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Critical review

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Abstract: Quaternary intermediate volcanic rocks of the Monmouth Creek volcanic complex, located west of Squamish, British Columbia were mapped to determine their extent and origin. The deposits are distributed within a deep embayment in the granite wall of the Howe Sound, and have a present day thickness of about 200 m. They comprise a sequence of andesite lavas, domes, and lobes, and associated monolithological andesitic breccia units. Cogenetic, en echelon andesite dykes intrude the entire complex, and their erosional remnants outcrop as a series of steep-sided, enigmatic pinnacles and spires. On the basis of petrographic and geochemical criteria the authors identify two distinct magma types expressed as aphyric andesite and hornblende andesite. On the basis of field relationships and the properties of the volcanic deposits and their distributions, the Monmouth Creek volcanic complex is shown to have a glaciovolcanic origin. A model is presented for the emplacement of the volcanic deposit that indicates the presence of a major fjord-filling glacier, likely greater than 1 km thick and occupying Howe Sound to an elevation of about 800 m above present-day sea level at the time of eruption.

Résumé : Les roches volcaniques de composition intermédiaire du Quaternaire du complexe volcanique de Monmouth Creek, situé à l'ouest de Squamish (Colombie-Britannique), ont été cartographiées afin d'en identifier l'étendue et l'origine. Ces dépôts volcaniques sont contenus dans une profonde échancrure du mur granitique de la baie Howe et leur épaisseur actuelle est d'environ 200 m. Ils sont constitués d'une séquence de laves, de dômes et de lobes d'andésite auxquels sont associées des unités de brèches monolithiques de composition andésitique. Des dykes d'andésite cogénétiques en échelon traversent l'ensemble du complexe volcanique et leurs vestiges résultant de l'érosion prennent la forme d'une série d'aiguilles et de pitons énigmatiques aux pentes abruptes. Selon les critères pétrographiques et géochimiques, nous pouvons identifier deux types de magma distincts qui se manifestent par de l'andésite aphyrique et de l'andésite à hornblende. En se fondant sur les relations observées sur le terrain ainsi que sur les propriétés et la répartition des dépôts volcaniques, nous avons déterminé que l'origine du complexe volcanique de Monmouth Creek est glaciovolcanique. Nous proposons un modèle de mise en place des dépôts volcaniques recourant à la présence d'un important glacier de remplissage de fjord, dont l'épaisseur était vraisemblablement supérieure à 1 km et qui occupait la baie Howe jusqu'à une altitude d'environ 800 m au-dessus du niveau de la mer actuel au moment de l'éruption.

INTRODUCTION

Glaciovolcanism encompasses the interaction of volcanism with ice in all of its forms, as well as any meltwater that is created by volcanic heating (Kelman et al., 2002a; Smellie, 2008; Russell et al., 2014). Glaciovolcanic edifices have distinctive morphologies and deposits indicative of ice enclosure or contact (Mathews, 1947, 1951, 1952b, 1958; Allen et al., 1982; Hickson, 2000; Lescinsky and Fink, 2000; Edwards et al., 2002; McGarvie et al. 2007; Smellie, 2008; Lodge and Lescinsky, 2009, McGarvie, 2009; Stevenson et al., 2009; Edwards et al., 2010). These edifices have great potential to inform the climatological sciences as they establish the paleopresence of ice and may enable the reconstruction of ice thickness and extent (Mathews, 1947; Edwards et al., 2002, 2010; Kelman et al., 2002a; Schopka et al., 2006; Smellie et al., 2008; Stevenson et al., 2009; Tuffen et al., 2010).

The Garibaldi volcanic belt of southwest British Columbia comprises a large number of calc-alkaline, basaltic to rhyodacitic eruptive centres active over the last 2 Ma (Fig. 1) (Green et al., 1988; Hickson, 1994; Kelman et al., 2002a, b). Much of the volcanism in the belt occurred during a complex history of encroaching and retreating Cordilleran ice (Mathews, 1958; Grove, 1976; Green et al., 1988; Hickson, 1994; Kelman et al., 2002a, b; Bye et al., 2000).

The Monmouth Creek volcanic complex comprises a series of enigmatic volcanic pinnacles protruding above a broader mass of lava and unconsolidated breccia, draped across the western slope of Howe Sound (Mathews, 1958; Green, 1994; Kelman et al., 2002a). Literature regarding these deposits is limited, and current knowledge and understanding are based on a small number of volcanological accounts (Mathews, 1958; Green et al., 1988; Green, 1994; Kelman et al., 2002a). As such, the history, chemistry, and age of the Monmouth Creek volcanic complex are largely unconstrained.

Here, the authors describe the geology of the Monmouth Creek volcanic complex. This research comprises a preliminary geological map that constrains the distribution of the complex, describes variations in the volcanic facies, and creates a stratigraphic framework which is used to understand the origin of the deposit. Field and laboratory analyses show the complex to comprise a minimum of two compositionally distinct groups of intermediate lavas, breccia units, and cogenetic dykes. The nature and distribution of the volcanic facies and the textural features preserved in the lavas are indicative of eruption under and against ice. The complex preserves a record of glaciovolcanism in the Garibaldi volcanic belt that is also expressed by glaciovolcanic deposits from Watts Point (Green et al., 1988; Bye et al., 2000), the Mount Garibaldi and Garibaldi Lake volcanic fields (Mathews, 1948, 1951, 1952b, 1958; Green, 1981, 1990; Green et al., 1988; Hickson, 1994; Kelman et al., 2002a), the Mount Cayley volcanic field (Kelman et al., 2002a, b), the Cheakamus Valley basalt group (Mathews, 1958), and the Bridge River cones (Roddick and Souther, 1987) (Fig. 1).

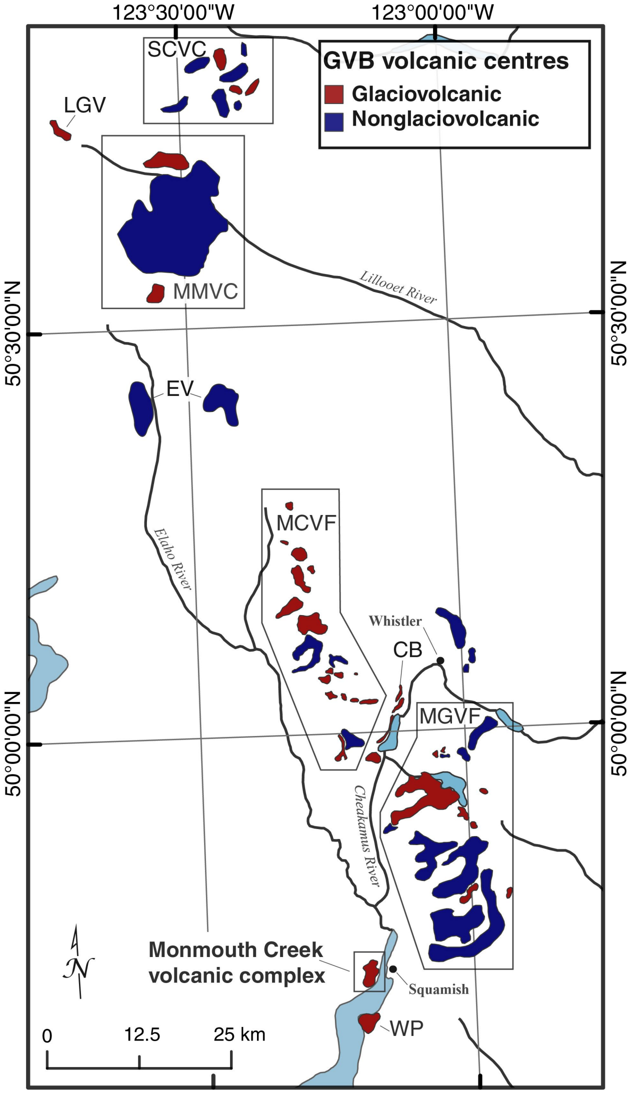

Figure 1. Distribution of glaciovolcanic and nonglaciovolcanic edifices in the Garibaldi volcanic belt (GVB) (*after* Hickson, 1994; Kelman et al., 2002a, b). SCVC = Salal Creek volcanic complex, LGV = Lillooet Glacier volcanics, MMVC = Mount Meager volcanic complex, EV = Elaho volcanics, MCVF = Mount Cayley volcanic field, CB = Cheakamus basalts, MGVF = Mount Garibaldi volcanic field, WP = Watts Point. Monmouth Creek volcanic complex is shown in the lower centre. The Bridge River cones (not displayed) are located about 5 km north of the Salal Creek volcanic complex.

FIELD METHODS

Geological mapping of the rocks exposed at Monmouth Creek was conducted at 1:5000 throughout May to October 2015. Mapping used a 1:20 000 TRIM (Terrain Resource

Information Management) DEM (Digital Elevation Model), with GPS (Global Positioning System) assistance for enhanced accuracy (±1–3 m). The area underlain by the Monmouth Creek volcanic complex features extremely steep topography and is situated on the west side of the Squamish River, restricting access by foot, boat, or helicopter. Much of the map area (Fig. 2) is obscured by colluvium, recent alluvial deposits of the Squamish River, and dense forest of the Coastal Western Hemlock bioclimatic zone (e.g. Fig. 3). All lithostratigraphic units were sampled for geochemical and petrographic study, as well as for future geochronological work (Fig. 2).

GEOLOGY OF THE MONMOUTH CREEK VOLCANIC COMPLEX

Quaternary volcanic rocks at Monmouth Creek intrude and unconformably overlie glaciated, mid-Cretaceous, phaneritic granodiorite (unit Kppg) of the Coastal Plutonic Complex (Armstrong and Bostock, 1963; Cui and Russell, 1995). The Monmouth Creek volcanic complex comprises a thin veneer of Quaternary volcanic rocks, draped across the granodiorite hillside in a broad oval striking northeast. The complex covers an area that is approximately 3 km long and 1 km wide, and extends from 800 m in elevation to sea level.

The geological map (Fig. 2) comprises three distinct domains. The northern map area is dominated by several large, coarsely radial jointed masses of coherent andesite lava (unit Qvl). Creeks running through this area have eroded several steep-sided, vertical canyons that trend northeast, exploiting the contact with underlying granodiorite bedrock (unit Qppg). Fragmental deposits are rare in this area, with only minor pockets of andesite breccia (unit Qvmb) exposed along the crests of the ridges. The central area contains numerous andesite dykes (unit Qvi) and smaller lava lobes and domes (unit Qvd) that are surrounded by, and intrude, a thick mass of unconsolidated, poorly sorted, coeval andesite breccia (unit Qvmb). In the southwestern map area, unconsolidated volcanic breccia (units Qvmb and Qvbb) sporadically outcrop along a knife-edge ridge at an elevation of 800 m. These are the highest volcanic units in the complex. The Monmouth Creek volcanic complex is bound on its western margin by a narrow steep-sided river canyon, created as a result of erosion by the Box and Monmouth creeks.

Volcanic rocks are divided into coherent lava flows, lobes, and domes; monolithological volcanic breccia units; and intrusive dykes. Two distinctive petrographic groups are observed, differing primarily due to the presence or absence of phenocrysts of hornblende and/or orthopyroxene. Below, the authors describe the individual volcanic facies. Organization is first by assemblage (aphyric andesite versus hornblende-phyric andesite) and then by facies, arranged from the oldest unit to the youngest.

APHYRIC ANDESITE ASSEMBLAGE

Aphyric andesite lava flows (unit Qvl), domes (unit Qvd), dykes (unit Qvi), and their associated breccia units (units Qvmb and Qvbb) comprise the bulk of the Monmouth Creek volcanic complex. In hand sample the andesite is devoid of phenocrysts. Trace quantities of fresh granodiorite xenoliths are present. In thin section, the aphyric andesite assemblage is characterized by the presence of minor quantities (1–5%) of microphenocrystic (0.1 mm) orthopyroxene (Fig. 4a). The groundmass has a trachytic texture, and comprises abundant plagioclase microlites, Fe-Ti-oxide minerals and variable amounts of interstitial groundmass glass. Xenolithic material occurs as small (1–2 mm), partially digested grains of quartz and feldspar.

Aphyric andesite lava (unit Qvl)

Aphyric, moderately to sparsely vesicular, orthopyroxene microphenocryst-bearing, fine-grained to glassy, jointed andesite lava flows form several northeast-trending, steep-sided, elongate ridges in the northern map area. Near Monmouth Creek (station 1, Fig. 2), columnar-jointed lava is exposed in an approximately 100 m thick, subvertical cliff section. Here, the creek has formed a narrow canyon, exploiting the unconformable contact with basement granodiorite. At the base of the exposure, 20–30 cm diameter columnar joints are tilted at 45° and plunge northwest. Outcrops situated 10–20 m above the contact, however, feature radiating column orientations with the column axis becoming increasingly horizontal before fanning toward vertical near the top of the ridge (Fig. 3a). The eastern side of the ridge (stations 2-3, Fig. 2) displays column orientations distinct from the western side. Here, andesite lava forms steep bluffs, towering over the banks of the Squamish River. The cliff faces undulate, presenting several large, lobe-like extensions (e.g. stations 2-3, Fig. 2). Column orientations are dominantly normal to the exposure face, and fan from subhorizontal near the base to subvertical near the crest of the ridge (station 4, Fig. 2. Note: subvertical columns are not visible in Fig. 3a). Figure 2 displays structural joint data as lineation measurements with the arrows indicating the long axis of the column, and pointing downdip.

Aphyric andesite lobes, domes, and sheets (unit Qvd)

Dark, aphyric, glassy, sparsely vesicular andesite outcrops in a number of highly jointed lava masses (lobes, domes, and sheets) in the southern and central map areas (e.g. stations 9, 10, 13, 14, 15, etc.). Lava masses situated near station 9 vary in diameter from 3 m to 10 m (e.g. Fig. 3b). Width and aspect ratio vary considerably, with some masses displaying low aspect ratios (subequal width and height) (e.g. Fig. 3b), and others forming wider sheet-like structures. At the western edge of the map area, a large (>50 m high, >100 m wide)

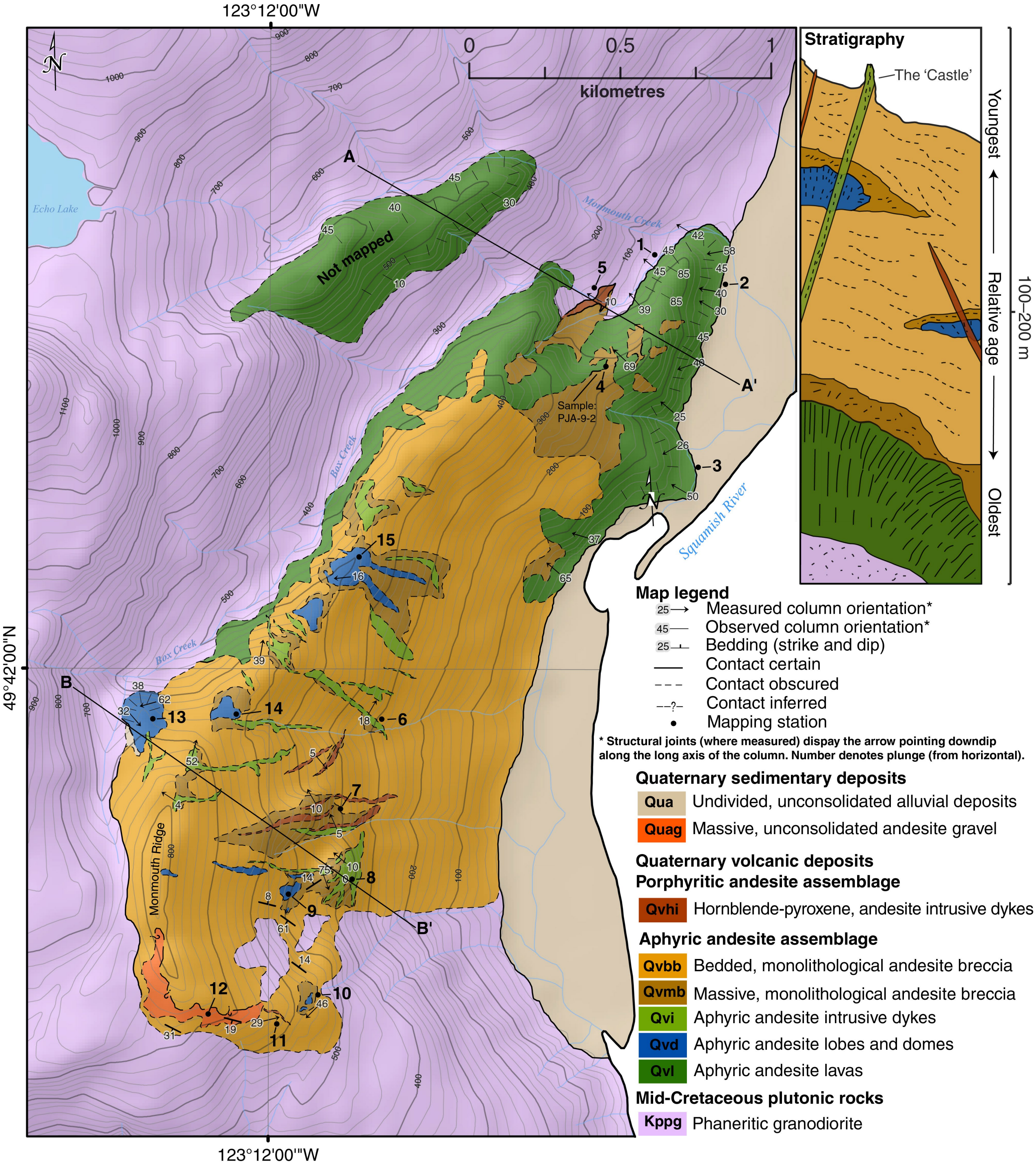

Figure 2. Geological map at 1:20 000, showing the distribution of geological units exposed at Monmouth Creek. Structural joint measurements are displayed as lineations, with the arrow pointing downdip along the long axis of each column. Topographic contours are based off a TRIM DEM. The topographic contour interval is 20 m.

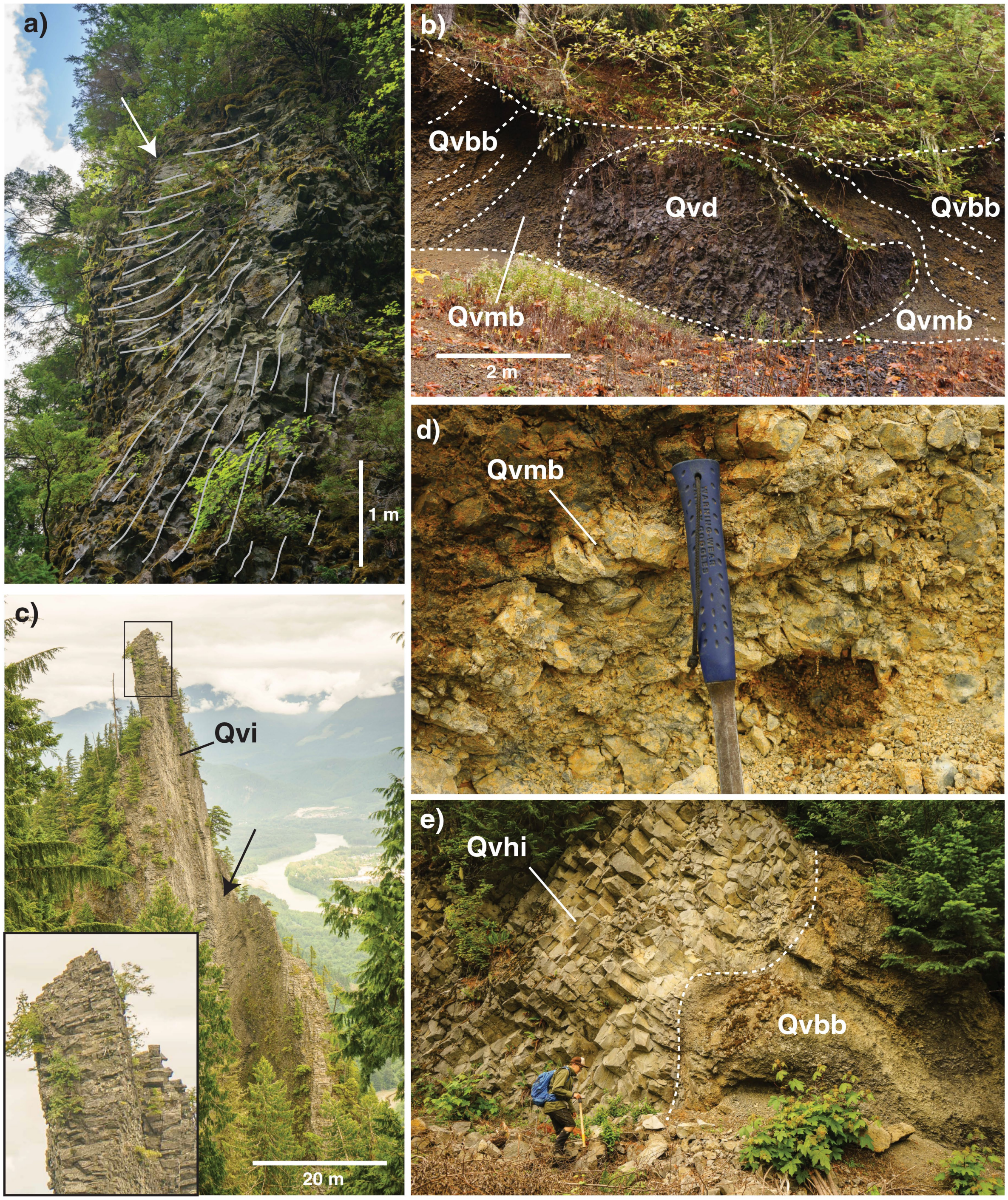

Figure 3. a) Columnar jointed andesite (unit Qvl). Arrow denotes rapid change in joint orientation from subvertical to subhorizontal over several metres. 2016-064. **b)** Small lobe or dome of lava (unit Qvd) exposed at station 9. Note the carapace of massive, monolithological breccia (unit Qvmb) grading rapidly into weakly bedded breccia (approximate dip displayed) (unit Qvbb) on both sides. 2016-063. **c)** The deeply eroded remnant of a major intrusive dyke set (named the 'Castle') viewed from the south (unit Qvi). Note the pervasive jointing, oriented perpendicular to the strike of the dyke (*see* insert). The southern face of the 'Castle' is well exposed. Arrow denotes prominent U-shaped cavity at the intersection of a branching dyke. 2016-060. **d)** Typical outcrop of massive, monolithological, angular to subangular, jigsaw-textured breccia exposed at station 4. Note the distinct orange colour given by abundant matrix of palagonite. Handle of hammer is approximately 23 cm. 2016-061. **e)** Cross-sectional view of a hornblende-phyric dyke (unit Qvhi) crosscutting weakly bedded breccia (unit Qvbb). Geologist for scale about 178 cm. 2016-062. All photographs by A. Wilson.

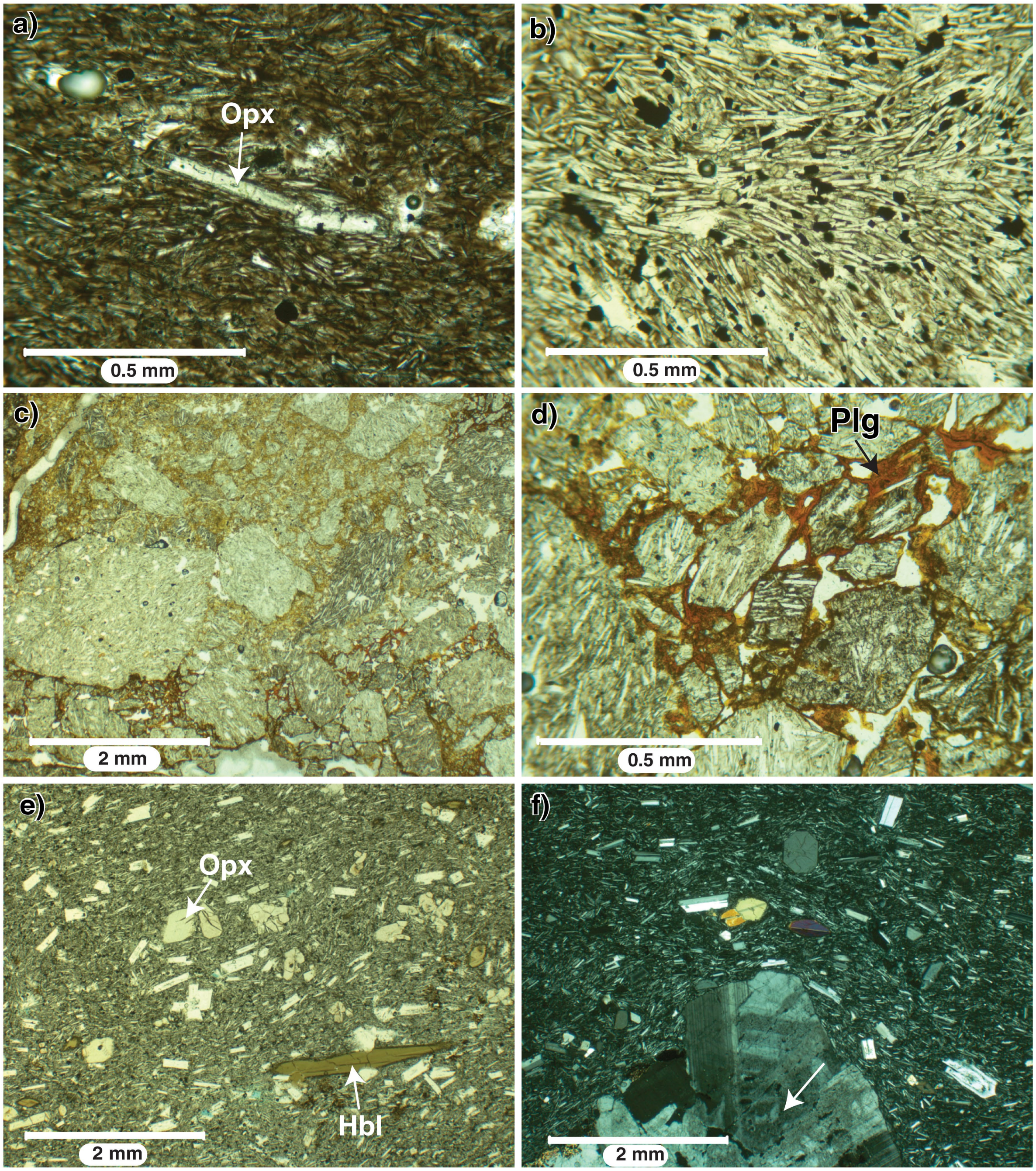

Figure 4. a) Orthopyroxene (Opx) microphenocryst set in near-aphyric trachytic groundmass of plagioclase and glass (unit Qvl). 2016-065. **b)** Trachytic, glass-poor groundmass of aphyric andesite dyke (unit Qvi). Individual crystals are oriented subparallel to vertical sheet flow. 2016-066. **c)** Monolithological, poorly sorted palagonite-rich breccia (unit Qvbb) associated with units Qvl, Qvd, and Qvi. Note the variable groundmass concentrations between clasts. 2016-067. **d)** Palagonatization (Plg) of fine matrix clasts within unit Qvbb. 2016-068. **e)** Porphyritic andesite dyke exposed at station 5. Hbl = hornblende, Opx = orthopyroxene. 2016-069. **f)** Arrow denotes xenolith of plutonic granodiorite derived from the underlying Costal Plutonic Complex. 2016-070. All photographs by A. Wilson.

lobe of highly glassy, aphyric lava forms a steep bluff above Box Creek (station 13, Fig. 2). Pervasive, radial jointing is present within all lava masses. Jointing near the margins is characteristically fine and hackly (<10 cm diameter columns). Near the centres and bases of the structures, jointing becomes significantly coarser (up to 30 cm in diameter).

Aphyric andesite intrusives (unit Qvi)

En echelon dykes form a number of erosion-resistant pinnacles, spines, and ridges throughout the map area (e.g. stations 6, 7, 8, 14, 15, etc.) (Mathews, 1958; Green, 1994; Kelman et al., 2002a). Of these, one pinnacle, named the "Castle" by Mathews (1958) (station 8, Fig. 3c), is enigmatic, and features a sheer, vertical, eastern face over 180 m high (Culbert, 1965).

Like many Monmouth Creek volcanic complex dykes, the 'Castle' comprises light-grey, fine-grained, aphyric, sparsely vesicular andesite, stacked in at least three northeast-southwest oriented, subvertical, 5–10 m wide, subparallel sheets. The southern face is well exposed (Fig. 3c), showing the dykes branching to form a vertical, U-shaped cavity. Pervasive, polygonal columnar jointing is oriented subhorizontally, with the long axes of the columns radiating around the inner part of the structure (Fig. 3c).

In thin section, the rocks are fine grained and highly trachytic. They contain an equigranular groundmass dominated by plagioclase microlites, and only minor interstitial glass (Fig. 4b).

Massive to weakly bedded, monolithological andesite breccia (units Qvmb, Qvbb)

Southern and central portions of the Monmouth Creek volcanic complex are covered by thick accumulations of massive to weakly bedded, unconsolidated, monolithological, poorly sorted, andesite breccia. The authors divide these breccia units into two lithofacies, Qvmb and Qvbb, based on their massive versus bedded characteristics, respectively. Outcrop is rare; however, exposure is found in a number of access tracks emplaced to service a major liquid natural-gas pipeline and several power lines that traverse the area. Locally (e.g. station 4, Fig. 2), these breccia units are massive, clast-supported, poorly sorted and angular (Fig. 3d). They contain fine-grained to glassy jigsaw-textured clasts up to 20 cm in diameter, and feature a moderately palagonitized matrix (e.g. Fig. 4d). At station 4, breccia is intimately associated with the upper portion of a major unit Qvl flow, where it forms a thin, 1–3 m carapace exposed along the crest of the ridge (Fig. 3d). In the southern and central map area, massive, glassy breccia (unit Qvmb) forms a thin carapace, surrounding the majority of lobes and domes and major dykes. The breccia rapidly grades in both directions into a crudely bedded equivalent (e.g. Fig. 3b).

The southern and central map areas (stations 7–11) are dominated by breccia displaying crude bedding; a dominance of less glassy, moderately vesicular clasts; and variable matrix support (unit Qvbb). Accumulations around the base of the 'Castle' (station 8) are up to 15 m thick.

In thin section, Qvbb and Qvmb breccia units appear monolithological. The clasts comprising these units are mineralogically and texturally identical to the coherent volcanic facies described above. Specifically, the clasts have a groundmass of plagioclase microlites, variable groundmass glass, and are trachytic (Fig. 4c). Palagonitization of finer matrix clasts, and the rims of some larger glassy clasts (e.g. Fig. 4d) is locally abundant, giving many outcrops a distinctive orange-brown hue (e.g. Fig. 3d).

PORPHYRITIC ANDESITE ASSEMBLAGE

Rocks at Monmouth Creek are divided into two petrographically distinct groups, based on the presence or absence of visible hornblende phenocrysts (i.e. aphyric andesite and hornblende andesite). The aphyric andesite assemblage, including lava flows (unit Qvl), domes and lobes (unit Qvd), and intrusive rocks (unit Qvi), is intimately associated with significant accumulations of monolithological breccia units of aphyric andesite (units Qvbb, Qvmb). In contrast, there are no monolithological hornblende-bearing breccia units within the map area, and the porphyritic andesite assemblage comprises intrusive rocks only.

Hornblende-pyroxene, andesite intrusive rocks (unit Qvhi)

Light grey, fine-grained, hornblende (1–2 mm) and pyroxene-phyric (crystals <1 mm), andesite dykes form tall, erosion-resistant spines, pinnacles, and ridges distributed throughout the Monmouth Creek volcanic complex. At station 5 (Fig. 2), a 10 m thick, approximately 100 m long dyke intrudes both underlying granodiorite basement and massive, aphyric andesite breccia (unit Qvmb). Farther south (station 7), porphyritic dykes are interspersed with aphyric lava masses (lobes and domes) (unit Qvd) and dykes (unit Qvi), sharply crosscutting crudely bedded breccia (unit Qvbb) (Fig. 3d).

In thin section, these dykes are strongly porphyritic with prominent 1–2 mm phenocrysts of elongated hornblende (5%) and less than 1 mm euhedral orthopyroxene (2%) (Fig. 4e). The groundmass is trachytic, and comprises plagioclase (95%), Fe-Ti-oxide minerals (~5%) and minor interstitial glass (<1%). Similar to the aphyric andesite assemblage, the porphyritic andesite units also contain xenoliths and disaggregated xenocrysts derived from the underlying granodiorite (Fig. 4f).

SEDIMENTARY DEPOSITS

Massive to weakly bedded, well sorted, unconsolidated colluvial gravel (unit Quag)

Well sorted, locally bedded, subrounded to subangular, clast- to matrix-supported volcanogenic gravel forms a thin (1–2 m) veneer across the southern side of the Monmouth ridge. Clasts are dominated by fine-grained, dark aphyric andesite. Poor exposure restricts accurate delineation, however it is likely that these gravel units cover a significant portion of the southern complex.

Undivided, unconsolidated alluvial deposits (unit Qua)

Unconsolidated, poorly sorted sand, silt, and conglomerate form a wide alluvial fan on the banks of the Squamish River. Clasts lithologies are dominated by granitic and volcanogenic material. Alluvial material partially overlies and obscures jointed andesite lava in the northeastern map area.

GEOCHEMISTRY

Five samples from the Monmouth Creek volcanic complex were analyzed for major elements by X-ray fluorescence at the Washington State University, GeoAnalytical laboratory. Results are reported in Table 1. All samples are subalkaline and andesite (Fig. 5) (LeBas et al., 1986). Units Qvd, Qvi, and Qvbb plot within a narrow field, near the boundary between basaltic andesite and andesite. Lava flows (unit Qvl) in the northern end of the map area have slightly higher SiO_2 contents (63 weight per cent versus 57 weight per cent) and plot separately near the boundary between andesite and dacite. A single geochemical analysis reported by Mathews (1958) is also plotted (Fig. 5). Mathews' report indicated that the sample was obtained from the "Castle", one of several aphyric andesite dykes (equivalent to unit Qvi) that outcrop in the map area. His data point plots in between the two chemical groups defined by the present work, and the difference could represent a difference in sampling or in analytical techniques. The Watts Point lavas are geographically the closest Quaternary volcanic rocks in the Garibaldi volcanic belt to the Monmouth Creek volcanic complex and are glaciovolcanic in origin (Green et al., 1988; Bye et al., 2000; Kelman et al., 2002a). Chemical compositions of the Watts Point dacite lava flows (Bye et al., 2000) are plotted in Figure 5 for comparative purposes.

The present field mapping established an intimate relationship between the coherent facies (i.e. units Qvd, Qvi) and breccia deposits (unit Qvbb). Geochemical data clearly corroborate this observation and suggest a strong genetic connection between these units. Additional chemical data are required to explore further the relationship between the breccia units, lobes and/or domes, and dykes of the southern complex, and the extensive lava flows (unit Qvl) in the north, and to establish the relationship of the porphyritic andesite assemblage with the wider volcanic complex.

Table 1. Major element whole-rock chemical analyses for samples from the Monmouth Creek volcanic complex

Label[1]	**005**	**006**	**007**	**011**	**017**	**M-1958[2]**
Unit	**Qvl**	**Qvbb**	**Qvi**	**Qvd**	**Qvl**	**Qvi**
Rock type	**Andesite lava**	**Breccia**	**Andesite dyke**	**Andesite lobe**	**Andesite lava**	**Andesite dyke**
Latitude	49.70888011	49.69658361	49.69374013	49.69318165	49.70360069	-
Longitude	123.1850669	123.1978927	123.1966635	123.198847	123.1854196	-
SiO_2	61.05	57.36	56.79	57.16	61.66	60.53
TiO_2	0.63	0.75	0.75	0.74	0.63	1.04
Al_2O_3	16.97	18.56	18.97	19.00	17.11	17.42
FeO[3]	4.79	6.22	6.31	6.13	4.92	2.73
MnO	0.10	0.12	0.12	0.12	0.10	0.12
MgO	3.05	4.00	3.96	3.81	3.06	2.74
CaO	5.39	6.66	6.81	6.86	5.49	5.60
Na_2O	4.50	4.56	4.43	4.50	4.56	3.98
K_2O	1.44	0.97	0.79	0.83	1.44	1.13
P_2O_5	0.28	0.33	0.26	0.26	0.28	0.21
Total	98.20	99.54	99.20	99.40	99.25	99.72
LOI%	0.90	0.00	0.24	0.60	0.21	N/A

[1] All samples collected during 2015 summer field season contain prefix: "AW-15-".

[2] Analysis of sample from the "Castle" reported by Mathews (1958).

[3] Total Fe expressed as FeO.

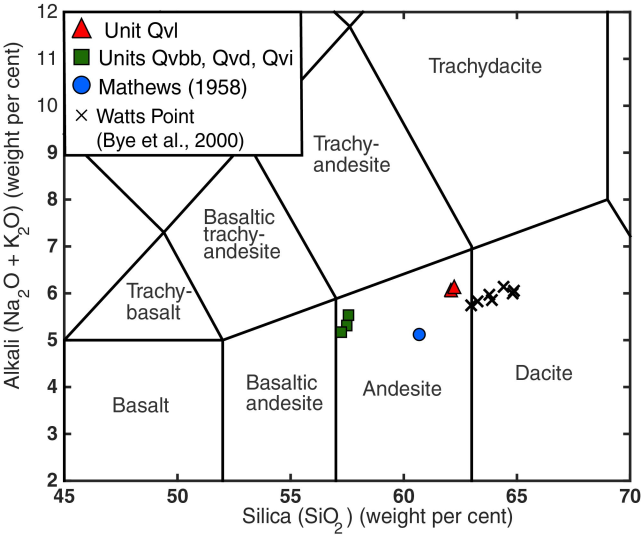

Figure 5. Total alkali-silica (TAS) diagram (*after* LeBas et al., 1986), displaying preliminary geochemical analyses of selected Monmouth Creek volcanic complex units and analyses of the Watts Point volcanic centre (*modified from* Bye et al., 2000). Monmouth Creek volcanic complex volcanic units are subalkaline andesite, displaying a wide variation in SiO_2.

DISCUSSION

An analysis of previous interpretations

The only detailed account of the Monmouth Creek volcanic complex geology derives from Mathews (1958). Mathews focused his work on the unique outcrop morphology of the tallest volcanic pinnacle located in the area (named the “Castle”). He described the structure as a radially jointed, steep-sided mass of lava closely resembling a dacite Peléan spine, surrounded at its base by a mass of agglutinated breccia. Mathews described the structure as having a “semi-cylindrical groove, extending up its southern end,” and postulated that the core of the pinnacle might have “drained away” while still partially molten. Mathews did consider a glaciovolcanic origin for the pinnacles; however, he perceived a lack of diagnostic glaciovolcanic features at the “Castle” which caused him to propose the area as ice-free during emplacement. He suggested that erosional processes would be inadequate to produce the steep-sided features and reasoned that the survival of such delicate structures throughout a major glacial event would be highly unusual. Based on this evidence, Mathews postulated that the pinnacles were likely emplaced during the waning stages of the Wisconsinan (Fraser) glaciation (Mathews, 1958).

Subsequent work (Green, 1994; Kelman et al., 2002a), suggested that the pinnacles at Monmouth Creek are unlikely to be Peléan spines, and instead offered an alternate interpretation as a swarm of en echelon dykes. The present authors’ preliminary investigation supports this latter interpretation. No evidence was seen for Peléan-style spine emplacement at any of the pinnacle structures within the area. The present authors suggest that the pinnacles are the eroded remnants of a swarm of dykes emplaced into a thick carapace of associated breccia. This is evidenced by their high aspect ratios of about 25:1, coupled with subparallel, en echelon outcrop morphology; dense, nonglassy, trachytic texture, with individual crystals aligned subparallel to vertical flow; and finer than metre-scale pervasive jointing oriented perpendicular to the strike of each structure. The present authors interpret the “semi-cylindrical groove” described by Mathews, to be the intersection of two branches of a single dyke. Fanning columnar joints distributed throughout the U-shaped structure (Fig. 3c) are oriented perpendicular to the outcrop surface. This jointing is attributed to subsurface, in situ formation after dyke injection into a pile of volcanic breccia. Protection within this carapace of breccia may provide an explanation for the remarkable preservation of the dykes throughout the last major glaciation (e.g. Edwards and Russell, 2002; Edwards et al., 2010).

An alternate interpretation is that the swarm of dykes was intruded directly into the base of the overlying glacier during the waning stages of the Fraser or older glaciation. The preservation of the “spires” may be due to the rapid downwasting of ice at the end of the glacial period, when the ice had stagnated. This interpretation is not fully supported, however, due to the lack of characteristically fine-scale jointing on the outer surface of the dykes, and the presence of crosscutting relationships with poorly bedded breccia (unit Qvbb, Fig. 3e). Where seen elsewhere (cf. Watts Point (Bye et al., 2000; Hickson, 2000)) some glass and very small columns (<10 cm) are preserved on the dyke surface along with significant glassy detritus in the colluvial material surrounding the dykes. This interpretation would also have implications regarding the age of the complex. The fragile, volcanic spires are unlikely to survive a major glacial event, thereby constraining their age to the waning stages of the Fraser glaciation.

A glaciovolcanic origin

The authors’ analysis supports a glaciovolcanic origin for the Monmouth Creek volcanic complex based on the evidence listed below:

The pervasive presence of radially oriented fans of medium-scale, glassy, columnar joints within lava flows (unit Qvl) in the northern map area is consistent with rapid cooling of the outer margins of the flow. The highly variable orientation of the joints (*see* Fig. 3a, 6a) indicates pronounced simultaneous cooling in multiple directions (e.g. horizontal and vertical) (e.g. Mathews, 1952a, 1958; Edwards and Russell, 2002; Lodge and Lescinsky, 2009). Substantial erosion has likely removed the finest scale jointing that is typically preserved in glaciovolcanic lavas (e.g. Bye et al., 2000; Edwards et al., 2002, 2010; Edwards and Russell, 2002; Kelman et al., 2002b). Several major lobes and domes (e.g. station 13) were likely extruded directly into ice. These deposits have retained their glassy, fine-scale, chaotically oriented jointing, presumably due to encasement and protection within carapaces of associated breccia (e.g. Fig. 3b, station 9).

Large accumulations of glassy, angular, monolithological hyaloclastite breccia units are chemically and petrographically linked to units Qvl, Qvi, and Qvd. The glassy, angular nature of these deposits, and the presence of jigsaw-fit textures (e.g. Fig. 3d) suggests quench fragmentation, a response likely triggered by the significant quantities of meltwater produced by volcanic heating during emplacement (e.g. Edwards et al., 2002; Edwards and Russell, 2002; Stevenson et al., 2009; McGarvie, 2009). A lack of well bedded, well sorted fragmental deposits suggest that the meltwater was not stagnant; rather, the steep topography likely caused the water to drain from the edifice as soon as it was produced.

A number of the smaller, radially jointed lobes and domes (e.g. Fig. 3b) are highly analogous to glaciovolcanic deposits described at Kerlingarfjöll, Iceland by Stevenson et al. (2009). Here, these deposits display apparent intrusive relationships with the surrounding vitriclastic material. At Monmouth Creek, intrusive relationships are only observed in the low aspect ratio bodies (near equal width and height). The higher aspect ratio bodies (sheets and flows) appear to display extrusive relationships with the surrounding breccia. This suggests that the dome, lobe, and sheet emplacement processes were likely a combination of both intrusive (into loose, unconsolidated breccia) and extrusive.

Pockets of highly angular, glassy breccia contain abundant palagonite, a product of hydration and breakdown of mafic volcanic glass, further affirming a water-saturated eruption environment (Harder and Russell, 2006). Crude bedding of the breccia deposits in the central map area suggests minor amounts of local reworking during deposition. The presence of minor subangular, less glassy aphyric andesite clasts within the bedded facies suggests that some of these breccia may be autoclastic, derived from mechanical collapse of lava lobes and domes during emplacement.

Poorly consolidated breccia accumulations are more than 200 m thick and are preserved on an exceptionally steep (near 45°) glaciated granodiorite slope. This thick fragmental pile suggests that the growing volcanic edifice was probably impounded on its eastern margin by a wall of fjord-filling glacial ice. Near the centre of the complex, bedding attitudes (where measurable), change rapidly (*see* Fig. 2, station 9); however, typically dip into the hillside (i.e. toward the west), further supporting the argument for impoundment on the eastern margin of the complex.

An emplacement model

The authors propose the following model for the evolution of the Monmouth Creek volcanic complex (Fig. 6): the initial phase of volcanism was subglacial and emplaced the lavas (unit Qvl) that are now exposed in the northern part of the map area. Given the form of these flows, and the distribution of columnar jointing, it is likely that significant accumulations of hyaloclastite breccia were associated with these flows during emplacement (Fig. 6). Large quantities of these breccia units have been removed due to erosion by Monmouth Creek. The steep slope may have contributed to the rapid removal of meltwater from the subglacial surface, promoting the formation of more massive lavas as opposed to thick sequences of pillows and pillow breccia units as seen elsewhere (cf. Wells Gray (Hickson, 2000, Hickson and Vigouroux, 2014); Mount Cayley volcanic field (Kelman et al., 2002a)).

Volcanism then concentrated toward the central portion of the map area, where magma, injected as dykes (unit Qvi), formed a number of subglacial lava masses (lobes, domes, and sheets) (unit Qvd) that were continually intruding, extruding, and feeding a growing pile of monolithological, cogenetic hyaloclastite and autoclastic breccia (e.g. Fig. 6b).

Continued injections of magma inflated and expanded the volcanic pile, causing additional melting of the fjord-filling glacier. The paleorelief of these deposits (i.e. 800 m to sea level) suggests a minimum ice thickness of approximately 1 km. The last stage of volcanism is represented by a series of hornblende-phyric andesite dykes that intrude the aphyric andesite deposits in the central and northern map area. The timing of this magmatism relative to the earlier events is uncertain, although there is no evidence suggesting that they are not coeval. There are no extrusive lithofacies that are petrographically associated with the hornblende-bearing dykes. This suggests that either they did not intrude all the way to the surface, or all of their extrusive descendants have since been removed by erosion.

CONCLUSION

Field mapping and geochemical, petrographic, and geochronological analyses delineate the major lithofacies units that comprise the Monmouth Creek volcanic complex. The authors present evidence attributing the distinctive deposit morphologies to glaciovolcanism and provide evidence to show that enigmatic pinnacles such as the 'Castle' are the eroded remnants of a swarm of en echelon dykes, not Peléan-style spines, as suggested by Mathews (1958). Glaciovolcanic features within Monmouth Creek volcanic complex suggest that ice covered the complex to at least 800 m in elevation at the time of eruption. These deposits record the presence of a major fjord-filling glacier within the Squamish River valley that is likely to be concurrent with

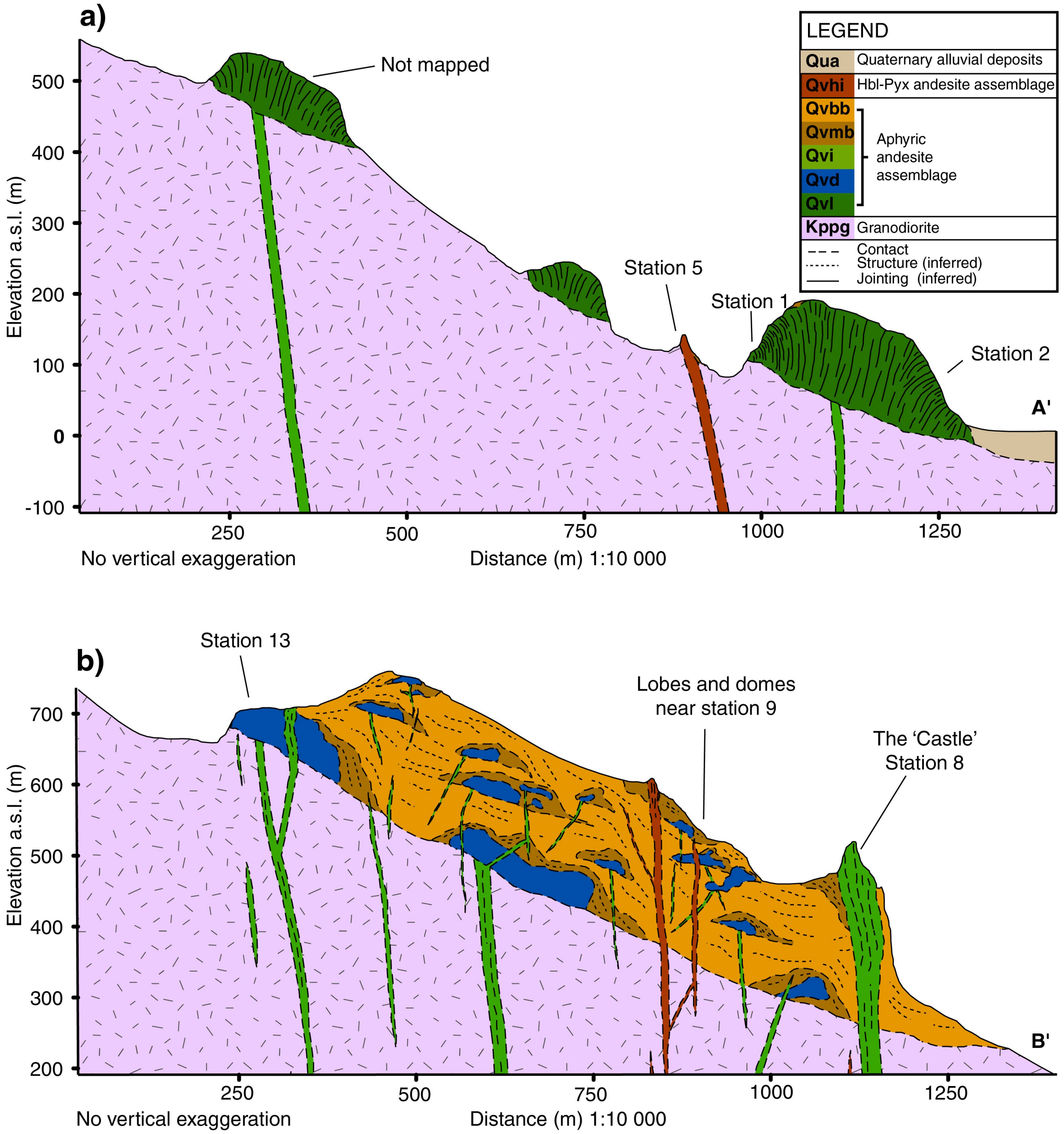

Figure 6. a) Interpreted cross-section (A-A′, Fig. 2) at 1:10 000, displaying the nature and orientation of columnar joints within three large unit Qvl flows in the northern map area; Hbl = hornblende, Pyx = pyroxene. The highest elevation flow was not mapped during this field season; however, photographs suggest it displays a similar jointing character to its lower elevation counterparts (area indicated "not mapped", Fig. 2). **b)** Interpreted cross-section (B-B′, Fig. 2) at 1:10 000, showing internal structure of the central Monmouth Creek volcanic complex area. Lobes and domes fed by injecting dykes likely built the edifice, intruding and sourcing a growing pile of associated hyaloclastite breccia. The deeply eroded remnants of major dykes suggest that significant postdepositional erosion has occurred. A minimum, residual complex thickness of about 200 m is estimated by extrapolating the basal granodiorite contact at about 45°.

the late Fraser glaciation (e.g. Friele and Clague, 2002). This last hypothesis requires testing via future geochronometry studies.

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