	Plinth Formation – Dacite	Pebble Creek Formation – Dacite	Pebble Creek Formation – Banded mafic andesite
Overall characteristics	highly porphyritic; plagioclase dominates the phenocryst assemblage, but biotite and quartz are also abundant, and amphibole and clinopyroxene are present fine-grained, hyalocrystalline and microvesicular groundmass locally partly devitrified crystalline portion of the groundmass comprises plagioclase, amphibole, pyroxene and oxides less than 1 mm in size Orthopyroxene is absent or rare.	magmatic crystal clots of magmatic minerals occur (e.g., Fig. 4d) and range from 2 to 7 mm in diameter and, in decreasing abundance, comprise: i) sieved-textured plagioclase, ii) red-brown pleochroic biotite cores with amphibole and oxide (±pyroxene) reaction rims (Fig. 4d), iii) plagioclase and orthopyroxene, iv) brown, pleochroic amphibole and oxide, and v) intergrowth of pyroxene and apatite. groundmass glass comprises 80–90% of rock by volume and is generally colourless; although some glass is tan or light-brown in colour (cf. Fig. 4a, b) glass also occurs as colourless and coloured melt inclusions within crystals	banding occurs as parallel and complexly refolded or convoluted layers 0.5 to 2 cm thick, some thicker (5–10 cm) bands observed banding defined by contrasts in colour – white to grey-white host and subordinate grey to black enclaves – which sometimes coincides with variations in vesicularity (Fig. 4e). light coloured material is petrologically identical to the other PCF dacite
Plagioclase	phenocrysts (2–4 mm) show coarse albite twinning and oscillatory zoning; some are partly resorbed. contain some glass inclusions	phenocrysts takes two main forms: 1. Large, 1–3 mm diameter, subhedral, equant, sieve-textured plagioclase crystals (Fig. 4c). Typically, crystals are strongly corroded and show vestiges of coarse albite twinning and complex zoning and growth features. Late plagioclase overgrowth rims are common and restore the euhedral character of the plagioclase (Fig. 4c). Glass inclusions in these crystals appear to follow cleavages, and some are vesiculated 2. small (0.2–1.0 mm), euhedral, twinned, lath-shaped crystals with optically discernible zoning. These crystals differ from the larger disequilibrium plagioclase crystals in that they lack both abundant glass inclusions and corroded grain boundaries	lath-shaped microlites 1.51–2 mm
Quartz	(1–3 mm) are rounded, corroded or have pyroxene reaction rims	rare (<1%) and strongly corroded	rare, fractured and corroded xenocrysts
Biotite	(1–2 mm) euhedral, red-brown phenocrysts and as rounded clots that have been partially reacted to amphibole	most common form is ragged, corroded rounded crystals (0.5–1.0 mm), or partially reacted crystals, or have reaction rims of amphibole + oxides ± pyroxene less commonly found, mainly in the lava flow, is euhedral microphenocrysts	oxide-rimmed biotite grains
Amphibole	less abundant than biotite they form brown-green pleochroic laths	next most abundant ferro-magnesian phase, occurring as strongly green-brown pleochroic, subhedral, 0.1–0.25 mm long prisms and as reaction rims on larger biotite crystals (Fig. 4d)	rare euhedral crystals
Apatite	none noted	common accessory phase, forming inclusions that are concentrated along internal growth boundaries within plagioclase	none noted
Fe-Ti Oxides	none noted	none noted	equant Fe-Ti oxides in the ground mass
Pyroxene	clinopyroxene	orthopyroxene is the most abundant ferromagnesian phase and occurs as euhedral prismatic crystals, 0.2–0.4 mm in length with characteristic green-pink pleochroism clinopyroxene occurs as rare, broken crystals and as reaction rims on larger biotite crystals (Fig. 4d)	large equant-shaped orthopyroxene (0.6–1 mm) and clinopyroxene

oxides less than 1 mm in size. Orthopyroxene is absent or rare.

All primary volcanic rocks of the Pebble Creek Formation share a common mineralogy (Fig. 4a–d) that differs from that of the Plinth Assemblage (Table 1 and 2). Clusters or clots of magmatic minerals occur in all Pebble Creek rock types (e.g., Fig. 4d), range from 2 to 7 mm in diameter and, in decreasing abundance, comprise: i) sieved-textured plagioclase, ii) red-brown pleochroic biotite cores with amphibole and oxide (±pyroxene) reaction rims (Fig. 4d), iii) plagioclase and orthopyroxene, iv) brown, pleochroic amphibole and oxide, and v) intergrowths of pyroxene and apatite. Glass, excluding vesicles, comprises 80–90% of the volcanic rocks. The groundmass glass is generally colourless, although glass in samples of welded breccia (cf. Fig. 4a, b) and in at least one of the lava samples is tan or light-brown in colour. Glass also occurs as colourless and coloured melt inclusions within crystals.

Plinth Assemblage rocks differ from Pebble Creek Formation rocks by having abundant quartz, biotite and clinopyroxene (micro-) phenocrysts. The Pebble Creek Formation has only rare broken or corroded crystals of quartz and clinopyroxene and small amounts of biotite. Pebble Creek Formation rocks contain significant phenocrystic orthopyroxene and sieve-textured plagioclase, whereas Plinth Assemblage volcanic rocks have neither.

Banded rocks are an important lithologic subset of the Pebble Creek Formation (Table 1), and their presence may have important genetic implications. The banding occurs as parallel and complexly refolded or convoluted layers manifested in the field by contrasts in colour between a lighter host (white to grey-white) and subordinate darker (grey to black) enclaves. The mineralogical and textural character of the darker lenses and bands is significantly different from that of the parallel lighter bands (cf. Table 1).

Geochemistry

Major and trace element compositions of primary volcanic rocks of the Pebble Creek Formation and older Plinth Assemblage were measured by X-ray fluorescence spectrometry (Cui and Russell 1995). Table 2 presents chemical compositions of representative samples of the two units.

The chemical compositions of the two rock suites are similar. Both are strongly quartz normative and dacitic to trachydacitic compositionally (Fig. 5; Le Bas et al. 1986). A single sample (out of multiple samples) of the Plinth Assemblage plots as trachyandesite. Also shown in Fig. 5 are the chemical compositions of other mafic to felsic volcanic rocks from the Mount Meager volcanic complex (Ke 1992). These compositions range from basalt to dacite. None of the samples is a rhyolite, though the Plinth volcanic rocks contain quartz and have been described as rhyodacitic on the basis of their mineralogy (Read 1977a, b).

In general, rocks of the Mount Meager volcanic complex are strongly sub-alkaline (Fig. 5). Rocks of the Pleistocene Mosaic Assemblage (Fig. 2; Read 1977a, b) are an exception; they are slightly alkaline (Irvine and Baragar 1971) and range from alkali olivine basalt to trachybasalt (Stasiuk and Russell 1989).

Stratigraphy and field observations

Mapping for this project represents a more detailed study than was undertaken by Read (1977a, b) and ex-

Table 2 Major element chemical compositions of selected volcanic rocks from the Pebble Creek Formation (PCF) and the Plinth Assemblage (PL)

Stratigraphy	PCF	PCF	PCF	PCF	PCF	PCF	PCF	PL	PL	PL	PL	PL	PCF	PCF
Unit	tf	tf	pf_2	pf_2	bx_3	vd	vd	vd	vd	vd	vd	vd	tf	tf
Rock Type	pumice	pumice	pumice	pumice	breccia	lava	lava	lava	lava	lava	lava	lava	pumice	pumice
Sample No.	88-2a	88-2b	90-1	90-3	88-7	88-16	88-32	88-26	88-29	88-30	88-39	88-40	*	**
SiO_2	64.35	67.69	66.90	68.11	68.33	68.64	68.82	67.10	68.74	60.50	68.10	66.94	63.94	66.05
TiO_2	0.57	0.46	0.50	0.46	0.47	0.44	0.44	0.54	0.47	0.84	0.48	0.52	0.45	0.50
Al_2O_3	16.57	16.10	16.63	16.23	16.45	16.18	16.09	16.02	15.72	17.74	16.15	16.75	16.34	15.48
Fe_2O_3	2.09	1.06	0.95	0.56	1.37	1.44	1.14	1.82	1.65	3.40	3.34	1.96	n.d.	1.31
FeO	2.32	1.86	2.75	2.63	1.68	1.43	1.70	1.40	1.32	2.02	0.04	1.60	3.57	2.00
MnO	0.08	0.07	0.08	0.07	0.07	0.07	0.07	0.08	0.07	0.09	0.08	0.09	n.d.	0.07
MgO	1.92	1.36	1.59	1.39	1.46	1.29	1.31	1.74	1.42	2.73	1.68	1.89	1.38	1.38
CaO	4.17	3.06	3.49	3.17	3.33	3.07	3.07	3.28	2.70	5.06	3.28	3.62	3.18	3.30
Na_2O	5.10	5.16	5.32	5.28	5.48	5.32	5.30	4.99	5.10	5.43	5.16	4.90	n.d.	4.30
K_2O	2.23	2.41	2.22	2.37	2.44	2.46	2.46	2.83	3.06	1.74	2.55	2.44	n.d.	2.21
P_2O_5	0.19	0.15	0.17	0.15	0.15	0.15	0.15	0.23	0.17	0.36	0.14	0.17	n.d.	0.23
Total	99.59	99.39	100.61	100.43	101.22	100.49	100.55	100.03	100.44	99.89	101.01	100.86		94.98
LOI	1.66	2.14	1.73	0.74	0.42	0.56	0.45	0.29	0.19	0.94	0.14	0.95	2.75	n.d.
H_2O+	1.34	1.96	1.48	0.75	0.31	0.40	0.28	0.23	0.28	0.90	0.08	0.98	–	2.21
H_2O-	0.28	0.19	0.24	0.10	0.11	0.08	0.08	0.07	0.06	0.10	0.02	0.14	–	2.25

All compositions measured by X-ray fluorescence except for FeO and H_2O, which were measured volumetrically and gravimetrically, respectively (Ke 1992). Also included are chemical analyses by *Drysdale (1916) and ** Stevenson (1947)

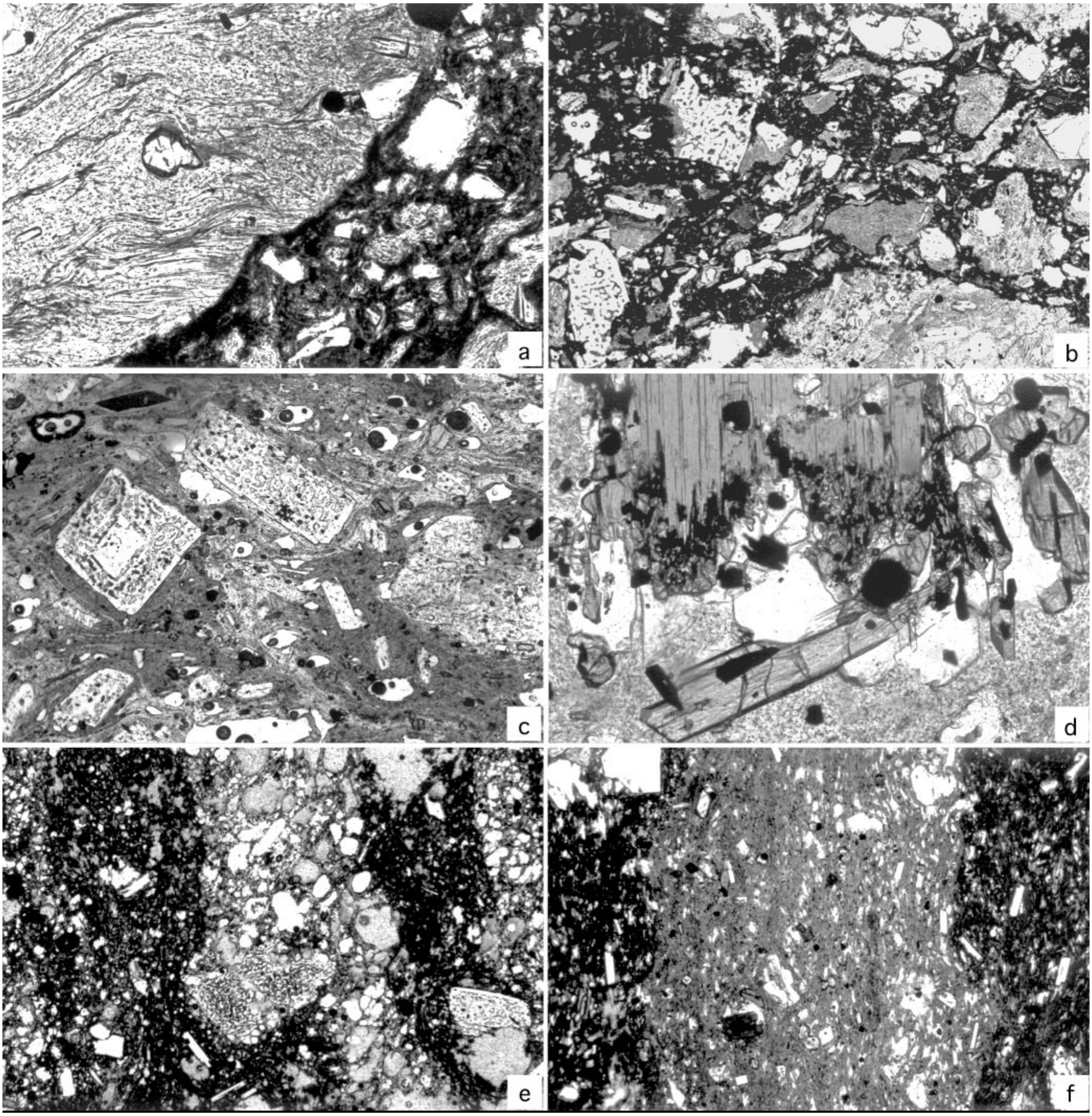

Fig. 4a–f Photomicrographs of Pebble Creek Formation volcanic rocks: **a** wispy structures in glassy lava clasts in unit bx_2 interpreted to be collapsed vesicles (field of view is 7.8 mm); **b** vitroclastic matrix of unit bx_2 (field of view is 7.8 mm); **c** lava showing sieve-textured plagioclase with glass inclusions (field of view is 7.8 mm); **d** crystal clots of early biotite rimmed by reaction products (field of view is 2 mm); **e** commingling of mafic and felsic members (field of view is 7.8 mm); note different vesicle sizes; **f** subtle interface between co-mingled lavas (field of view is 7.8 mm)

pands on the work of Stasiuk and Russell (1990). Read's four subdivisions of the Bridge River Assemblage have been further subdivided into ten and renamed the Pebble Creek Formation. Each of these units represents a significant and distinct component in the history of the Pebble Creek Formation. Relationships between units within the Pebble Creek Formation are tabulated in Table 3 and shown in stratigraphic and cross-section in Figs. 6 and 7. The following discussion describes the units in ascending stratigraphic order as inferred from field relationships (Table 3). Petrography and rock chemical compositions of the primary volcanic units within the formation suggest that all are cogenetic, and field evidence shows them to be co-eruptive.

The paleotopography at the time of eruption of the Pebble Creek Formation was similar to the present-day

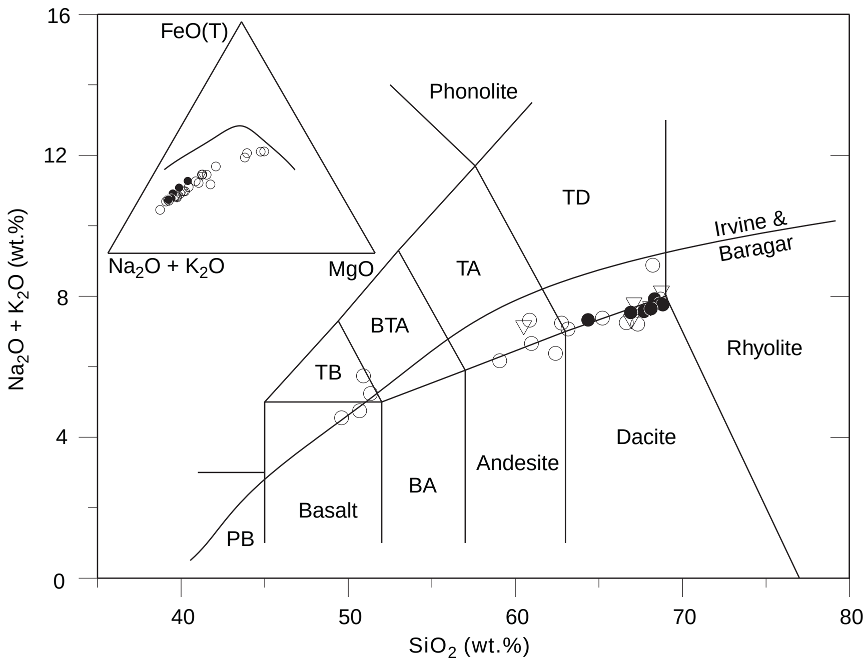

Fig. 5 Chemical classification of Pebble Creek Formation (*solid circles*), Plinth Assemblage (*open triangles*) and other Mount Meager volcanic complex rocks (*open circles*) (Ke 1992). PB – picrite basalt, BA – basaltic andesite, TB – trachybasalt, BTA – Basaltic trachyandesite, TA – trachyandesite, TD – trachydacite (fields from LeBas et al. 1986). The heavy curved line is the alkaline-subalkaline division of Irvine and Baragar (1971). Inset shows AFM diagram representation of Pebble Creek Formation, Plinth Assemblage, and other Mount Meager volcanic rocks. Line separates the calcalkaline field (below) and the tholeiitic field (above), from Irvine and Baragar (1971)

mountainous topography characterized by narrow valleys, high relief and unstable colluvium and till-covered slopes drained by high-energy streams flowing into glaciated valleys. Valley bottoms contain alluvium and locally, rock avalanche deposits. The Lillooet River is a high volume, high-energy river draining a large catchment area. Both slopes and valley bottoms have significant accumulations of easily mobilized sediment.

Pre-eruption rock avalanche deposit: $Avbx_1$

A non-indurated, unsorted, monolithologic deposit of angular to subrounded boulders and cobbles in a grey to tan matrix of very coarse sand to granules forms the basal unit ($Avbx_1$) of the Pebble Creek Formation upstream from Keyhole Falls near Salal Creek (Fig. 3, 6 and 7). The clasts are mainly derived from Plinth Assemblage lava flows that form the peaks, ridges and slopes above the Pebble Creek Formation vent area (Fig. 3). The top 10 to 20 cm of the deposit is reddened and clay-rich; the boundary between this unit and the overlying fallout pumice (unit *tf*) is marked by a thin veneer of dark plant matter ("soil"). Evans (1992) traced this unit 5 km up Salal Creek from its confluence with the Lillooet River to an elevation of 1158 m, where he reports it to be 35 m thick. Here, the deposit dammed Salal Creek, impounding a lake.

Pyroclastic fall deposit: *tf*

A pyroclastic fall deposit, up to 80 m thick, blankets slopes in the vicinity of Mount Meager (Fig. 8a). The deposit has an open framework, is well sorted and consists of 98–99% angular, well-sorted pumice clasts (1–50 cm in diameter) (Fig. 8b). The pumice clasts are light grey, fibrous and commonly have reddish or orange-coloured vesicular cores. Large clasts are pervasively fractured, and surface breadcrust textures are common. About 1–5% of the pumice clasts are banded from white to dark grey (see above and Stasiuk et al. 1996).

About 1 to 2% of the clasts are derived from Plinth Assemblage rocks. These fragments are significantly smaller than the pumice clasts. Four other accidental and accessory clast types total $<<1\%$ of the deposit. The most common is a slightly inflated, breadcrusted grey clast, petrographically identical to the light-coloured pumice clasts. Another type, less common but of genetic significance (see Discussion), is a breadcrusted clast of variably welded pyroclastic flow material (ignimbrite). These clasts contain flattened to well-rounded white pumice fragments (typically 1–10 cm in diameter) in a red to pink, fine-grained, homogenous matrix. Accidental clasts of well-rounded, but glacially faceted, cobbles of quartz monzonite, similar to the Miocene Fall Creek Stock underlying the eastern portion of the map area, are another minor but ubiquitous component of the deposit (Fig. 8b). Rarest of the accidental clasts are fragments interpreted to be baked and charred clay-rich soil. All accidental and accessory clasts are found throughout the deposit and are not limited to any one section or horizon.

Grain-size analysis was carried out on eight tephra samples collected 2.1–4.3 km from the vent area using the methodologies proposed by Walker (1971), Sparks (1976), Fisher and Schmincke (1984) and Cas and Wright (1987). This analysis shows that the deposit is well sorted (Fig. 9; Walker 1971; Cas and Wright 1987).

Table 3 Stratigraphic summary of Pebble Creek Formation members and Plinth Assemblage (after Read 1990)

Member	Name	Thickness (m)	Internal structure	Clasts	Matrix	Other characteristics	Interpretation of deposit type, sequence of events and emplacement mechanism
Q	Quaternary cover over basement rock						
$Avbx_2$	post-eruption avalanche deposit		monolithologic, poorly sorted, lithic blocks, unconsolidated	PLvd clasts subangular to subrounded			rock avalanche related to over-steepened slopes of Plinth Peak
vd	dacite lava flow	15–20	vitrophyric, locally highly vesicular, porphyritic (plagioclase, orthopyroxene, amphibole and biotite) dacite	two populations of plagioclase >Opx>Amp>Aug, Bt, Ox, Kfs(?)	bands of colourless to brown glass		lava flow; waning eruption of gas-poor magma
la	hot outburst-flood deposit	10–2	unsorted to very poorly sorted, unconsolidated, matrix-supported polymictic deposit grading downstream into bedded deposits	granule to boulder size, prismatically jointed welded breccia blocks, clasts up to 15 m in size	polymictic granule size material	blocks of welded material are characteristically prismatically jointed, subangular	debris flow (lahar) of still hot, but welded unit bx_3 due to sudden failure of dam formed behind this deposit
bx_3	late phase, partially welded block and ash flor deposit	>50	reddish-grey, partially lithified, monolithologic, crudely bedded, matrix-to clast-supported breccia	crystal-rich vitroclastic welded breccia with dense black glassy clasts	grey weathering glassy matrix		welded block and ash flow; Merapi-type hot avalanches off the face of an advancing lava flow/dome
bx_2	middle phase welded block and ash flow deposit	100–15	welded vitrophyric block and ash flow, variably welded, rare granitic clasts; unconsolidated basal breccia of lithic blocks	50% clasts of dense vitrophyre, 5% granite clasts, angular, leucocratic monzonite fragments, and rarer fragments of Plinth Assemblage lava and biotite-feldspar gneiss	grey weathering glassy matrix, friable to welded, containing broken crystal fragments	volumetrically largest deposit	welded block and ash flow; Merapi-type hot avalanches off the face of an advancing lava flow/dome; formed a substantive dam in the Lillooet Valley
vs	crudely bedded sedimentary deposit	3	discontinuous, poorly sorted, crudely bedded, polymictic debris flow	subangular blocks of Pebble Creek Formation dominant; 20% subangular to subrounded granitic clasts			fluvial processes deposited during a short hiatus in eruption sequence, during which bx_1 was dissected by the Lillooet River
pf_2	late phase pyroclastic flow deposit	7	laterally discontinuous, lensoid shape; reverse grading of pumice, normal grading of lithic clasts	subrounded to breadcrust-textured vesicular pumice blocks weakly compositionally banded	fine-grained ash, crystal and rock fragments	no charred wood	pyroclastic flow; more gas-rich magma pulse
bx_1	early phase-welded block and ash flow deposit	5	laterally discontinuous, friable, welded vitrophyric angular blocks	jointed, welded, vitrophyric, black angular clasts	grey weathering glassy matrix	less intensely welded than bx_2, found only near Keyhole Falls	welded block and ash flow; Merapi-type hot avalanches off the face of an advancing lava flow/dome
pf_1	early phase pyroclastic flow deposit	3–10	laterally continuous; non-indurated and massive; exhibits only crude internal structure or sorting; reverse grading of pumice, normal grading of lithic clasts	subrounded breadcrust-textured pumice clasts 5 cm to 1 m in size, compositionally banded; rare (<1%) accidental clasts	fine-grained ash matrix	abundant charred wood, including whole trees typically oriented horizontally	pyroclastic flow deposit; early, gas-rich magma

Table 3 (continued)

Member	Name	Thickness (m)	Internal structure	Clasts	Matrix	Other characteristics	Interpretation of deposit type, sequence of events and emplacement mechanism
tf	early phase pyroclastic fall deposit	1 to >60	open-framework, matrix free, >90% well sorted large white to grey-white blocks, rare proximal blocks to 50 cm (max. dimension); 1–2% accidental clasts, upper portions and near vent substantially reworked	>90% white to grey-white pumice blocks, >20% macroscopic vesicularity; accidental clasts include, 1) slightly inflated, breadcrusted grey clasts petrographically identical to the pumice clast, 2) breadcrusted, inflated clasts of variably welded pyroclastic flow material (ignimbrite); 3) well-rounded cobbles of quartz monzonize; 4) baked to charred clay-rich soil	matrix-free, open framework	rare pumice clasts (1–5%) exhibit compositional heterogeneity (banding), large blocks have pinkish cores, breadcrusted surface and are fractured. Deposit thins rapidly outside of map area, to trace accumulations at distances of >1000 km	tephra fall deposit; early, gas-rich magma producing a vent-clearing phase after deposition of earlier ignimbrite
	ignimbrite	found only as clasts		inflated clasts of variably welded pyroclastic flow material (ignimbrite); clasts contain flattened to well-rounded white pumice lapilli and blocks (typically 1–10 cm in diameter) in a red to pink fine grained, homogenous matrix		rare clasts found within unit tf	initial or concurrently(?) formed proximal deposits, possibly vent infill representing the first phase of eruption and producing welded, proximal ignimbrite
$Avbx_1$	pre-eruption rock avalanche deposit	1–35	monolithologic Plinth Assemblage clasts, rocks; soil horizon developed on upper surface	PLvd clasts subangular to subrounded	grey to tan coloured, very coarse sand to granule sized		rock avalanche deposit; avalanche related to oversteepened slopes of Plinth Peak
PLvd	Plinth Assemblage		massive, dense and light to dark grey or red weathering, highly porphyritic, plagioclase dominates the phenocryst assemblage and biotite and quartz are also abundant			light grey, porphyritic (plagioclase, quartz, biotite) dacite flows, breccia and ash	pre-Pebble Creek Formation Assemblage

Maximum grain size concentrations are in the 1–5 cm range. Less than 10% is less than 0.1 cm in size and 10% is coarser than 6.4 cm size (Fig. 9). The most distal sample has a substantially higher percentage of finer-grained material.

Thin, very fine-grained, distal deposits of unit *tf* have been identified as far east as Alberta (530 km) (Stevenson 1947; Nasmith et al. 1967; Westgate and Dreimanis 1967). The central axis of the plume trends approximately 63° east-northeast (Nasmith et al. 1967).

Early phase pyroclastic flow deposit: pf_1

A pyroclastic flow deposit (unit pf_1) directly overlies fallout pumice (unit *tf*) in exposures along the Lillooet River (Figs. 3, 6, 7, 8c). The unit is matrix- to clast-supported, massive, non-indurated, and consists of subrounded to rounded pumice blocks in a fine grey clastic matrix. In some exposures it exhibits crude internal structure or sorting (Fig. 9). The deposit near the vent is generally 3 to 10 m thick. The most proximal exposure is close to Keyhole Falls (Fig. 3; Figs. 6, 7, section A); the most distal is at Pebble Creek (Fig. 3; Figs. 6, 7, section D).

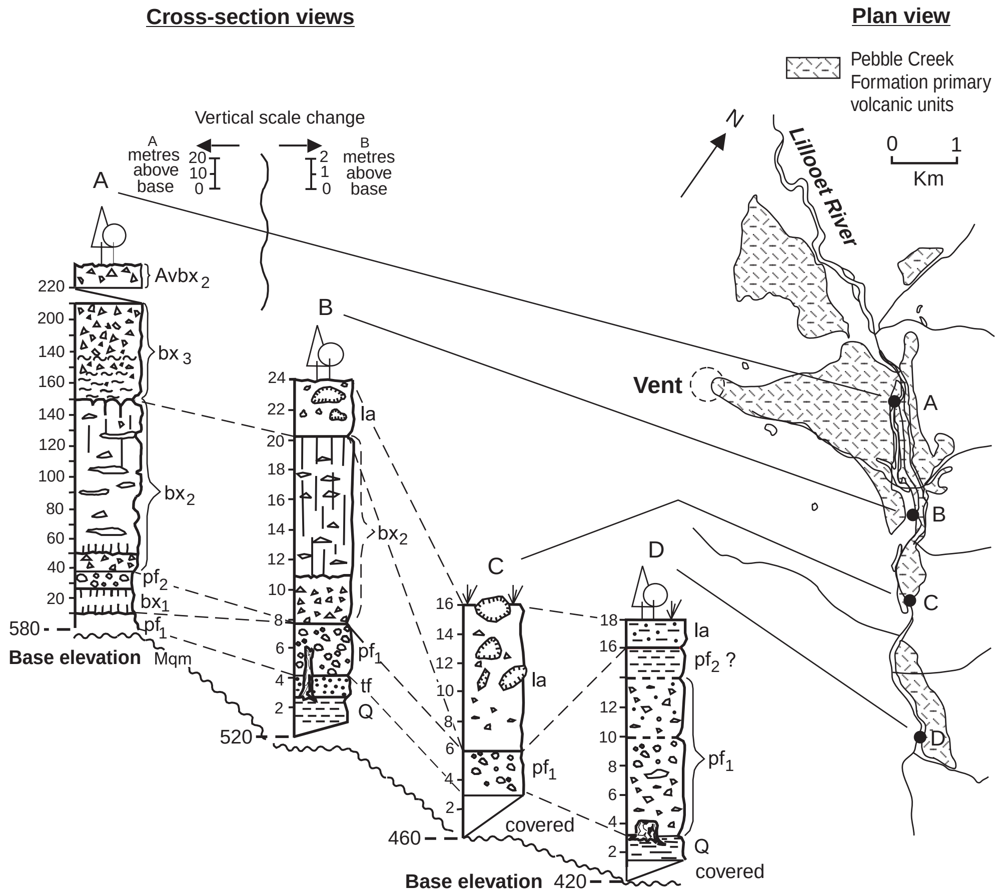

Fig. 6 Stratigraphic sections of Pebble Creek Formation. Solid circles and letters mark location of sections. Rock units as in Fig. 3. Measurements are given in metres above base elevation

The dominant clasts are 5-cm to 1-m blocks of pumice, commonly breadcrusted and compositionally banded. Blocks of Plinth Assemblage rocks, carbonized wood fragments, branches and rare whole trees are accidental components (Fig. 8c, d). Quartz monzonite cobbles are extremely rare, and no clasts of welded pyroclastic flow material or soil were found. The matrix consists of small, rounded pumice grains, curved glass shards and crystal fragments (predominantly plagioclase).

At section A (Figs. 3, 6) the base of unit pf_1 is not visible, though it presumably overlies units *tf* and $Avbx_1$. Here the deposit is at least 10 m thick, reversely graded, and contains subangular pumice blocks up to 25 cm in diameter. Banded pumice blocks are also present; charcoal is rare. Downstream, at section B, unit pf_1 is about 4 m thick and overlies 1.4 m of fallout pumice (unit *tf*). Trees rooted in underlying fluvial sands and gravels are buried by the pumice. At this site unit pf_1 displays reverse grading, contains numerous subangular pumice blocks up to a few tens of centimetres in diameter and horizontal carbonised tree branches and logs. At the most distal exposure (section D), unit pf_1 is 6 m thick, contains pumice blocks up to 2 m in diameter and numerous large, horizontal tree trunks up to 50 cm in diameter and 3 m long. Both the pumice blocks and charred tree trunks are concentrated near the top of the unit (Fig. 8c, d). At the base of the unit is a 40-cm-thick, massive fine ash layer that rests on a lithic and crystal-rich layer containing entrained reddish oxidized soil clots and pebbles from the underlying soil horizon. The soil is itself underlain by fluvial sand and gravel. Unit pf_1 pinches out abruptly downstream; near the end of the exposure, a vertical, slightly charred tree remains in growth position protruding through unit pf_1.

Early phase welded block and ash flow deposit: bx_1

Unit pf_1 is overlain by about 5 m of jointed, friable, welded vitrophyric breccia (Fig. 3; Fig. 6, section A). The breccia has closely spaced joints that range from irregular to radial in pattern and suggest rapid quenching by water. This deposit may be the first indication of the role of water as an influence in the eruptive products and is found only in the vicinity of Keyhole Falls.

Pyroclastic flow: pf_2

A second pyroclastic flow deposit (unit pf_2) overlies unit bx_1. In section A below Keyhole Falls (Fig. 6), it is lensoid in shape and approximately 7 m thick, with a lower, pumice-rich, reversely graded, 4-m-thick zone and an upper lithic-rich, crudely bedded normally graded layer. Pumice clasts in the deposit are subangu-

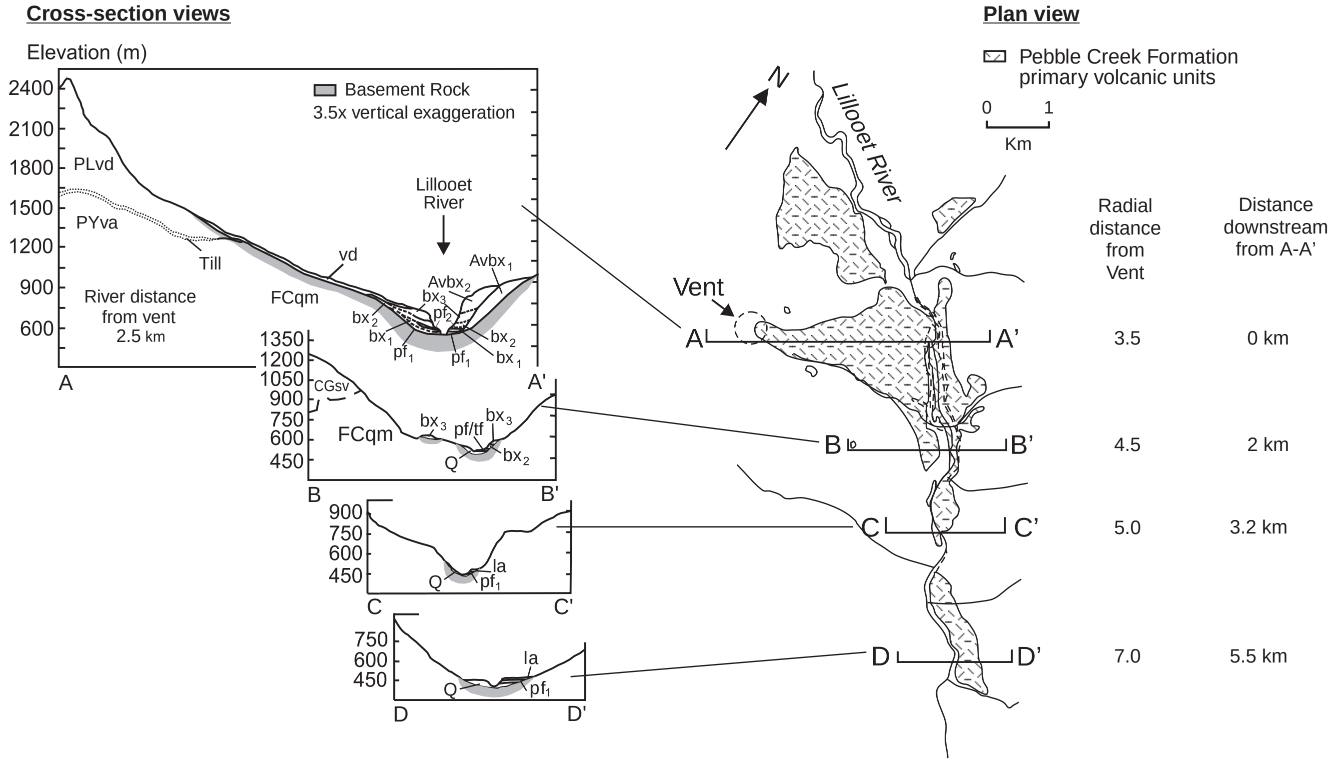

Fig. 7 Cross-sections showing the stratigraphy and distribution of members of the Pebble Creek Formation. Rock units as in Fig. 3

lar and up to 7 cm in diameter; lithic blocks are angular and up to 12 cm across.

A matrix-supported block and lapilli breccia overlies unit pf_1 at section D. This flow unit has conspicuously fewer large pumice blocks and charred wood fragments than unit pf_1. This exposure may be near the distal margin of unit pf_2.

Debris flow: *vs*

Unit *vs* is a crudely bedded, poorly sorted, heterolithic, 3 m thick, waterlain, deposit. It comprises rounded boulders of Pebble Creek Formation welded breccia, lithic clasts and rounded boulders and cobbles of leucocratic granite in a granule to sand matrix dominated by material other than clasts of the Pebble Creek Formation. Welded breccia boulders are not radially jointed as in unit bx_1. Unit *vs* was observed in only one location, downstream from section B (Figs. 3, 6, 7). Where observed, it clearly underlies unit bx_2 (see below), but its relationship to pf_1 (or possibly even pf_2) cannot be determined.

Welded block and ash breccia: bx_2

Unit bx_2 is volumetrically the largest member of the Pebble Creek Formation; it is a valley-filling deposit of variably welded, monolithologic, vitrophyric breccia. The unit thins from 100 m at Keyhole Falls (Fig. 8c, d) to 15 m just downstream of section B (Fig. 3). It forms an apron ahead of, and possibly beneath, the Pebble Creek Formation lava flow (unit *vd*; Fig. 3) but is not present where the base of the flow is exposed, along the middle to upper reaches of Fall Creek and above the Lillooet River.

The breccia has crude horizontal layering defined by zones of differing grain size and welding (Fig. 8d). The layers are several metres thick and are laterally discontinuous. Vertical columnar joints, with metre-scale spacing, cut the deposit irregularly, and smaller horizontal columnar joints, about 10 cm apart, form normal to the vertical joint surfaces (Figs. 8c, d). These horizontal joints are most prominent below Keyhole Falls near section B (Fig. 3).

The principal (50%) constituent of the breccia is black, dense, glassy, angular blocks of porphyritic lava, some of which are flow banded (Fig. 8e). Weathered surfaces commonly highlight a diffuse, waxy-grey, centimetre-scale banding, perhaps resulting from incipient devitrification. The clasts range in size from a few centimetres to about 1 m across and are variably flattened to produce conspicuous horizontal alignment. Fig. 10 compares aspect ratios of dense vitrophyric clasts in the welded interior of the breccia and the unwelded base. Analysis of the two data sets suggests that a maximum flattening of 30% took place during welding. Rare welded breccia clasts contain grey spherulites and lithophysae. These were noted in the thickest section of unit bx_2 near Keyhole Falls. Some glassy clasts are slightly vesicular. In thin section, wispy lineations within other-

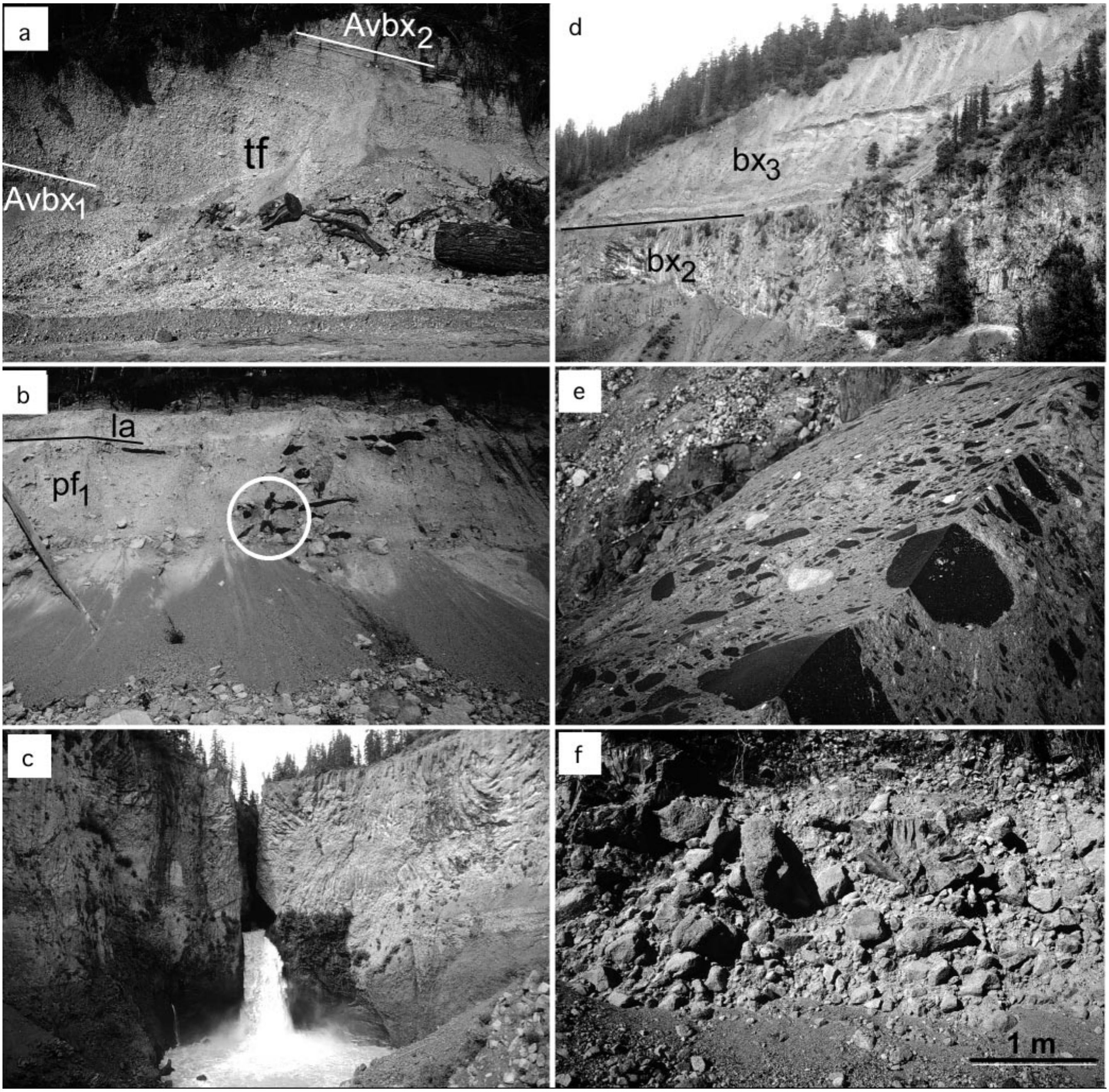

Fig. 8a–f Photographs of units of the Pebble Creek Formation: **a** fallout pumice deposit (unit *tf*, 2 m thick) underlain by and overlain by rock avalanche deposits (units $Avbx_{1\&2}$); **b** pyroclastic flow (unit pf_1) and overlying flood deposit (unit *la*) at section D (figure for scale, note circle); **c** cliffs of unit bx_2 at Keyhole Falls; cliffs are 100 m high and represent the welded breccia that formed the competent portion of the dam but was eroded by the catastrophic flood waters (the notch represents erosion by the Lillooet River since the 2350 B.P. eruption and catastrophic flood); **d** layered, variably indurated unit bx_3 (which failed catastrophically) overlying unit bx_2. B; **e** close-up view of massive welded lava breccia; **f** radial jointing in glassy blocks within unit *la* (block shown in photograph is 1 m in diameter)

wise homogeneous glass represent collapsed vesicles (Fig. 4a).

Accidental clasts include small, angular, leucocratic monzonite fragments, forming up to 5% of the breccia, and rarer fragments of Plinth Assemblage lava and biotite-feldspar gneiss. The accidental clasts do not have a preferred orientation and are not flattened. Black glassy clasts are slightly bent around sharp edges of accidental lithic clasts.

The matrix of the welded breccia ranges from light grey, friable, and granular to grey, porous and porcelain-like, to black, dense and glassy. In thin section the matrix is clastic, comprising comminuted fragments of the black glassy clasts (Fig. 4a, b). Where strongly

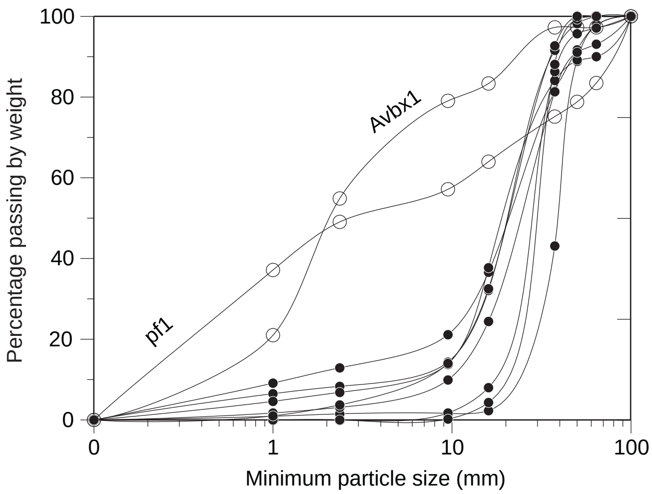

Fig. 9 Particle size distributions for eight samples of fallout pumice (solid circles), one sample of pyroclastic flow (unit pf_1) and one of the rock avalanche units ($Avbx_1$)

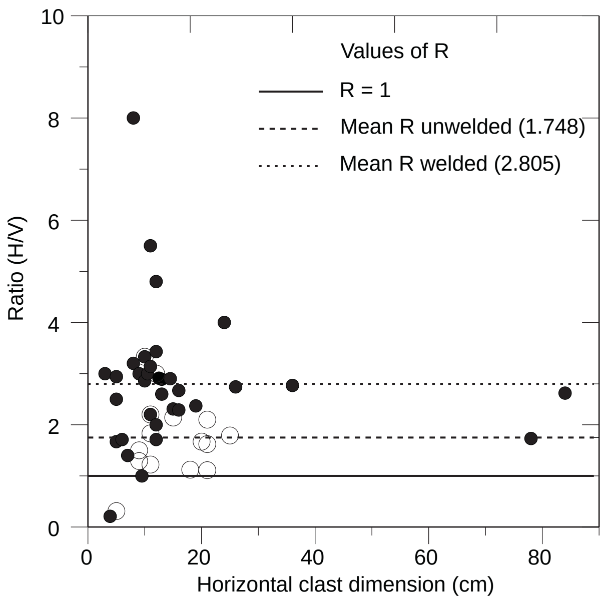

Fig. 10 Aspect ratios of lava clasts from the non-welded basal part of the breccia (*open circles*) and the strongly welded interior of the breccia (*closed circles*), shown as function of the horizontal dimension of the clast

welded, the matrix is a "dusty" glass containing broken crystal fragments (Fig. 4b).

Welding diminishes near the base and top of the unit. The uppermost material is a poorly indurated, massive, chaotic deposit described separately below (unit bx_3). The blocks in the unwelded part of the deposit range from vesicular pumice to dense vitrophyre but are petrographically identical to flattened clasts within the densely welded breccia.

Unit bx_2 contains cylindrical vertical holes tens of centimetres in diameter and metres long. The holes extend from the unwelded base of the unit into the welded interior and lie directly above the blackened stumps of trees protruding through the pyroclastic flow deposits (Stasiuk et al. 1996).

Late-phase partially welded block and ash flow deposit: bx_3

Unit bx_2 is overlain by variably indurated, crudely bedded breccia (unit bx_3) exposed in precipitous cliffs above Keyhole Falls (Fig. 8d), where it attains a thickness of more than 100 m. At this site the breccia contains a few thin (<1 m), strongly welded layers. Unit bx_3 is also present downstream from Keyhole Falls and is inferred to underlie much of the covered slopes below the lava flow and above unit bx_2 (Figs. 3, 6). The upper part of the breccia is deeply eroded in most locations and forms vegetated, recessively weathered slopes. The unit is clast to matrix supported. The clasts are angular and lithic textured in a coarse, granular matrix reddish-grey in colour.

Hot outburst flood deposit: *la*

A chaotic, unsorted and non-indurated, heterolithic mixture of subangular to subrounded granule- to boulder-size material overlies unit bx_2 downstream from section B (Fig. 8f). It is best exposed in a road cut at section C (Fig. 3, 6 and 7), where it is 10 m thick. From this point it thins and fines rapidly downstream to section D, where it is only 2 m thick.

Unit *la* is typically matrix supported, particularly in distal exposures, but is clast supported at a few localities. The matrix ranges from very coarse sand to pebble-sized material and locally forms crudely bedded, discontinuous lenses in interstices between larger clasts. Clasts in the deposit range from cobbles to boulders up to 15 m in long dimension. The dominant clasts are angular to subrounded blocks of welded glassy breccia, which are distinguished by numerous centimetre-scale cooling joints perpendicular to the clast surfaces, forming radial patterns (Fig. 8f). The cooling joints occur in all breccia blocks regardless of size.

Dacite lava flow: *vd*

The youngest primary volcanic deposit is a glassy, porphyritic dacite lava flow. The flow is weakly flow banded and ranges in vesicularity from almost pumiceous at the top to extremely dense at the base. The lava flow is heavily vegetated, but its original form is well preserved and is defined by a 10–20 m high scarp fringed by coarse talus blocks. The vent location is inferred to be close to the point where the lava outcrop narrows and disappears (Fig. 3 and 7a); ice and talus accumulation obscures all primary volcanic features in this area. The base of the unit, exposed along the lava's southern margin (along Fall Creek), is a partially welded, oxidized breccia. The thickness of the flow exposed along Fall Creek varies from 15 to 20 m over the 2 km length.

Post-eruption rock avalanche: $Avbx_2$

The uppermost unit of the Pebble Creek Formation is a chaotic and structureless monolithologic rock avalanche deposit derived from Plinth Assemblage lava flows (unit $Avbx_2$) (Fig. 3). Unit $Avbx_2$ is very difficult to distinguish from the older unit $Avbx_1$; both deposits comprise mainly blocks of dacitic lavas derived from Plinth Peak (Read 1977a, b; Evans 1992). Unit $Avbx_2$ can be separated from unit $Avbx_1$ where it overlies the fallout pumice deposit (unit *tf*). Additionally, a thin soil marks the upper surface of the older rock avalanche deposit where it is overlain by the fallout pumice. The younger rock avalanche sits conformably upon fallout pumice (Fig. 8a), other members of the Pebble Creek Formation, and basement rock. There is no evidence of a paleosol on the surface of unit $Avbx_2$, and clasts from other units of the Pebble Creek are not incorporated into the debris. Large (up to 5 m), angular blocks of Plinth lava can be found strewn on the upper surface of unit *vd*. These blocks are assumed to be thin proximal clasts of unit $Avbx_2$. The rock avalanche had sufficient energy to deposit only sparse debris on the west side of the valley prior to running up to an elevation of 914 m east of the river.

Discussion

The Pebble Creek Formation comprises primary and secondary volcanic deposits produced by a variety of processes and styles of volcanic activity. Field relationships suggest that all units were emplaced over a period of time that may have been as short as a few weeks, with the exception of the rock avalanches. The rapid emplacement of the primary volcanic units implies little or no hiatus in the supply of magma to the surface. The sequence of eruptive events is best described as a single, multi-phased volcanic eruption; here simply termed the 2350 B.P. eruption.

A notable aspect of the 2350 B.P. eruption is that explosive volcanism occurred in mountainous terrain drained by a high-energy river with a large catchment area. These geomorphic attributes had a significant impact on the eruption, controlling the distribution and character of the volcanic deposits. These factors also have specific implications for the hazards associated with other volcanoes in such areas. The discussion below is intended to elucidate some of the aspects of an eruption in such an environment.

Plinian phase

Eruption trigger

Blocks of banded pumice and lava flows are an important lithological subset of the Pebble Creek Formation. The banding is most evident in pumice blocks in the pyroclastic flow (pf_1) and fallout pumice units (*tf*). None of the accessory blocks of welded ignimbrite in unit *tf* is banded. Some clasts in the welded breccia are also banded, but this is less obvious because of welding and compaction. Enclaves of apparently unmodified mafic material and rare, dark-coloured, dense blocks containing subordinate 1–2 cm light-coloured bands provide the best constraints on the character of the more mafic magma type. Minerals in these enclaves and bands are dominantly equant, euhedral orthopyroxene (0.6–1 mm) and plagioclase (1.5–2 mm) phenocrysts (not sieve textured), augite and plagioclase microphenocrysts and groundmass plagioclase microlites and oxides. The light-banded material is characterized by i) sieved-textured plagioclase, ii) red-brown pleochroic biotite cores with amphibole and oxide (±pyroxene) reaction rims (Fig. 4d), iii) plagioclase and orthopyroxene, iv) brown, pleochroic amphibole and oxide, and v) intergrowth of pyroxene and apatite.

The banded pumice clasts in both the fallout and pyroclastic flow deposits are inferred to result from mingling and mixing (cf. Philpotts 1990) of i) volumetrically dominant dacite consisting of colourless glass, phenocrysts of sieve-textured plagioclase, orthopyroxene, amphibole, and biotite; and ii) subordinate basaltic andesite comprising phenocrysts of equant orthopyroxene, non-sieve-textured plagioclase, and clinopyroxene and a hyalocrystalline groundmass of Fe-Ti oxide, plagioclase, pyroxene and light-brown-yellow glassy mesostasis. Magma mingling rather than mixing more accurately describes the process, although, at least on a local scale, there is evidence of homogenization forming "hybrid" material that subsequently has been infolded into the uncontaminated dacite.

Field observations indicate that the mingling predates eruption of the fallout pumice but postdates formation of the welded ignimbrite, as inferred from accessory blocks of welded ignimbrite within unit *tf* that show no evidence of magma mixing or mingling. The mafic magma was volumetrically small compared to the dacite magma. The preservation of millimetre- to centimetre-scale banding and sharp compositional interfaces suggests that mixing occurred close to the initiation of the eruption of unit *tf* or during its early stages (e.g., Sparks et al. 1977; Koyaguchi 1985). Stasiuk et al. (1996) suggested the mixing may have triggered the eruption (e.g., Sparks et al. 1977). Field relationships observed within the Pebble Creek Formation are consistent with this suggestion.

Pyroclastic deposits

The fallout tephra deposit (unit *tf*) is the first direct evidence of volcanic activity during Pebble Creek time. The deposit is interpreted to be fallout material deposited from a turbulent convecting plume formed from a Plinian eruptive column (Sparks et al. 1978; Cas and Wright 1987). The accidental clasts of Plinth Assemblage volcanic rocks, glacially faceted quartz monzonite cobbles, and baked clay rich clots (soil?) suggest erosion of the conduit and surrounding margins during the eruption. The dense grey breadcrusted clasts and the inflated breadcrusted clasts of welded pyroclastic flow material may represent clasts of earlier or concurrently forming proximal deposits, possibly vent infill. These welded pyroclastic flow clasts are the clearest evidence of syn- or pre-Plinian "vent" deposits (Sparks et al. 1978).

The central axis of the Plinian eruption plume deposits trends approximately 63° east-northeast (Nasmith et al. 1967). Thin, very fine-grained, distal fallout deposits have been identified as far east as Alberta (530 km) (Stevenson 1947; Nasmith et al. 1967; Westgate and Dreimanis 1967). Attempts to constrain the characteristics of the eruption by relating size and density of pumice and lithic fragments to distance from the vent location (Luty 1994) were done using the methodology of Carey and Sparks (1986). Using their technique, we calculated a preliminary plume height of 15–17 km. This estimate may be low, as it does not include data from the most distal portions of the plume.

Much of unit *tf* was deposited on steep slopes where erosion rates are high. As a result, unit *tf* has been extensively modified and eroded by creep, slope wash and stream dissection. These processes have resulted in secondary (post-eruption) centimetre-scale laminations in the upper quarter or third of the deposit (see upper portion of Fig. 8a). At one site along the south side of the Lillooet River north of the vent, the entire deposit has been reworked into a complex, channelized accumulation of pumice 60 m thick (Russell and Stasiuk 1997). This is now the site of a commercial pumice-mining operation.

The eruption, once a Plinian column developed, produced at least two significant pyroclastic flows (e.g., Sparks et al. 1978). The first of the flows, unit pf_1, was larger and more energetic. The occurrence of banded, breadcrusted pumice blocks and large tree fragments suggests that unit pf_1 is laterally continuous between sections A and D, a distance of 5.5 km. The presence of a fine-grained basal unit further suggests that the elutriated cloud of the pyroclastic flow may have outrun the main avalanche phase.

Lava flow collapse and brecciation phase

Units $bx_{1,2\&3}$ are unusual deposits of similar origin. Their distribution, internal structure, constituents and textures are consistent with deposition from the collapse of a series of lava domes or lava flow fronts. Lava flow avalanches, also termed block and ash flows, are common in "Merapi-type" eruptions (e.g., Bardintzeff 1984; Boudon et al. 1993), and are caused by extrusion of viscous silicic magma on steep slopes. They have been documented at volcanoes in Chile (Francis et al. 1974), Guatemala (Davies et al. 1978; Rose 1987), Mexico (Rodriguez-Elizarraras et al. 1991) and Japan (Sato et al. 1992; Nakada 1993). Fragmentation of the lava is caused by gravitational collapse of the flow front on steep slopes, explosive decompression of exsolving volatiles, or some combination of these two processes (Moore et al. 1981; Heiken and Wohletz 1987; Stasiuk et al. 1993a, b). Deposits similar in character to the Pebble Creek Formation welded breccia have been described by Francis et al. (1974), Rodriguez-Elizarraras et al. (1991), Boudon et al. (1993) and Kerr et al. (1974). The deposits described by Francis et al. (1974) are similar in thickness (up to 100 m) and length (2–7 km) to those of the Pebble Creek Formation, but most Merapi-type block and ash deposits are substantially smaller.

Another striking contrast between Pebble Creek Formation welded breccias and most modern Merapi-type block and ash deposits is that all of the Pebble Creek Formation breccias are strongly or incipiently welded, similar to deposits described by Kerr et al. (1974) but very different from most modern examples (Francis et al. 1974; Rodriguez-Elizarraras et al. 1991; Boudon et al. 1993; Nakada 1993). Strong welding of lava basal breccias commonly occurs beneath thick lava flows (Bonnichsen and Kauffman 1987; Sparks et al. 1993) where there is significant heating through advection by the flowing lava. Such breccias, however, are normally only a few metres thick, occur in close proximity to the lava supplying the heat, have no internal structures such as layering and do not have a valley-infilling form.

The layered and welded nature of units $bx_{1\&2}$ and, to a lesser extent, unit bx_3 indicates that these units were deposited episodically and conserved heat during emplacement. This suggests that the source is close to the present location of the breccia and that the accumulation rate of hot material must have been sufficiently high to provide adequate heat to weld the material. The breccia was emplaced at temperatures in excess of the glass transition temperature, assumed to be greater than about 500 °C. A final contributing factor to the welding may have been the narrowness of the valley in which the breccia was deposited. Incision of the easily erodible unit $Avbx_1$ by the Lillooet River likely created a narrow gorge which was then filled by the breccia. This narrow valley conserved heat and promoted welding.

Variations in columnar jointing, welding, and clast size define layering within unit bx_2. On the basis of these differences, we suggest that unit bx_2 consists of up to four cooling units and hence was emplaced episodically, presumably from a number of closely spaced flow front collapses (avalanches) or explosions (e.g., Nakada 1993; Young et al. 1997). Two implications of the layering are that the lava extruded from the vent was highly unstable and that eruption styles may have varied rapidly (e.g., explosive vs. extrusive).

Support for changes in the style of the eruption derives from the stratigraphic relationship among units pf_1, bx_1 and pf_2 (Fig. 3, section A). An inflated pyroclastic flow, followed by emplacement of a welded breccia, then a second pyroclastic flow suggest unstable activity and rapid shifts from explosive to extrusive behaviour. This type of behaviour has been observed at Mount St. Helens (Moore et al. 1981) and Mt. Unzen (Sato et al. 1992), and is a common feature of prehistoric silicic eruptions (Fisher and Schmincke 1984; Heiken and Wohletz 1987). Such oscillations are of great practical importance, because they represent unpredictable switches from quiescent lava extrusion to dangerous explosions.

Catastrophic dam-failure phase and flood hazards

Unit *vs* is interpreted to be a debris flow deposit resulting from partial dissection of unit bx_1 by the Lillooet River. This deposit is the first direct indication of the competition between the volcanic deposits and the river.

Of even greater significance are the younger breccia units. Unit bx_2 dammed the Lillooet River to a height of at least 100 m (Fig. 8c), impounding a lake. This lake continued to fill as unit bx_3 was deposited. Deltaic deposits upstream from Salal Creek indicate that the lake attained a maximum elevation of 810 m and thus was at least 50 m deep. Its volume is estimated as 0.25–1.0 10^9 m^3.

As the water level rose, the dam of variably welded, poorly indurated breccia formed by unit bx_3 (above the welded bx_2 unit) failed catastrophically. Lake water rapidly cut through the still hot and poorly indurated unit bx_3 deposits (Fig. 8d). The water quickly removed the bulk of that unit and began to cut into the distal edge of the still cooling unit bx_2 (downstream of section B-B′ (Figs. 3, 6, 7). Once an incision point was established in the unwelded, distal portions of unit bx_2, rapid headward erosion undermined and removed massive blocks of unit bx_2. Boulders up to 15 m long were swept away and deposited up to 3.5 km downstream. This rapid headward erosion produced a canyon 0.5 km wide and 2 km long, and the flood was sufficient to leave deposits 30 m above the pre-existing valley floor 5.5 km downstream of the dam failure.

The outburst flood occurred after unit bx_2 had welded but still retained enough heat for breccia blocks plucked from the deposit to develop radially oriented cooling joints. The jointing most likely did not form during transport but rather shortly after the blocks came to rest in the water-saturated debris. Plucking of large intact blocks of unit bx_2 also produced the irregular pattern of columnar joints seen on some of the canyon walls. The removal of blocks resulted in larger-than-average fracture faces on the canyon walls. These faces were rapidly quenched from the passing flood, and small columns developed perpendicular to them.

The flood, however, was neither long nor large enough to complete headward erosion through the entire sequence of breccia deposits. A 0.5-km-wide deposit, mainly of unit bx_2 remains in the valley of the Lillooet River, which has presently cut a gorge 30 m deep and 10 m wide through the deposit.

Landscapes such as exist in the vicinity of the Pebble Creek Formation vent pose a serious threat of significant downstream flooding. Even though unit bx_2 was stable, units bx_1 and bx_3 were not. These breccia units created a serious hazard as the level of impounded water rose. Unit bx_1 was most likely the least stable of the three dams. The deposit was only a few metres thick, and when hot material ceased to be added at a rate that withheld the river, it failed and produced unit *vs.* Unit bx_2 was volumetrically larger and infilled the river valley sufficiently quickly that it formed a stable dam. Welding progressed in the narrow confines, solidifying the deposits. It may then have taken some time for bx_3 to be deposited and the lake levels to rise sufficiently to overtop and remove unit bx_3.

The importance of this reconstruction is that the primary eruption products may not directly impact surrounding infrastructure, but flooding may reach vulnerable structures at great distances downstream under these conditions. These temporary, and inherently unstable, "dams" must be closely monitored for signs of failure.

In addition to blockages by primary volcanic deposits, the Lillooet Valley is vulnerable to blockages by rock avalanches. This is a consequence of the topography and the fact that much of the adjacent slopes is underlain by unstable volcanic rock. As suggested by Evans (1992), the character and distribution of unit $Avbx_1$ is consistent with a rock avalanche derived from the volcanic rocks forming the steep slopes of Plinth Peak. The avalanche must have occurred sufficiently long before the 2350 B.P. eruption for soils to develop high on the valley walls and for unit $Avbx_1$ to be removed from the valley bottom. There is no evidence that it is linked to the eruption, but it likely blocked the Lillooet River. Similar rock avalanches have blocked streams in similar terrain to the south at Mount Cayley (Clague and Souther 1982; Evans and Brooks 1991; Cruden and Lu 1992) and near Mount Garibaldi (Moore and Mathews 1978).

The later avalanche, unit $Avbx_2$, may also have dammed the Lillooet River as suggested by Evans (1992). However, Evans (1992) did not distinguish unit bx_3, comprising quartz-poor dacite, from the younger unit $Avbx_2$, comprising mainly clasts of quartz-phyric Plinth Assemblage dacite. Our studies show these deposits derive from two separate events; it is likely that both events blocked the Lillooet River and impounded lakes.

Upstream of Keyhole Falls, Evans (1992) sampled a tree rooted in a rock avalanche deposit. The tree, radiocarbon dated at 1860±50, was subsequently killed by rising water after downstream damming of the river impounded a lake. We suggest that deposition of unit $Avbx_2$ may have formed this dam, placing the rock avalanche several hundred years after eruption.

The tight confines of the valley represent a continuing hazard. This narrow defile could be easily blocked by future landslides. The presence of at least two landslide deposits, seemingly unrelated to volcanic events, attests to the instability of the adjacent volcanic edifice of Plinth Peak. Regardless of future volcanic activity, other rock avalanches can be expected (Read 1990).

Summary

The Pebble Creek Formation records some of the hazardous events associated with eruptions in mountainous terrain. The formation comprises the eruptive products of the 2350 B.P. eruption of the Mount Meager volcanic complex and two unrelated rock avalanche deposits. The eruption was episodic, and the formation comprises fallout pumice, pyroclastic flows, welded breccias, lahars and a lava flow. The welded breccia dammed the Lillooet River. Collapse of the dam triggered an outburst flood with an estimated total volume of 10^9 m^3. The flood inundated the Lillooet Valley to a depth of at least 30 m above the paleo-valley floor 5.5 km downstream of the blockage. Rock avalanches comprising mainly blocks of Plinth Assemblage volcanic rocks underlie and overlie the primary volcanic units. Much of the stratigraphic complexity evident in the Pebble Creek Formation results from deposition in a narrow, steep-sided mountain valley containing a major river.

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References

Anderson RG (1975) The geology of the volcanics in the Meager Creek map-area, southwestern British Columbia. B.Sc. thesis, Dep Geological Sci, Univ British Columbia, pp 1–130

Bardintzeff JM (1984) Merapi Volcano (Java, Indonesia) and Merapi-type nuee ardente. Bull Volcanol 47:433–446

Bonnichsen B, Kauffman DF (1987) Physical features of rhyolite lava flows in the Snake River Plain volcanic province, southwestern Idaho. In: Fink JH (ed) The emplacement of silicic domes and lava flows. Geol Soc Am Spec Paper No. 212:119–145

Boudon G, Camus G, Gourgaud A, Lajoie J (1993) The 1984 nuee-ardente deposits of Merapi volcano, central Java, Indonesia: stratigraphy, textural characteristics, and transport mechanisms. Bull Volcanol 55:327–342

Carey S, Sparks RSJ (1986) Quantitative models of the fallout and dispersal of tephra from volcanic eruption columns. Bull Volcanol 48:109–125

Cas RAF, Wright JV (1987) Volcanic Successions: Modern and Ancient Regimes. Chapman and Hall, London, UK, pp 1–528

Clague JJ, Souther JG (1982) The Dusty Creek landslide on Mount Cayley, British Columbia. Can J Earth Sci 19:524–539

Clague JJ, Evans SG, Rampton VN, Woodsworth GJ (1995) Improved age estimates for the White River and Bridge River tephras, western Canada. Can J Earth Sci 32:1172–1179

Cruden DM, Lu ZY (1992) The rockslide and debris flow from Mount Cayley, B.C., in June 1984. Can Geotech J 4(9):614–626

Cui Y, Russell JK (1995) Magmatic origins of calc-alkaline intrusions from the Coast Plutonic Complex, southwestern British Columbia. Can J Earth Sci 32:1643–1667

Davies KD, Quearry M, Bonis SB (1978) Glowing avalanches from the 1974 eruption of the volcano Fuego, Guatemala. Geol Soci Am Bull 89:369–384

Drysdale CW (1916) Bridge River map area, Lillooet Mining Division. Geol Surv Can Summary Rep pp 1–75

Evans S (1992) Landslide and river damming events associated with the Plinth Peak volcanic eruption, southwestern British Columbia. In: Geotechnical and natural hazards. BiTech Publishers, Vancouver, BC, pp 405–412

Evans SG, Brooks GR (1991) Prehistoric debris avalanches from Mount Cayley volcano, British Columbia. Can J Earth Sci 28:1365–1374

Fisher RV, Schmincke H-U (1984) Pyroclastic Rocks. Springer-Verlag, Berlin, pp 1–472

Francis PW, Roobol MJ, Walker GPL, Cobbold PR, Coward M (1974) The San Pedro and San Pablo volcanoes and their hot avalanche deposits. Geol Runds 63:357–388

Gabrielse H, Yorath CJ (1991) The Cordilleran Orogen: Canada. In: Geology of Canada, no. 4. Geol Surv Can, pp 1–844 (Also Geol Soc Am, The Geology of North America, vol. G-2)

Green NL, Armstrong RL, Harakal JE, Souther JG, Read PB (1988) Eruptive history and K-Ar geochronology of the late Cenozoic Garibaldi volcanic belt, southwestern British Columbia. Geol Soc Am Bull 100:563–579

Guffanti M, Weaver CS (1988) Distribution of Late Cenozoic volcanic vents in the Cascade Range: Volcanic arc segmentation and regional tectonic considerations. J Geophys Res 93:6513–6529

Heiken G, Wohletz K (1987) Tephra deposits associated with silicic domes and lava flows. In: The Emplacement of Silicic Domes and Lava Flows (ed.), Fink JH (ed). Geol Soc Am Spec Pap 212:55–76

Hickson CJ (1994) Character of volcanism, volcanic hazards, and risk, northern end of the Cascade magmatic arc, British Columbia and Washington State. In: Monger JWH (ed) Geology and geological hazards of the Vancouver region, southwestern British Columbia (ed.). Geol Surv Can Bull 481:231–250

Irvine TN, Baragar WRA (1971) A guide to the chemical classification of the common volcanic rocks. Can J Earth Sci 8:523–548

Ke P (1992) A new approach to mass balance modelling: applications to igneous petrology. MSc thesis, Geol Sci Univ BC Vancouver, pp 1–153

Kerr PF, Gavesci AT, Bowes DR (1974) Welded glass-breccias from Marysvale, Utah. Geol Mag 111:15–22

Koyaguchi T (1985) Magma mixing in a conduit. J Volcanol Geotherm Res 25:365–369

Le Bas MJ, Le Maitre RW, Steckeisen A, Zanettin B (1986) Chemical classification of volcanic rocks. J Petrol 27:745–750

Leonard EM (1995) A varve-based calibration of the Bridge River tephra fall. Can J Earth Sci 32:2098–2102

Luty JR (1994) Eruption characteristics and industrial application potential of the Bridge River airfall pumice deposit, Mount Meager, southwestern British Columbia. BASc thesis, Univ. BC Vancouver, pp 1–41

Moore DP, Mathews WH (1978) The Rubble Creek landslide, southwestern British Columbia. Can J Earth Sci 15:1039–1052

Moore JG, Lipman PW, Swanson DA, Alpha TR (1981) Growth of lava domes in the crater, June 1980–January 1981. US Geol Surv Prof Pap 1250:541–548

Nakada S (1993) Lava domes and pyroclastic flows of the 1991–1992 eruption at Mount Unzen volcano. In: Yanagi T, Okada H, Ohta T (eds) Unzen Volcano: the 1990–1992 eruption, Nishinippon and Kyushu Univ Press, Fukuoka, Japan, pp 55–66

Nasmith H, Mathews WH, Rouse GE (1967) Bridge River ash and some other Recent ash beds in British Columbia. Can J Earth Sci 4:163–170

Philpotts AR (1990) Principles of igneous and metamorphic petrology. Prentice Hall, Eaglewood Cliffs, New Jersey, pp 1–498

Read PB (1977a) Meager Creek volcanic complex, southwestern British Columbia. In: Rep Activ:A Geol Surv Can Pap 77-1A:277–281

Read PB (1977b) Geology of Meager Creek geothermal area, British Columbia. Geol Surv Can Open File 603

Read PB (1990) Mount Meager Complex, Garibaldi Belt, southwestern British Columbia. Geo Can 17:167–174

Rodriguez-Elizarraras S, Siebe C, Komorowski JC, Espindola JM, Saucedo R (1991) Field observations of pristine block and ash flow deposits emplaced April 16–17, 1991 at Volcan de Colima, Mexico. J Volcanol Geotherm Res 48:399–412

Rohr KMM, Govers R, Furlong KP (1996) A new plate boundary model for the Pacific-North America-Juan de Fuca triple junction. In: Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) and Cordilleran Tectonics Workshop. Lithoprobe Report 50:213–214. Univ BC, Lithoprobe Secretariat [for the] Canadian Lithoprobe Program. British Columbia, Canada

Rose WI (1987) Volcanic activity at Santiaguito volcano, 1976–1984. In: Fink JH (ed) The emplacement of silicic domes and lava flows. Geol Soc Am Spec Pap 212:17–28

Russell JK, Stasiuk MV (1997) Characterization of volcanic deposits with ground-penetrating radar. Bull Volcanol 58:515–527

Sato H, Fujii T, Nakada S (1992) Crumbling of dacite dome lava and generation of pyroclastic flow at Unzen volcano. Nature 360:664–666

Sherrod DR, Smith JG (1990) Quaternary extrusion rates of the Cascade Range, northwestern United States and southern British Columbia. J Geophys Res 95:19645–19474

Sparks RSJ (1976) Grain size variations in ignimbrites and implications for the transport of pyroclastic flows. Sedimentology 23:147–188

Sparks RSJ, Sigurdsson H, Wilson L (1977) Magma mixing: a mechanism for triggering acid explosive eruptions. Nature 267:315–318

Sparks RSJ, Wilson L, Hulme G (1978) Theoretical modelling of the generation, movement and emplacement of pyroclastic flows by column collapse. J Geophys Res 83:1727–1739

Sparks RSJ, Stasiuk MV, Gardeweg M, Swanson DA (1993) Welded breccias in andesite lavas. J Geol Soc London 150:897–902

Stasiuk MV, Russell JK (1989) Petrography and chemistry of the Meager Mountain volcanic complex, southwestern British Columbia. In: Cur Res:E. Geol Surv Can Pap 89-1E:189–196

Stasiuk MV, Russell JK (1990) The Bridge River Assemblage in the Meager Mountain volcanic complex, southwestern British Columbia. I: Cur Res:E. Geol Surv Can Pap 90-1E:153–157

Stasiuk MV, Jaupart C, Sparks RSJ (1993a) On the variations of flow rate in non-explosive lava eruptions. Earth Planet Sci Lett 114:505–516

Stasiuk MV, Jaupart C, Sparks RSJ (1993b) Influence of cooling on lava-flow dynamics. Geol 21:335–338

Stasiuk MV, Russell JK, Hickson CJ (1996) Distribution, nature, and origins of the 2400 B.P. eruption products of Mount Meager, British Columbia: linkages between magma chemistry and eruption behaviour. Geol Surv Can Bull 486, pp 1–27

Stevenson LS (1947) Pumice from Haylmore, Bridge River, British Columbia. Am Mineral 32:547–552

Walker GPL (1971) Grain-size characteristics of pyroclastic deposits. J Geol 79:696–714

Westgate JA, Dreimanis A (1967) Volcanic ash layers of Recent age at Banff National Park, Alberta, Canada. Can J Earth Sci 4:155–161

Young S, Sparks RSJ, Robertson R, Lynch L, Aspinall W (1997) Eruption of Soufriere Hills volcano in Montserrat continues. EOS Trans 78:401–409