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Abstract: Quaternary volcanic rocks at Ember Ridge were mapped at 1:20 000 scale as part of a larger investigation of glaciovolcanism within the Mount Cayley volcanic field in southwestern British Columbia. These deposits consist of at least six isolated, steep-sided andesite mounds, whose morphology and complex fine-scale jointing indicate lava quenching beneath ice. The scarcity of volcaniclastic material at the Ember Ridge deposits suggests the suppression of explosive fragmentation during eruption. If these deposits are coeval, then the elevation range covered by the glaciovolcanic rocks indicates a minimum ice thickness of at least 670 m.

Résumé : Une cartographie à l'échelle de 1/20 000 des volcanites du Quaternaire de la crête Ember a été entreprise dans le cadre d'une étude plus large du glaciovolcanisme dans le terrain volcanique du mont Cayley (sud-ouest de la Colombie-Britannique). Les accumulations glaciovolcaniques se composent d'au moins six monticules isolés à parois abruptes de composition andésitique. La morphologie de ces monticules ainsi que la configuration complexe des fractures à petite échelle témoignent d'une cristallisation rapide sous une couverture de glace. La faible abondance de matériaux volcanoclastiques dans les accumulations de la crête Ember laisse croire à une suspension de la fragmentation explosive au cours de l'éruption. Si toutes ces accumulations sont contemporaines les unes des autres, l'intervalle altitudinal occupé par les roches glaciovolcaniques révèle que l'épaisseur de la couche de glace était d'au moins 670 m.

INTRODUCTION

Throughout the Quaternary, southwestern British Columbia's Garibaldi volcanic belt (Fig. 1) has experienced numerous volcanic eruptions and been subjected to repeated continental-scale glaciations; its current climate is capable of sustaining alpine glaciers, and numerous icefields are present. Consequently, interactions between volcanoes and ice have been common throughout the past two million years (e.g. Mathews, 1947, 1951, 1952, 1958; Green, 1977; Moore and Mathews, 1978; Souther, 1980; Green et al., 1988; Hickson, 2000; Kelman et al., in press). Examples of volcanic landforms that have been shaped or modified by ice include subglacial domes such as Watts Point and Slag Hill, tuyas

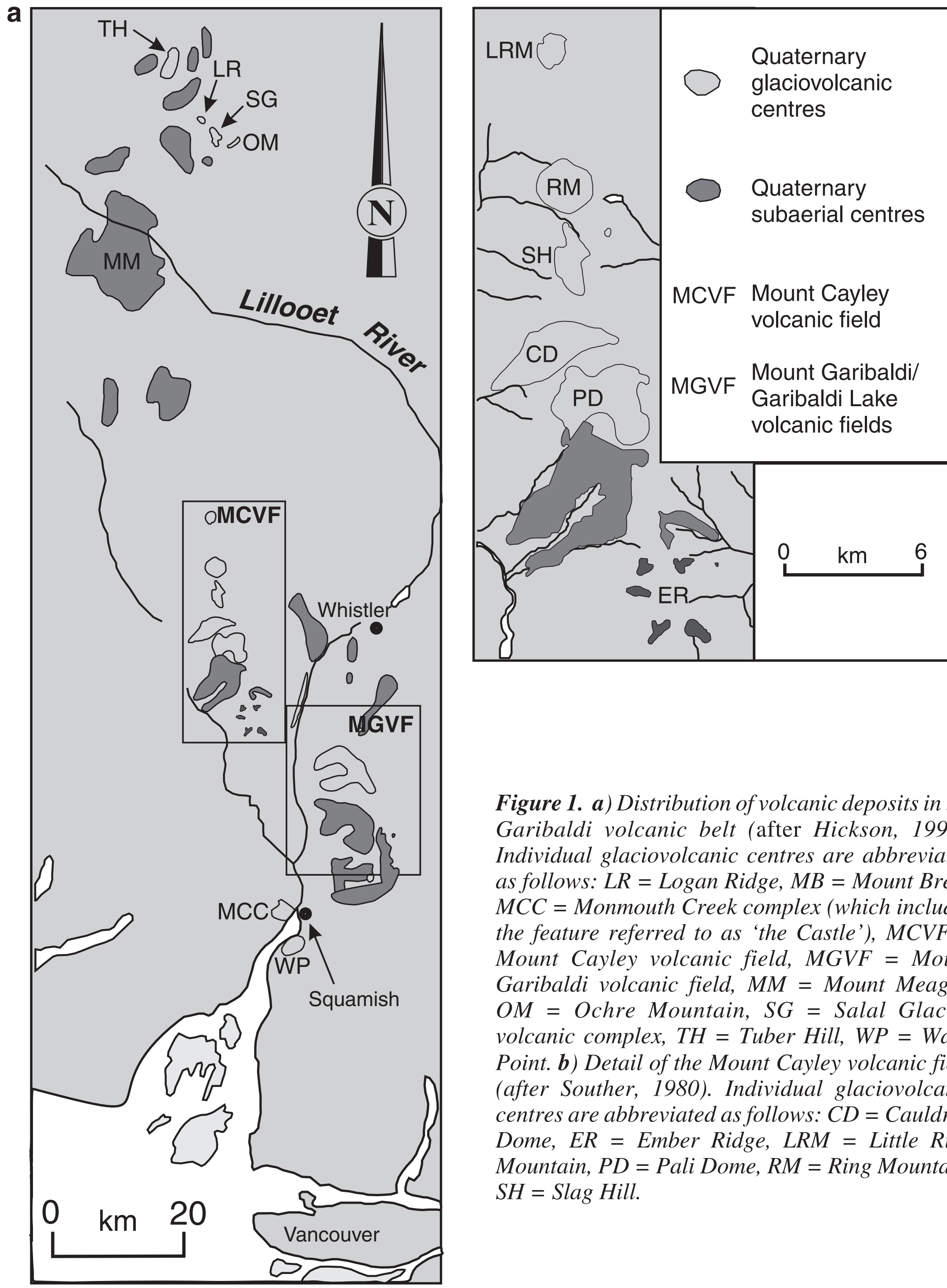

Figure 1. ***a****) Distribution of volcanic deposits in the Garibaldi volcanic belt (*after *Hickson, 1994). Individual glaciovolcanic centres are abbreviated as follows: LR = Logan Ridge, MB = Mount Brew, MCC = Monmouth Creek complex (which includes the feature referred to as 'the Castle'), MCVF = Mount Cayley volcanic field, MGVF = Mount Garibaldi volcanic field, MM = Mount Meager, OM = Ochre Mountain, SG = Salal Glacier volcanic complex, TH = Tuber Hill, WP = Watts Point.* ***b****) Detail of the Mount Cayley volcanic field (after Souther, 1980). Individual glaciovolcanic centres are abbreviated as follows: CD = Cauldron Dome, ER = Ember Ridge, LRM = Little Ring Mountain, PD = Pali Dome, RM = Ring Mountain, SH = Slag Hill.*

such as the Table, Ring Mountain, and Tuber Hill, and lavas impounded against ice, such as The Barrier, Pali Dome, and Ochre Mountain. Field mapping of the Mount Cayley volcanic field during the 2001 field season has delineated the glaciovolcanic deposits collectively known as 'Ember Ridge', which record subglacial eruptive events at six discrete locations. Recognition and understanding of glaciovolcanic features is important because they serve as unequivocal indicators of the past presence of ice, and because careful study and dating of these features may elucidate relationships between volcanism and glaciation. Spatial and temporal correlations between glacial episodes and volcanic events have been used to suggest a causal relationship (Mathews, 1958; Grove, 1974; Gudmundsson, 1986; Sigvaldason et al., 1992; Jull and McKenzie, 1996; Edwards et al., in press). In this paper, we describe in detail the morphology and textural characteristics of the Ember Ridge volcanic deposits, and provide new data to constrain eruptive conditions, the relative age of this volcanism, and the distribution of contemporaneous ice.

GEOLOGICAL SETTING

The Garibaldi volcanic belt is the northern extension of the Cascade magmatic arc of the United States (Green et al., 1988; Guffanti and Weaver, 1988; Read, 1990; Sherrod and Smith, 1990; Hickson, 1994). It stretches from Watts Point, a small centre near the head of Howe Sound, northward to Silverthrone Mountain. Volcanism in the Garibaldi volcanic belt is a result of subduction of the Juan de Fuca Plate beneath the North American Plate (Green et al., 1988; Rohr et al., 1996), and has produced rocks ranging in composition from basalt to rhyolite. The most recent eruption in the belt occurred at Mount Meager at 2350 BP (Clague et al., 1995; Leonard, 1995). The Mount Cayley volcanic field (Fig. 1) lies in the central part of the Garibaldi volcanic belt, 45 km north of Squamish. It consists of Miocene to Pleistocene volcanic deposits of basaltic to rhyolitic composition, and includes at least 15 centres, most of which do not overlap spatially. All but two of these centres show evidence of eruption in the presence of ice.

The earliest studies of the Mount Cayley volcanic field focused on landslide hazards and geothermal potential (e.g. Souther, 1980; Clague and Souther, 1982; Brooks and Hickin, 1991; Evans and Brooks, 1991). Poorly consolidated slopes have led to several major historic debris avalanches at Mount Cayley (Clague and Souther, 1982; Evans, 1986; Jordan, 1987; Lu, 1988), and prehistoric landslide deposits are also present (Evans and Brooks, 1991). The first geological map was prepared by Souther (1980), but did not include the lava flows south of Tricouni Peak or Little Ring Mountain (the northernmost and southernmost deposits). Petrographic and chemical attributes of rocks of the Mount Cayley volcanic field are summarized in Souther (1980) and Kelman et al. (2001). During the 2001 field season, the senior author completed 1:20 000 mapping of the Quaternary volcanic rocks of the Mount Cayley volcanic field.

DESCRIPTION OF EMBER RIDGE DEPOSITS

The Ember Ridge volcanic deposit comprises six isolated, but morphologically similar, outcrops of grey to black lava, ranging from 160 to 900 m across (Fig. 2). Table 1 summarizes individual outcrop volumes and glaciovolcanic characteristics. The total volume of the six deposits is estimated at less than 0.1 km³. All have bulbous, colloform surfaces locally eroded into narrow spines and knobs (Fig. 3a) and are

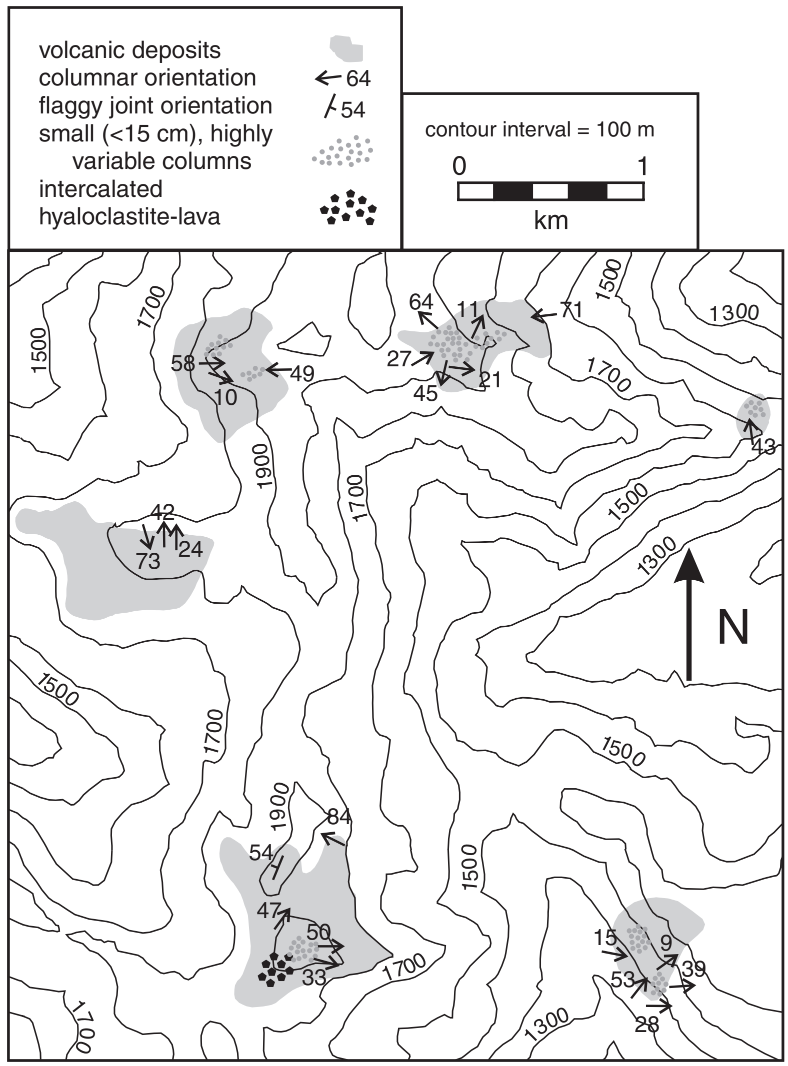

Figure 2. Distribution of volcanic deposits at Ember Ridge. Measured orientations of prominent columns and flaggy joints are shown. Zones having columns smaller than 15 cm and varied orientations are also indicated. In many cases, these intensely jointed deposits have numerous small vertical or steep-sided pinnacles and knobs.

*Figure 3. **a**) A typical outcrop of Ember Ridge, consisting of irregular knobs and spines of lava with small columns (<15 cm). The knob in the centre of the image is approximately 40 m high. **b**) Fine-scale (15–20 cm) columns at the southwesternmost outcrop of Ember Ridge. The backpack (lower left) provides scale. **c**) Columns near the summit of the northernmost outcrop of Ember Ridge. Joint orientations change by 90° over less than 1 m. The Brunton compass (centre) provides scale. **d**) Flaggy jointing, which occurs as patches on the northern and western sides of the same outcrop as in **a**. The 32 cm long hammer (centre) provides scale. **e**) Hyaloclastite intercalated with lava in pods less than 5 m wide, at the same outcrop as in **a**.*

Table 1. Lava volumes and glaciovolcanic characteristics of the six Ember Ridge outcrops.

Outcrop	Estimated lava volume (m^3 x 10^6)	Column size (cm)		Glass evident in hand sample	Fragmental material
		Maximum	Minimum		
1	0.6	15	5	no	none
2	30	20	3	yes	none
3	20	60	20	no	none
4	5	35	5	no	none
5	40	35	10	no	hyaloclastite
6	10	70	15	no	hyaloclastite float

dominated by fine-scale, complexly oriented columnar jointing (Fig. 3b). Overall, the orientations of the columns suggest dome-shaped cooling surfaces. Typically, columns average 15 to 30 cm in diameter and increase in size toward the stratigraphically lowest portions of outcrops. The upper surfaces of outcrops commonly feature columns less than 5 cm across; as column size decreases, column orientations typically become more varied (Fig. 3c). Planar jointing perpendicular to columns, with spacing up to 10 cm, or flaggy jointing (Fig. 3d), with spacing 1 cm or less, occurs at numerous locations. Flow banding perpendicular to columns at a scale of 1 to 6 cm is less common.

Most lava is plagioclase-hornblende-pyroxene-phyric andesite, with rare 1 mm rounded quartz xenocrysts; however, a single outcrop consists of olivine-plagioclase-pyroxene-phyric andesite. Several lavas also contains xenoliths of basement rocks up to 5 cm across, some of which are partially fused, as evidenced by their vitreous appearance. Abundant glass occurs at only a single location.

Hyaloclastite (Fig. 3e) occurs at one location as pods less than 5 m wide intercalated with coherent, jointed lava. It is matrix supported, with 0.2 to 15 cm, subangular to subrounded lava clasts with the same lithology as the coherent units. Hyaloclastite cobbles also occur as float within several hundred metres of a second outcrop. A patch of atypical jointing several metres across occurs near the highest part of one ridge; it consists of hemispherical fractures up to 1 m in diameter, with irregular, poorly developed joints perpendicular to their curved surfaces. These unusual features are best described as ‘pseudopillows’; pseudopillow jointing is described in detail by Lescinsky and Fink (2000).

DISCUSSION

The presence of abundant, varied, very fine-scale joints, the hemispherical cooling surfaces suggested by variations in column orientation, and the abundant glass at the least eroded outcrop, suggest that the Ember Ridge lava cooled rapidly on all sides in a confined environment. At subglacial volcanoes elsewhere in the world, however, the stratigraphic sequence commonly comprises not only coherent lava, but also pillows and fragmental material (hyaloclastite and breccia) (Mathews, 1947; Jones, 1969; Werner et al., 1996). Hyaloclastite is a glass breccia formed during subaqueous or submarine eruptions by 1) steam-related quench fragmentation caused by explosive expansion of steam formed from water enclosed in magma, or at magma–water contact surfaces (Kokelaar, 1986), 2) cooling contraction, or 3) primary volatile exsolution.

Hyaloclastite is uncommon in the Garibaldi volcanic belt compared to Iceland and many other locations. Within the Ember Ridge deposits, hyaloclastite outcrops at only one locality. The explanation for this is not clear, although it is probably linked to magma composition and eruptive conditions (Kelman et al., in press). One possibility is that hyaloclastite may have once been present in moderate to large quantities surrounding the coherent lava, but has since been removed by erosion. Since Garibaldi volcanic belt uplift rates, and thus erosion rates, are high (Parrish, 1983; Monger and Journeay, 1994), the easily eroded fragmental material may have been totally removed. However, basaltic subglacial edifices near Mount Meager, the Bridge River cones, and the Salal Glacier volcanic complex contain numerous examples of hyaloclastite, suggesting that erosion alone cannot account for the difference in percentages of fragmental material among the Garibaldi volcanic belt and other areas. Of the three fragment-generating processes, quench fragmentation and primary volatile exsolution may be suppressed by high hydrostatic pressure at great water depths (Kokelaar, 1986). Under sufficiently thick ice, it may be difficult to generate large quantities of hyaloclastite, although small amounts could still be generated as a result of cooling and contraction of pillow or flow surfaces. Thus, a second possible explanation for the scarcity of fragmental material at Ember Ridge is that only minimal amounts of hyaloclastite formed due to suppression of all hyaloclastite-generating processes except cooling contraction as a result of high ambient water pressure (reflecting thick ice). A paucity of water resulting from continuous drainage through permeable ice or along meltwater tunnels, which would be enhanced by the steep topography, would lead to eruption in direct contact with ice rather than within a water-filled chamber. This is a third possible explanation for the scarcity of hyaloclastite.

The Ember Ridge volcanic deposits, although lithologically varied and up to 1.4 km apart, are remarkably similar in overall outcrop morphology, jointing style, and degree of erosion. All outcrops have varied but high fractions of fine-scale columnar joints, although only one still contains macroscopic fresh glass. The finely jointed outcrop surfaces are highly unstable and easily eroded, and it is hypothesized that all Ember Ridge deposits date from the Fraser Glaciation (prior to 13 000 BP; Mathews et al., 1970; Armstrong, 1981; Clague, 1981). Souther (1980) hypothesized that the Ember Ridge outcrops originated from a common magma source; however, significant variations in phenocryst percentages are found in the six deposits (with olivine occurring in only one of them). Chemical analyses of two deposits show them to be andesite (Kelman et al., in press), but the others have not yet been analyzed chemically or petrographically. Variations in phenocryst types and percentages among the lava units suggest that they originate from at least two different magmatic sources.

The six Ember Ridge outcrops are closely spaced and have undergone the same amounts of isostatic rebound since glaciation (Monger and Journeay, 1994). If they are coeval, then ice at least 670 m thick must have been present at the time of eruption. This thickness is defined by the lowest and highest elevations at which ice-contact features have been observed, and covers elevations from 1360 to 2030 m. The current valley floors are several hundred metres below the lowest Ember Ridge deposits and have been partly filled with sediments since the end of glaciation. Therefore, the ice may have extended a considerable distance below 1360 m. Furthermore, the ice sheet may have extended to elevations well above the highest Ember Ridge deposit. Thus, 670 m is a minimum estimate for ice thickness. At glacial climaxes, ice thickness is estimated to have been as great as 2500 m over portions of British Columbia (Fulton, 1967; Clague, 1983).

Numerous subglacial domes having a morphology and composition similar to those of Ember Ridge occur elsewhere in the Garibaldi volcanic belt (the Eenostuck mass, Glacier Pikes, knobs at Round Mountain, Slag Hill, etc.). If dates and contemporaneous ice-thickness information can be obtained for these features, it may be possible to quantitatively correlate ice thickness with subglacial edifice morphology and use this to estimate ice thickness at localities where it is unknown.

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