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Preliminary petrography and chemistry of the Mount Cayley volcanic field, British Columbia

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Abstract

Sixty-two samples from five volcanic centres (Ember Ridge, Mount Fee, Slag Hill, Ring Mountain, and Little Ring Mountain) were collected as part of a preliminary petrological investigation of the Mount Cayley volcanic field. The sampled deposits are flows and domes, and many show features indicative of ice contact during eruption (e.g. abundant glass, fine-scale jointing). Mineralogically, the samples range from andesite to rhyodacite, and chemically, the rocks span a range from andesite to dacite. Glassy samples are abundant, with glass contents as high as 70%.

Résumé

Soixante-deux échantillons ont été prélevés dans cinq centres volcaniques (Ember Ridge, Mount Fee, Slag Hill, Ring Mountain et Little Ring Mountain) dans le cadre d'une étude pétrologique préliminaire du Complexe volcanique de Mount Cayley. Les dépôts échantillonnés sont des coulées et des dômes volcaniques; bon nombre d'entre eux montrent des caractéristiques (telles que l'abondance de verre et la présence de diaclases à petite échelle) qui laissent supposer l'existence d'un contact glaciaire durant l'éruption. D'un point de vue minéralogique, les échantillons vont de l'andésite à la rhyodacite et d'un point de vue chimique, de l'andésite à la dacite. Les échantillons vitreux sont abondants; leur teneur en verre peut atteindre jusqu'à 70 p. 100.

INTRODUCTION

The Garibaldi Volcanic Belt of southwestern British Columbia is the northern extension of the Cascade magmatic arc of the western United States (Green et al., 1988; Guffanti and Weaver, 1988; Read, 1990; Sherrod and Smith, 1990; Hickson, 1994). It extends from Mount Garibaldi, near the head of Howe Sound, northward to Silverthrone Mountain. Eruptive units in the Garibaldi Volcanic Belt range from Miocene to Holocene and are largely related to subduction of the Juan de Fuca Plate beneath the North American Plate (Green et al., 1988; Rohr et al., 1996). The belt comprises at least 14 separate volcanoes and includes rocks ranging in composition from high-alumina basalt to rhyolite. Volcanism within the Garibaldi Volcanic Belt has produced stratovolcanoes, isolated flows, domes, spines, cones, and tuyas. The most recent eruption in the Garibaldi Volcanic Belt occurred at Mount Meager at 2350 BP (Clague et al., 1995; Leonard, 1995).

The Mount Cayley volcanic field is located in the central part of the Garibaldi Volcanic Belt, 45 km north of Squamish, in southwestern British Columbia (**Fig. 1**). It comprises mainly Miocene to Pleistocene volcanic rocks, and includes specific centres at Ember Ridge, Mount Fee, Mount Cayley, Pali Dome, Cauldron Dome, Slag Hill, Ring Mountain, and Little Ring Mountain. These younger volcanic rocks unconformably overlie older crystalline basement (Souther, 1980). Some edifices display morphologies and/or lithological characteristics associated with subglacial or ice-contact volcanism.

Because of difficult access, the Mount Cayley volcanic field has not been studied or mapped in detail. To date, most geological studies of the Mount Cayley volcanic field have focused on landslide hazards and geothermal potential (e.g. Souther, 1980; Clague and Souther, 1982; Brooks and Hickin, 1991; Evans and Brooks, 1991). Because of its poorly consolidated slopes, Mount Cayley has been the site of two major historical debris avalanches (Clague and Souther, 1982; Evans, 1986; Jordan, 1987; Lu, 1988); prehistoric landslide deposits are also present (Evans and Brooks, 1991). Mount Cayley, at 2394 m elevation, is a composite volcano consisting of poorly lithified pyroclastic rocks and lavas, which underwent at least three stages of eruptive activity (Souther, 1980). The most recent eruptions are dated at 310 000 years ago (K-Ar; Green et al., 1988).

In this paper, we review the distribution of volcanic rocks in the Mount Cayley volcanic field. We present petrological data on rocks from five separate volcanic centres based on sampling conducted in 1998; a geological mapping project is currently underway. Finally, we compare the major-element chemical composition of these rocks to that of other volcanic centres within the Garibaldi Volcanic Belt.

MOUNT CAYLEY VOLCANIC FIELD

Mount Cayley volcano and a number of discrete eruptive centres were described by Souther (1980; Fig. 2). These eruptive centres are Ember Ridge, Mount Fee, Mount Cayley, Cauldron Dome, Pali Dome, Slag Hill, and Crucible Dome (this paper uses the topographic map name 'Ring Mountain', except where summarizing the observations of Souther (1980), who used the name 'Crucible Dome'). The initial descriptions and interpretations (Souther, 1980) are summarized in the following paragraphs.

Ember Ridge (at the southern known extent of the Mount Cayley volcanic field) consists of a series of steep-sided domes of glassy, complexly jointed, hornblende-phyric basalt. Lithological and structural similarities suggest that the domes are of similar age and could have originated from a single source. Their morphologies and colloform surfaces may be due to rapid quenching during a period of extensive ice cover. Thus, rather than spreading out as flows, the lavas would have piled up directly over the vents.

The Mount Fee complex is situated approximately 1 km north of Ember Ridge (Fig. 3a) and consists of a narrow summit ridge of biotite-plagioclase-phyric rhyodacite lava and breccia approximately 1 km long, with numerous spines rising 100 to 150 m above it. Pyroclastic material is present at several locations, suggesting that the ridge may once have been surrounded by a mantle of pyroclastic rocks that has now been mostly removed by erosion. The central intrusive spine was probably the final event occurring at Mount Fee (from crosscutting relationships). No known quench features have been found at Mount Fee. Furthermore, the absence of underlying till suggests that the volcanism is preglacial.

At Mount Cayley (Fig. 3b, showing approximately 250 m of relief), three eruptive stages were recognized. The first (Mount Cayley stage) is represented by a complex pile of plagioclase-hypersthene-hornblende-phyric dacite flows, tephra, and breccia, which are hydrothermally altered to varying degrees. The Vulcan's Thumb stage followed, named for the largest of a number of slender pinnacles protruding from the sharp summit ridge of Pyroclastic Peak. Its products consist of vent breccia, massive lava, and agglutinated breccia of plagioclase-hypersthene-hornblende-biotite-phyric dacite deposited as part of an edifice that grew upon the southwestern flank of the ancestral Mount Cayley. Finally, the Shovelnose stage produced two small plagioclase-hypersthene-biotite-phyric dacite domes and related flows and tephra units that are exposed in the Shovelnose Creek valley. There are no obvious indications of volcano–ice interaction at Mount Cayley.

Pali Dome (north of Mount Cayley) is currently partially obscured by ice. It is dominated by coarsely plagioclase-hypersthene-(±hornblende)-phyric andesite flows. Proximal parts of flows have vertical, well developed, large-diameter columnar joints, and are underlain by scoriaceous oxidized flow breccia, indicating a probable subaerial origin. Distal parts of flows are glassy and have smaller diameter columnar joints with horizontal or locally radial orientations; flow terminations occur as subvertical cliffs up to 200 m high. These are features consistent with eruption against ice.

Cauldron Dome (northwest of Pali Dome) is an almost flat-topped pile of coarsely plagioclase-orthophyroxene-phyric andesite flows. Its gross morphology is similar to that of a tuya; however, any direct record of quenching (i.e. glass, fine-scale jointing) has likely been removed by erosion. Two compositionally identical flows extend to the southwest from the base of the pile. It is possible that Cauldron Dome was erupted subglacially and the related flows were extruded through a meltwater channel.

The Slag Hill centre consists of glassy, augite-phyric basaltic andesite in steep-sided, glassy, finely jointed domes similar to those of Ember Ridge, and one small, flat-topped bluff. The morphologies and quench features suggest that eruption occurred subglacially.

Ring Mountain (Fig. 3c, showing approximately 590 m relief from its top to the lowest part of the surrounding valley) has the classical tuya morphology, being a nearly circular, flat-topped pile of plagioclase-hypersthene-phyric andesite surrounded by a talus apron. The uppermost surface is covered with bomb-like fragments of vesicular, oxidized lava, indicating that the upper flows were subaerial; however, as is the case at volcanoes of similar morphology elsewhere, lower levels could have erupted subglacially.

Little Ring Mountain (270 m in height, Fig. 3d), located at the northernmost known extent of the Mount Cayley volcanic field, was not included in the original geological map of the region (Souther, 1980). It is a nearly circular, flat-topped, steep-sided feature, approximately 270 m high and 120 m across (on the top surface). It has the outward morphology of a tuya, although its internal stratigraphy is currently unknown. Its top surface is strewn with loose rubble consisting of prismatically jointed blocks, although some in situ lavas can be accessed at its cliff edges. The surface rubble contains approximately 1% xenoliths, as loose blocks or as fused fragments within lava. Lavas are fine-grained to glassy black plagioclase-augite-phyric andesite.

PETROLOGICAL CHARACTERISTICS

Sample suite

Sixty-two samples were collected from both previously mapped centres (Ember Ridge, Mount Fee, Slag Hill, and Ring Mountain (Souther, 1980)) and one new locality (Little Ring Mountain) (Fig. 2).

Petrography

The mineralogy of selected samples is summarized in Table 1; Table 2 lists the co-ordinates of all samples discussed in this paper. The rocks range from andesite to rhyodacite on the basis of mineralogy; however, an abundance of glass, a scarcity of phenocrysts, and an abundance of possible xenoliths and/or xenocrysts in many samples hinder an accurate mineralogical classification.

Reconnaissance petrological observations made at Ember Ridge, Mount Fee, Slag Hill, and Ring Mountain, previously studied by Souther (1980), concur with or complement his descriptions.

Ember Ridge andesite lava consists of up to 55% brownish-green glass with trachytic groundmass plagioclase. Phenocryst content ranges up to 35%, comprising some or all of plagioclase, hornblende, orthopyroxene, and augite, as isolated crystals and clots. A discrete centre south of Ember Ridge, possibly unrelated (due to its topographic isolation), is informally named 'Betty's Bump'. It consists of dark grey andesite, having 20% dark brown glass and 15% to 20% phenocrysts of olivine, plagioclase, and augite.

Mount Fee lavas are primarily dacite (and rhyodacite), containing up to 70% brown glass and up to 15% vesicles (Fig. 4a). Crystal content ranges up to 25%, consisting of inclusion-rich plagioclase, hornblende (overgrown by oxides), and orthopyroxene, with rare quartz and probable K-feldspar xenocrysts. One sample from the southwest side of Mount Fee contains no glass, but instead has an unusual cryptocrystalline groundmass (Fig. 4b), suggesting that it may have formed as part of a shallow intrusion.

Slag Hill consists of andesite lavas with up to 70% dark brown glass with varied degrees of trachytic texture in the groundmass plagioclase, and less than 5% vesicles. Phenocryst content ranges from 1% to 10% and include some or all of plagioclase (inclusion-rich and embayed), hornblende, and augite. Very rare K-feldspar crystals, which are probably xenocrysts, are present.

Ring Mountain andesite lavas (**Fig. 4c**) contain up to 70% brown glass and up to 15% vesicles (commonly distorted by later flow). The groundmass plagioclase is trachytic. Microphenocrysts of augite, biotite, plagioclase (inclusion-rich, with embayed edges), and hornblende make up 1% to 7% of the rocks. Microxenocrysts of quartz are common; possible microxenocrysts of K-feldspar also occur.

The petrography of Little Ring Mountain has not been studied previously. Its lava units contain up to 70% brown glass, with sparse plagioclase phenocrysts. Possible xenocrysts of quartz (sometimes fringed by very fine-grained clinopyroxene) are present. Vesicularity (up to 5%) suggests that the lava erupted subaerially. The xenolith fragment (taken from the loose surface rubble) examined petrographically contains abundant quartz xenocrysts and polycrystalline quartz xenoliths in a glassy groundmass with trachytic plagioclase (**Fig. 4b, Table 1**), and cannot be easily related to the surface lavas. More study is required to determine the source of the xenoliths, their relationship to the other lavas, and the overall stratigraphy of Little Ring Mountain.

Geochemical composition

Preliminary major- and trace-element chemical analyses of whole-rock powders by X-ray fluorescence were conducted at McGill University Geochemical Laboratories on 11 of the more glassy samples. Samples were prepared as described in Russell and Snyder (1997). Results are summarized in **Table 3**. All samples are andesite or dacite (**Fig. 5a**) of calc-alkaline affinity (**Fig. 5b**).

The major-element compositions of samples from the Mount Cayley volcanic field are compared to samples from two other locations in southwestern British Columbia (Fig. 1), Mount Garibaldi (Green, 1977) and Mount Meager (Stasiuk and Russell, 1988; Hickson et al., 1999) (Fig. 5a, 5b, **5c**). The Mount Garibaldi suite includes samples from the Cheakamus River valley basalts, and from two centres at which volcano–ice interaction is evident, The Table and The Barrier. Mount Meager samples display a broader chemical range than those of Mount Cayley; however, the Mount Meager sample set is larger, and further sampling in the Mount Cayley region may reveal a similarly broad compositional range. Mount Cayley samples are most similar in composition to the andesites of The Barrier, near Garibaldi Lake, and are calc-alkaline.

FURTHER INVESTIGATIONS

Further investigations of the Mount Cayley volcanic field will involve extensive geological mapping and sampling, more major- and trace-element analyses of rock samples, electron-microprobe analyses of mineral compositions, and Ar-Ar dating to establish chronologies. The investigations will elucidate the nature of volcano–ice interaction at intermediate to felsic volcanoes.

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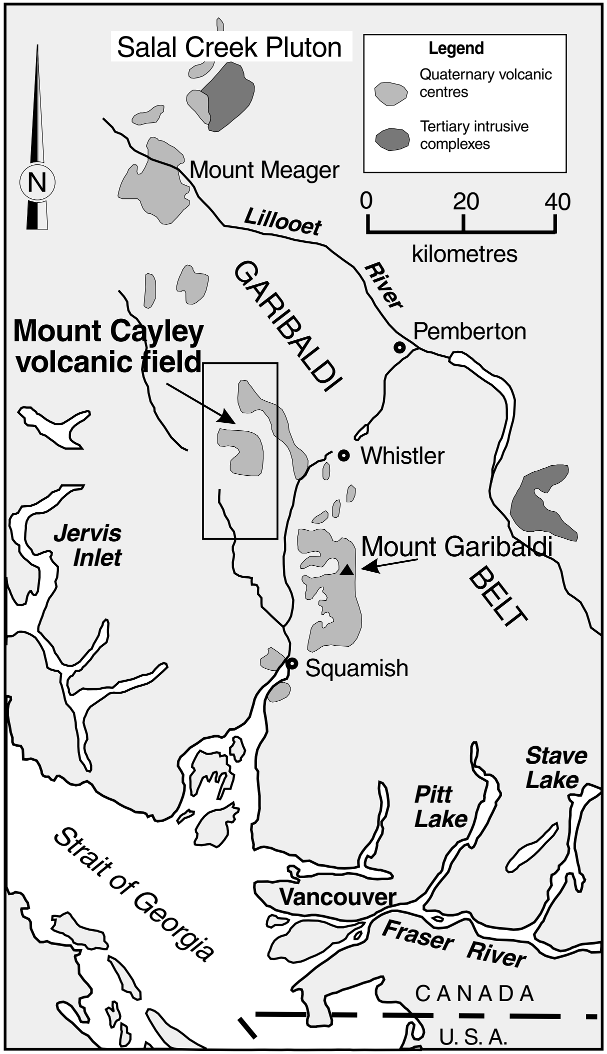


Figure 1. Location of the Mount Cayley volcanic field (box) with respect to other Quaternary volcanic rocks of the Garibaldi Volcanic Belt, southwestern British Columbia (*after* Hickson, 1994).

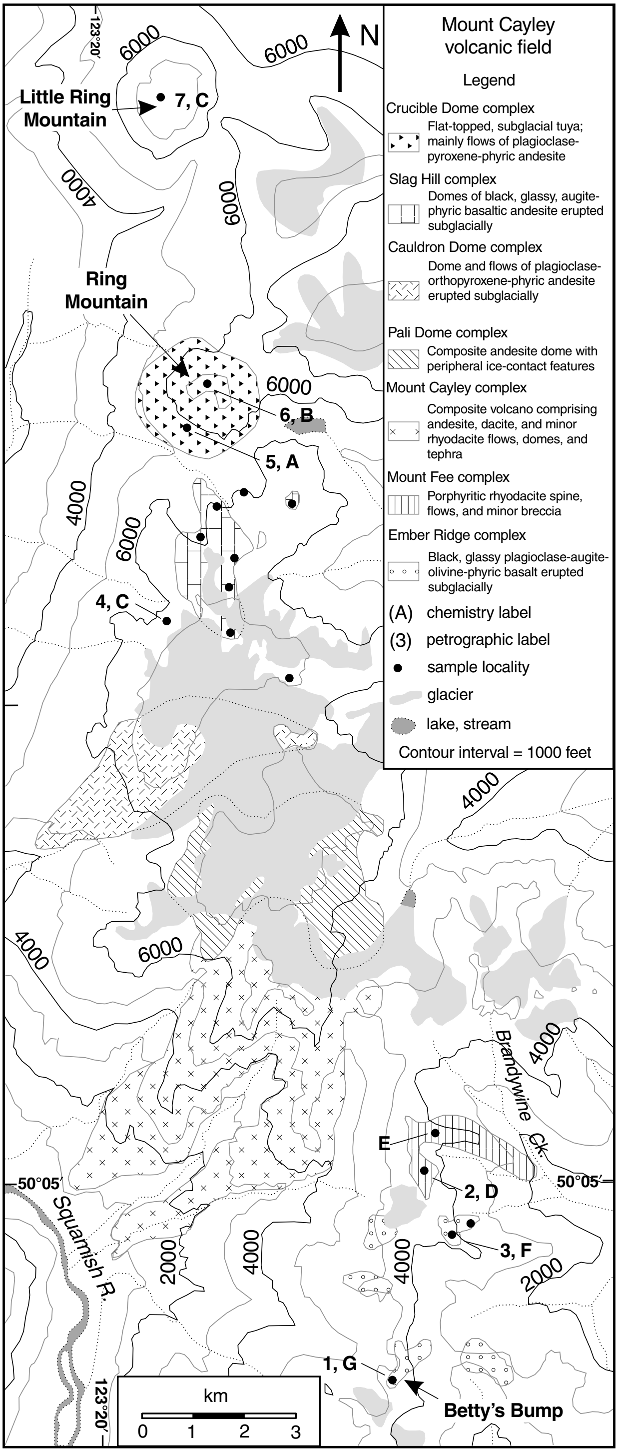
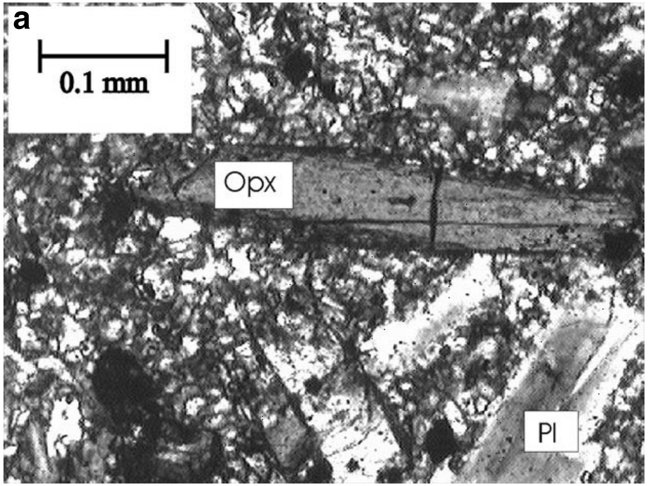
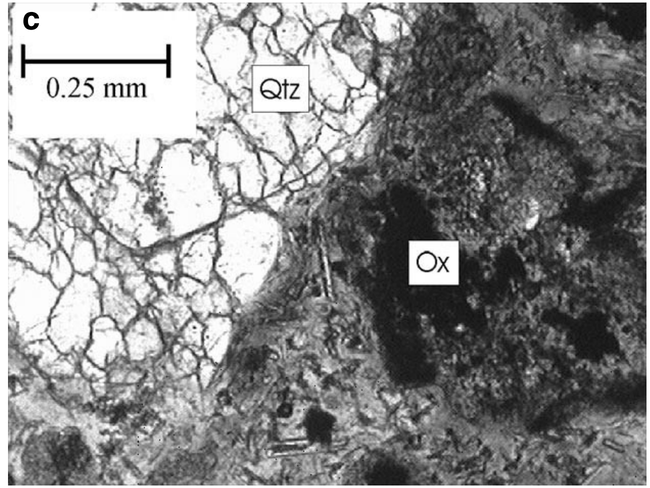


Figure 2. Geological map showing the location of complexes and volcanic features of the Mount Cayley volcanic field (*modified from* Souther, 1980). Little Ring Mountain was not included in the original map.

Figure 3. Morphology of four volcanic centres in the Mount Cayley volcanic field, **a)** Mount Fee, **b)** Mount Cayley, **c)** Ring Mountain, and **d)** Little Ring Mountain.





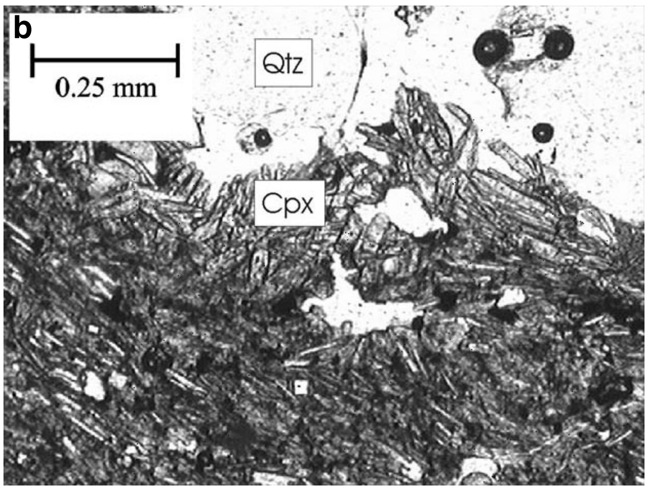


Figure 4. Petrographic textures of Mount Cayley volcanic field samples in plane-polarized (ppl) and crosspolarized (cpl) light. Images are of samples from **a)** Mount Fee (cpl), showing orthopyroxene (opx) and plagioclase (pl) in an unusual cryptocrystalline groundmass (no glass is present); **b)** Little Ring Mountain's top surface (ppl), showing a polycrystalline quartz xenolith (qtz) and fine-grained oxide-bearing xenoliths (ox) in glassy groundmass; and **c)** Ring Mountain's uppermost flow (ppl), showing quartz (qtz) fringed by finer grained acicular clinopyroxene (cpx), surrounded by brown glass with trachytic plagioclase, Fe-Ti oxides, and minor clinopyroxene.

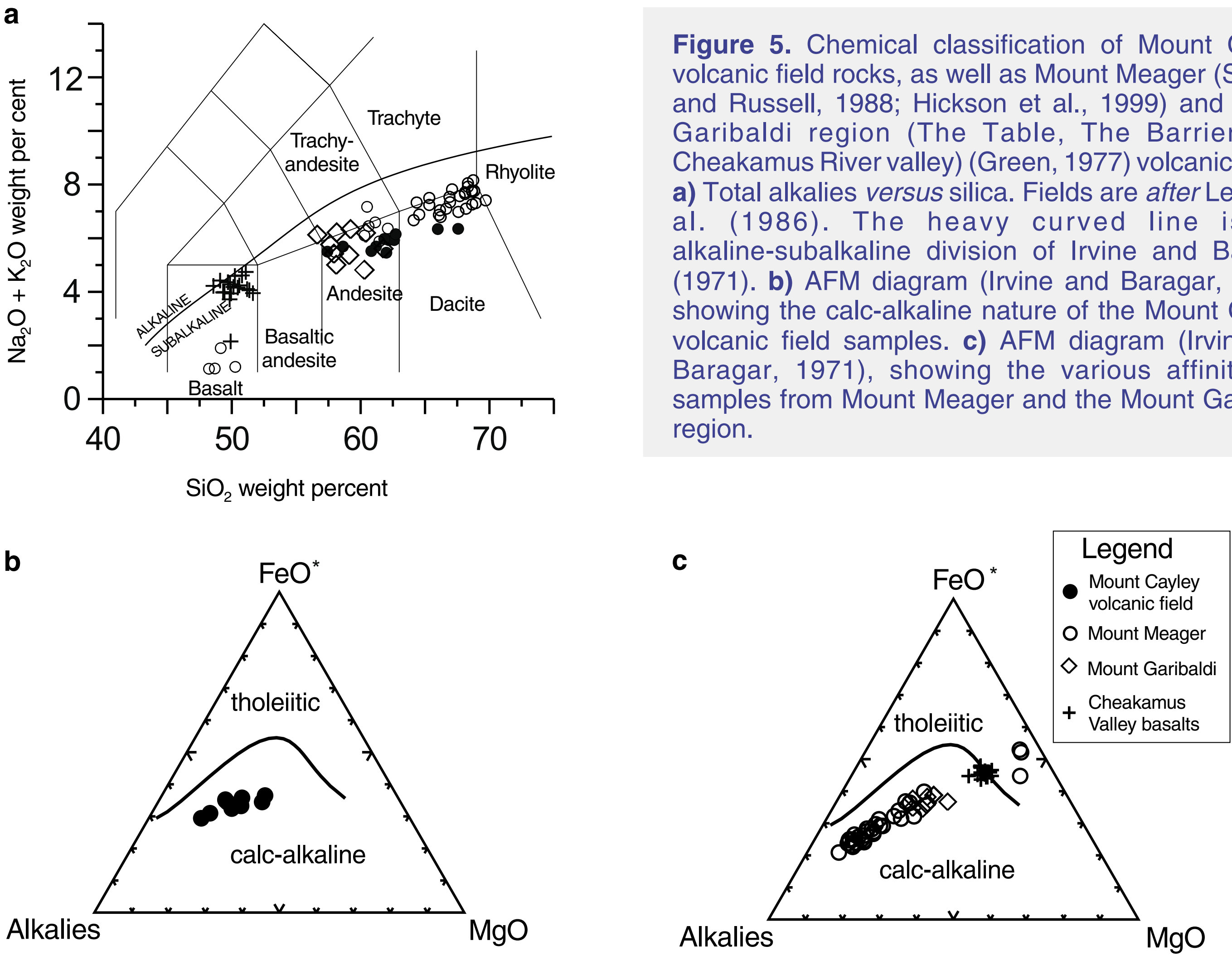


Figure 5. Chemical classification of Mount Cayley volcanic field rocks, as well as Mount Meager (Stasiuk and Russell, 1988; Hickson et al., 1999) and Mount Garibaldi region (The Table, The Barrier, and Cheakamus River valley) (Green, 1977) volcanic rocks. **a)** Total alkalies *versus* silica. Fields are *after* LeBas et al. (1986). The heavy curved line is the alkaline-subalkaline division of Irvine and Baragar (1971). **b)** AFM diagram (Irvine and Baragar, 1971), showing the calc-alkaline nature of the Mount Cayley volcanic field samples. **c)** AFM diagram (Irvine and Baragar, 1971), showing the various affinities of samples from Mount Meager and the Mount Garibaldi region.

Table 1. Mineralogy[1] and petrography of selected samples from the Mount Cayley volcanic field.

No.[2]	Label	Phenocrysts	Groundmass	Xenocrysts [3]/xenoliths	Sample description
1	KR-15*	Ol ~ Pl ~ Aug	20% dark brown glass, Pl, Px, oxides		grey-brown porphyritic, weakly trachytic andesite lava
2	KR-11*	Opx > Pl > Qtz > Ksp ~ Bt; oxide overgrowths common	cryptocrystalline	Qtz, (?) Ksp	grey porphyritic dacite lava; 5% microvesicles
3	KR-13*	Pl > Hbl > Opx >> Aug	55% pale brown glass, Pl		black, dense, porphyritic, seriate-textured andesite lava
4	KR-9-5	Aug > Pl > Ksp microphenocrysts	55% dark to medium brown glass, Pl, oxides, Px		dark brown trachytic, microporphyritic, brecciated (?)rhyodacite lava
5	KR-2*	Rare (~1%); Opx ~ Pl; oxide overgrowths common	45% medium brown glass, Pl, Opx, oxides		grey-black, very fine-grained trachytic andesite lava; 10-15% vesicles/microvesicles (commonly distorted by flow)
6	KR-5*	Pl > Bt > Hbl >> (?) Opx	70% pale brown glass, Pl, oxides	Qtz-Aug xenoliths, polycrystalline Px xenoliths	dark brown-black, fine-grained, microporphyritic trachytic andesite lava; 5% vesicles (some distorted by flow); rare amygdules; phenocrysts commonly partially resorbed
7	KR-8-5	Pl (?) ~ Aug	55% medium brown glass, Pl, oxides	Qtz xenoliths/ xenocrysts	dark brown-grey trachytic (?)andesite; 5% microvesicles

[1]Abbreviations for minerals are from Kretz (1983).
[2]All samples have the prefix HHB-98-, and the numbers in the first column are keyed to localities in Figure 4.
[3]Inferred to be xenocrystic based on texture and habit.
*Chemically analyzed; *see* Table 3.

Table 2. Locations of samples described in Table 1 and Table 3.

Label[1]	Latitude (N)	Longitude (W)	Complex	[2]Petrography code	[3]Chemistry code
KR-15	50°3.86′	123°14.95′	Ember Ridge	1	H
KR-13	50°4.21′	123°12.95′	Ember Ridge	3	G
KR-10	50°5.17′	123°14.70′	Mount Fee		E
KR-11	50°5.59′	123°14.47′	Mount Fee	2	F
KR-9-5	50°11.83′	123°17.42′	Slag Hill	4	
KR-9-1	50°11.83′	123°17.37′	Slag Hill		D
KR-9-2	50°11.83′	123°17.37′	Slag Hill		D
KR-1	50°12.97′	123°18.32′	Ring Mountain		A
KR-2	50°13.10′	123°18.16′	Ring Mountain	5	A
KR-4	50°13.21′	123°18.11′	Ring Mountain		B
KR-5	50°13.31′	123°18.63′	Ring Mountain	6	B
KR-8-2	50°16.75′	123°19.04′	Little Ring Mountain		C
KR-8-5	50°16.77′	123°19.04′	Little Ring Mountain	7	

[1]All samples have the prefix HHB-98-
[2]The sample's petrography is summarized in Table 1.
[3]The sample's chemistry is listed in Table 3.

Table 3. Major and trace element whole rock compositions of volcanic rocks from the Mount Cayley volcanic field.

Sample[1]	KR-1 (A)	KR-2 (A)	KR-4 (B)	KR-5 (B)	KR-8-2 (C)	KR-9-1 (D)	KR-9-2 (D)	KR-10 (E)	KR-11 (F)	KR-13 (G)	KR-15 (H)
Rock type	andesite	andesite	andesite	andesite	andesite	andesite	andesite	dacite	dacite	andesite	andesite
SiO_2	62.18	58.63	62.60	62.72	61.20	60.83	62.00	65.99	67.57	61.83	57.42
TiO_2	0.63	0.64	0.62	0.61	0.71	0.80	0.59	0.45	0.41	0.58	0.71
Al_2O_3	17.97	18.09	17.93	17.38	17.49	17.64	18.31	16.72	16.26	17.99	18.41
FeO	4.41	5.25	4.45	4.27	4.45	4.68	4.16	3.69	3.31	4.39	5.63
MnO	0.08	0.10	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.09	0.11
MgO	2.27	4.28	2.25	2.76	2.96	2.88	2.88	1.88	1.60	2.40	4.31
CaO	5.73	6.29	5.74	5.62	6.18	6.82	6.12	4.27	3.88	5.55	7.17
Na_2O	4.38	4.68	4.37	4.49	4.26	4.12	4.33	4.55	4.46	4.53	4.44
K_2O	1.55	1.01	1.56	1.66	1.43	1.40	1.13	1.79	1.89	1.44	1.06
P_2O_5	0.27	0.25	0.27	0.23	0.26	0.31	0.20	0.18	0.16	0.19	0.24
H_2O^-	0.15	0.26	0.01	0.08	0.20	0.10	0.19	0.08	0.22	0.30	0.12
H_2O^+	0.09	0.56	0.11	0.09	0.50	0.27	0.18	0.01	0.00	0.49	0.01
Total	99.71	100.04	99.98	100.00	99.72	99.93	100.16	99.69	99.84	99.77	99.62
LOI	0.14	0.55	0.03	0.11	0.42	0.21	0.11	0.02	0.12	0.90	0.00
Ba	562	427	570	643	479	472	373	775	798	555	493
Rb	19	12	19	24	20	19	15	27	28	21	14
Sr	1439	1020	1429	1088	1300	1942	1242	644	580	758	909
Cr	180	38	66	57	51	23	50	31	25	85	40
Sc	16	11	b.d.	17	16	b.d.	11	b.d.	10	15	13
Pb	9	8	9	7	8	7	6	9	9	7	7
Ga	20	19	19	19	20	20	19	17	17	18	19
Nb	3	4	3	4	3	1	3	6	6	5	5
Th	3	b.d.	2	2	3	5	1	b.d.	b.d.	b.d.	b.d.
U	b.d.	b.d.	1	b.d.	b.d.	1	b.d.	b.d.	b.d.	b.d.	b.d.
Y	11	13	10	12	11	9	9	15	14	14	15
Zr	135	92	132	132	156	141	95	117	108	103	102
Hf	6	5	6	6	6	6	6	6	6	6	6
Ce	57	52	48	64	49	75	42	41	52	33	34
La	10	3	11	10	11	14	1	5	4	5	7

[1] All samples have prefix HHB-98-, and the letters in parentheses after the sample number are keyed to localities in Figure 4.
b.d. = below detection limits