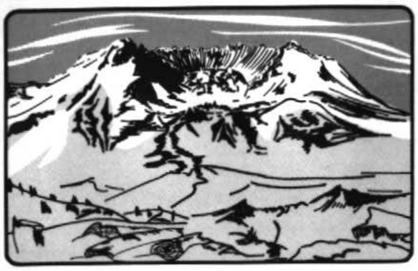

# Late Cenozoic Volcanism in the Mount Garibaldi and Garibaldi Lake Volcanic Fields, Garibaldi Volcanic Belt, Southwestern British Columbia

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### Summary

At least twelve Pleistocene-Holocene calc-alkaline eruptive complexes were formed in the Mount Garibaldi and Garibaldi Lake volcanic fields during the intervals 1.1-1.3 Ma, 0.4-0.7 Ma, 0.2-0.3 Ma, and 0.10 Ma to present. Mildly alkalic basalts, which resemble extensional magma types, were erupted only during the last 100,000 years.

Evolution of basaltic andesite and andesite magmas can be explained by polybaric crystal fractionation of more mafic parental magmas. The dacitic and rhyodacitic magmas probably originated by continued fractionation of andesitic liquids accompanied by extensive assimilation of heterogeneous crustal contaminants. Erupted basalts and calc-alkaline rocks, however, can not be related by fractionation processes.

### Introduction

Late Cenozoic subduction of the Juan de Fuca plate beneath the continental margin of southwestern British Columbia and northwestern Washington has been accompanied by volcanism along the Garibaldi volcanic belt (Souther, 1977; Keen and Hyndman, 1979). This chain of stratovolcanoes, volcanic domes and isolated lava flows, which possibly includes Mount Baker and Glacier Peak volcanoes in northern Washington, defines a northwest-trending axis that is subparallel to and about 250 km inland from the convergent plate boundary, and oblique to the north-south trend of the High Cascades in Washington and Oregon. In the southern Garibaldi belt, extensive volcanism occurred in the Mount Garibaldi and Garibaldi Lake areas where numerous complexes were constructed on an erosion surface that truncates well-foliated to massive Cretaceous quartz diorites, granodiorites, and quartz monzonites of the Coast Crystalline Complex (Mathews, 1958, 1972; Woodsworth, 1977).

### Eruptive History

The Pleistocene-Holocene eruptive history of Mount Garibaldi and Garibaldi Lake volcanic fields has been delineated on the basis of stratigraphic relationships and limited K-Ar, $^{14}$C and paleomagnetic data (Figure 1).

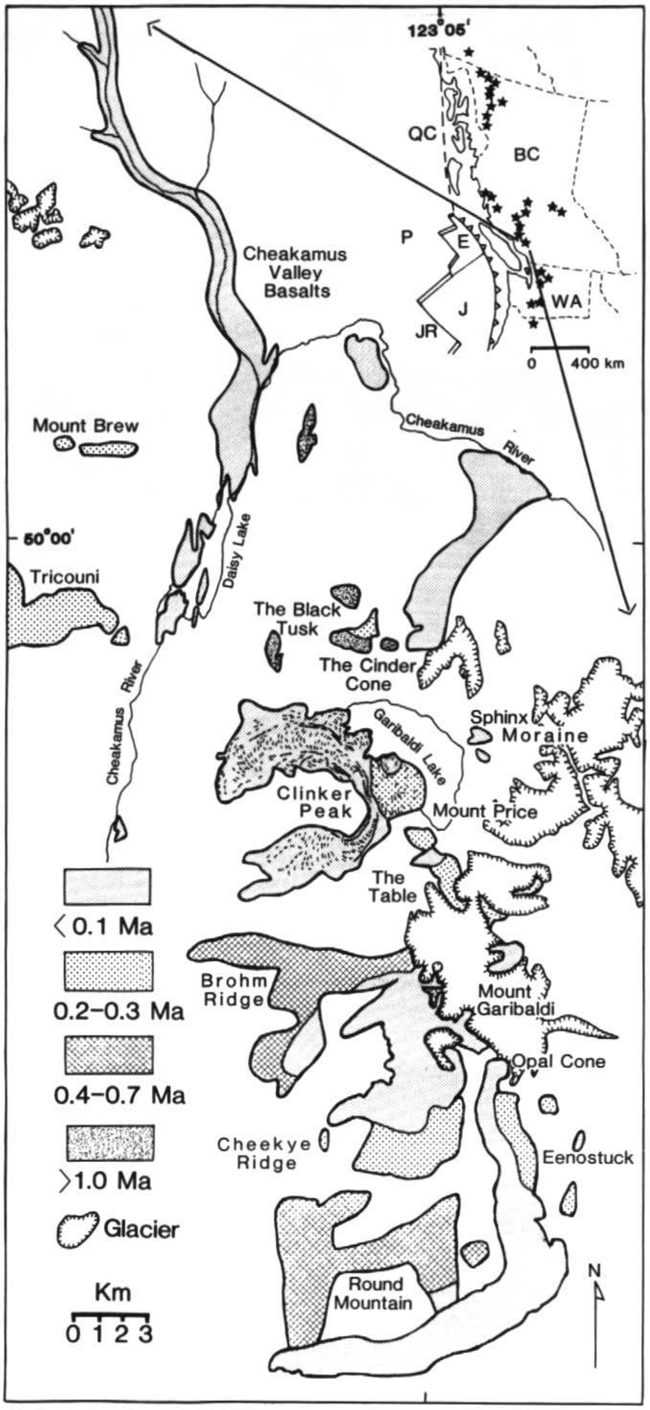


**Figure 1** *Timing and distribution of Pleistocene-Holocene volcanic rocks in the dominantly dacitic Mount Garibaldi and andesitic Garibaldi Lake volcanic fields. Inset illustrates the configuration of the Juan de Fuca ridge system (**JR**), Queen Charlotte fault system (**QC**), and Juan de Fuca (**J**), Explorer (**E**), and Pacific (**P**) plates along the continental margin of British Columbia (**BC**) and Washington (**WA**). Stars show Quaternary volcanic centres.*

The volcanic complexes formed during at least four periods of activity, defined by the presence of erosional discontinuities or glacial deposits within the volcanic succession and (or) by volcanic products that originated from different vents or groups of vents. Eruptive products representing different magma types tend to be both temporally and spatially distinct.

***Pre-1.0 Ma Volcanism.*** The oldest known volcanic products postdate an early Pleistocene glaciation. These andesite lavas and pyroclastic rocks, which were erupted between 1.1 and 1.3 million years B.P., are restricted to the basal eruptive groups at The Black Tusk and Mount Price (Figure 1).

***0.4-0.7 Ma Volcanism.*** This period of activity has only been identified in the Mount Garibaldi area (Figure 1). The volcanism began 670,000 to 700,000 years ago, and produced andesitic pyroclastic and laharic breccias that filled several paleovalleys preserved within the slopes of Round Mountain (Mathews, 1952a; Thompson, 1968). Between 0.44 and 0.55 Ma, andesite and dacite lavas and pyroclastic rocks occupied paleovalleys extending along Brohm Ridge (Green, 1989). The age of these Mount Garibaldi eruptive suites suggests that volcanic activity migrated southward during the earliest stages of Garibaldi belt development (Green *et al.*, 1988).

***0.2-0.3 Ma Volcanism.*** The older volcanic complexes underwent considerable dissection prior to the onset of widespread andesitic and dacitic volcanism between 0.2 and 0.3 Ma (Figure 1). Episodic eruptions produced 0.3 Ma andesite-dacite lavas and tuff breccias at the Mount Price complex, a 0.22-0.26 Ma dacite (Cheekye stage) composite cone at Mount Garibaldi, and 0.21 Ma andesitic lavas and a related plug dome at The Black Tusk (Figure 2a). With the exception of The Black Tusk summit, the volcanic complexes were subsequently overridden by a continental ice sheet.

***Post-0.1 Ma Volcanism.*** Volcanic activity was renewed about 100,000 years ago following a period of glacial retreat. This volcanism was marked by the first appearance of basalt and basaltic andesite lavas (Green *et al.*, 1988). Basaltic andesites were erupted from vents east of the volcanic front, whereas basaltic volcanism generally occurred trenchward of the andesitic centres. Eruptions produced the Sphinx Moraine basaltic andesite complex on the eastern shore of Garibaldi Lake, and The Cinder Cone tuff ring (Figure 2b) with an associated 9-km-long basaltic andesite lava within a glacial valley carved into the eastern flank of The Black Tusk (Green *et al.*, 1988). Prior to 50 ka, three episodes of olivine basalt extrusion, separated by periods of erosion of unknown duration, also formed a 22-km-long, 50-m-thick plateau sequence within the glaciated Cheakamus River valley (Mathews, 1958; Green, 1981). This basaltic volcanism was followed by an advance of the Cordilleran ice sheet and its retreat during the Olympia Interstade, the non-glacial interval (26-50 ka) preceding the last major (Fraser) continental glaciation (Fulton *et al.*, 1976, Green, 1981).

Volcanism recommenced at Mount Garibaldi after the Fraser ice sheet had filled

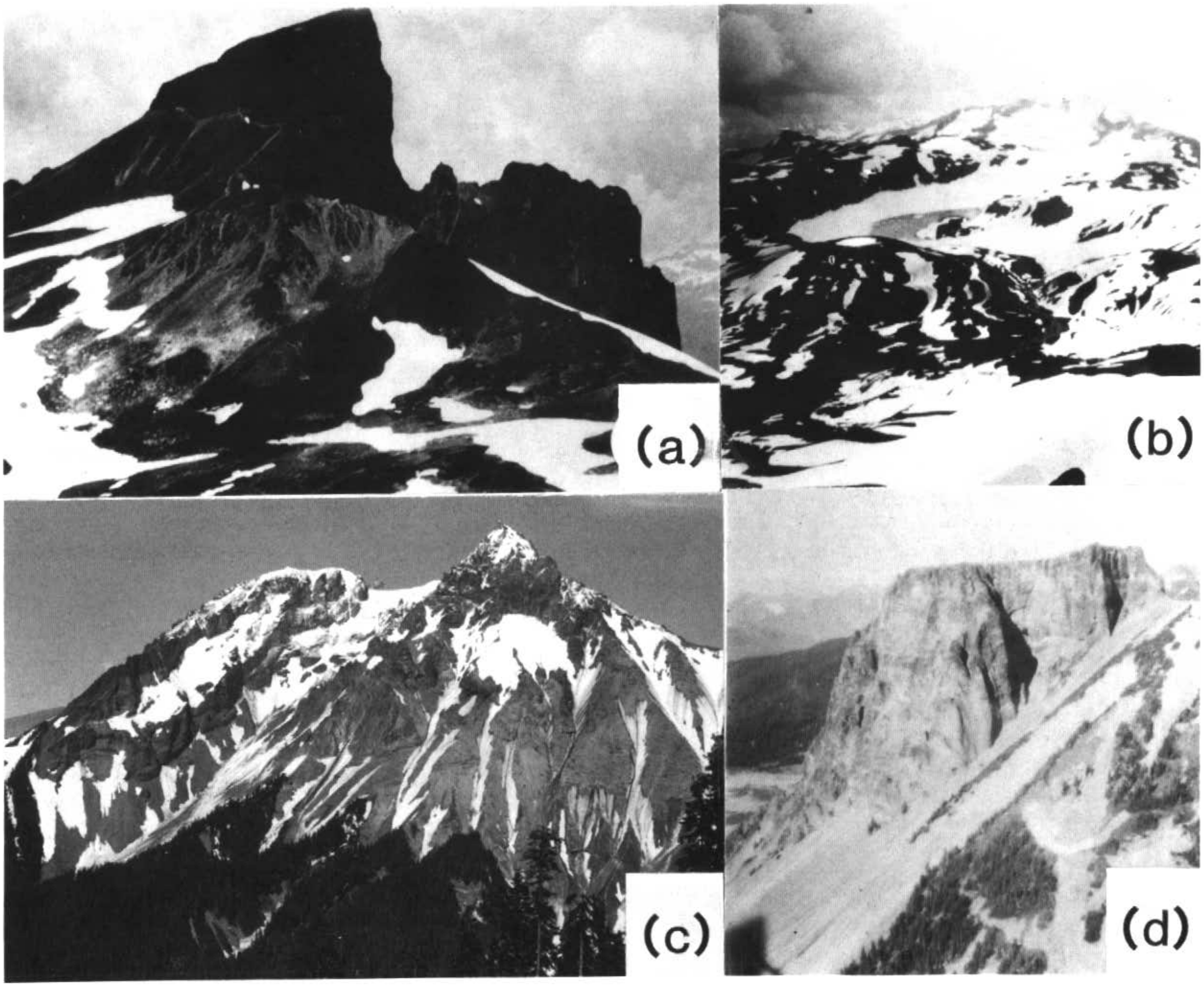
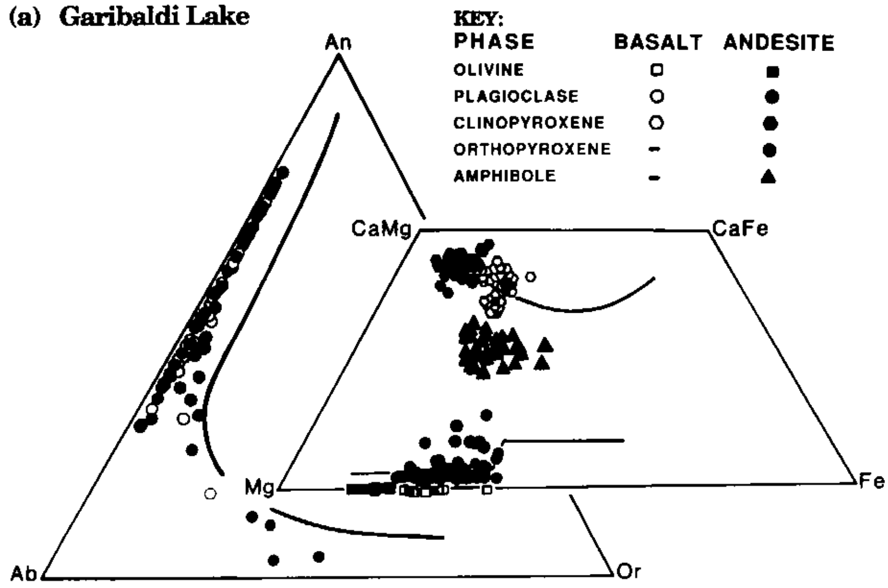


**Figure 2** (**a**) *The Black Tusk dominated by the second-stage plug dome capped by a younger lava.* (**b**) *The Cinder Cone, an older tuff ring (foreground) buried by younger Strombolian cinder cone.* (**c**) *Pelean tuff breccias, exposed in landslide scar produced by collapse of west flank of Mount Garibaldi, originated from a vent at Atwell Peak* (***right***)*, and were succeeded by outpouring of lava from Dalton Dome* (***left***). (**d**) *The Table, a hornblende andesite tuya, is elongate parallel to the local direction of ice sheet movement.*

deep valleys incised into the western flanks of the older Cheekye cone. Pelean eruptions constructed a supraglacial dacitic tuff breccia cone that surrounded the funnel-shaped Atwell Peak plug dome (Figure 2c). While the ice sheet still stood at or near the summit of Brohm Ridge, eruptions from a subglacial vent constructed The Table complex, about 3 km north of Mount Garibaldi (Figure 1). This edifice, which has the classical form of a tuya (Figure 2d), probably developed when andesitic lavas repeatedly flooded a pit thawed through the declining ice sheet (Mathews, 1951). Possibly contemporaneously, subglacial extrusion of basaltic andesites formed the drumlin-shaped Eenostuck mass, approximately 7 km southeast of Mount Garibaldi (Figure 1), and dome-shaped knobs that protrude from the southern flank of Round Mountain.

Progressive melting of ice tongues that filled underlying valleys led to the collapse of the western flank of the supraglacial Atwell Peak cone (Mathews, 1952a). After most of the ice sheet beneath the cone had disappeared, a new vent opened at the northern end of the second-stage cone. This activity produced the Dalton Dome dacite lava that flowed westward down the landslide scar which truncates more gently dipping tuff breccias (Figure 2c). Partial destruction of this flow by additional collapse of the tuff breccias on which it lies suggests that the lava was extruded not long after withdrawal of the ice sheet (Mathews, 1952a).

After retreat of the continental glacier from higher elevations, a small andesitic dome was constructed on the northern flank of Mount Price, and two 300-m-thick andesite lavas (Barrier and Culliton Creek flows) emanated from Clinker Peak, a breached lava ring on the western shoulder of the Mount Price edifice. Mathews (1952b) attributed the anomalously large thicknesses of the flows to ponding of lava against the Cordilleran ice sheet when it still filled valleys at lower elevations. Within the nearby Cheakamus River valley, approximately coeval "esker-like" basaltic flows with basal hyaloclastite breccias were extruded on the glaciated surface of older basalts, possibly by passage of lavas along tunnels or trenches thawed in the ice sheet by heated meltwater (Mathews, 1958). Strombolian eruptions at The Cinder Cone constructed a small pyroclastic cone on the eastern rim of the older basaltic andesite tuff ring (Figure 2b). Lava, which ranges from basalt to mugearite, issued from the base of the cone and flowed 9 km northward.


(a) Garibaldi Lake

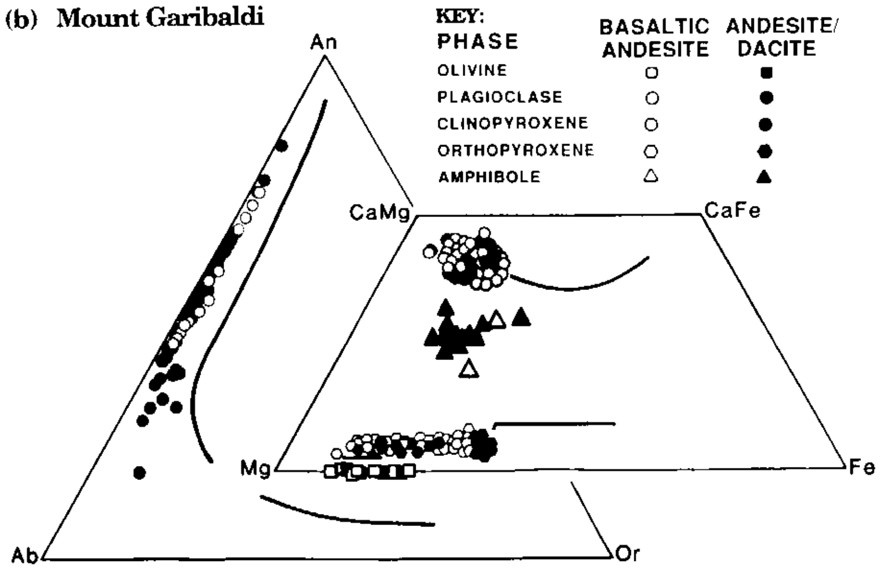

(b) Mount Garibaldi

**Figure 3** *Compositions of phenocryst phases in* (a) *Garibaldi Lake and* (b) *Mount Garibaldi lavas.*

The most recent eruptive activity occurred at Opal Cone on the southeastern slope of Mount Garibaldi (Figure 1). The Ring Creek lava, which issued from the cone, extended 15 km along the eastern and southern flanks of Round Mountain. As the lower half of the Ring Creek lava shows no evidence of glacial erosion or ponding (Sivertz, 1976), the Opal Cone eruption probably occurred after the Fraser ice sheet had disappeared from the vicinity of the flow terminus (Mathews, 1958). The presence of Mazama ash within a succession of limnic peat resting on glacial drift near the westernmost extension of Brohm Ridge indicates that the ice sheet had evacuated the Mount Garibaldi area before 6,670 years B.P. (Mathews, 1972).

## Magma Evolution

The Mount Garibaldi and Garibaldi Lake lavas represent two distinct magmatic associations, one comprising hy-normative hawaiites and ne-normative mugearite with subordinate olivine tholeiites, and the other comprising calc-alkaline basaltic andesites through rhyolite. The basaltic rocks most closely resemble magmatic associations considered to characterize regions of recent uplift, extensional tectonism, and high heat flow (Lipman, 1969; Best and Brimhall, 1974). As younger basalts tend to exhibit increased concentrations of large-ion-lithophile elements, successive batches of basaltic liquid may have been generated by progressively smaller degrees of melting, possibly due to declining magma production under drier source conditions associated with reductions in late Cenozoic plate convergence rates along the continental margin (Keen and Hyndman, 1979; Green, 1982a).

Limited compositional variation in basalts of each Cheakamus Valley eruptive phase can be explained by low-pressure (<5 kbar) fractionation of olivine, plagioclase, and clinopyroxene phenocrysts (Green, 1981; Green and Henderson, 1984). Phase relationships exhibited by cognate xenoliths further suggest that the andesitic lavas evolved by polybaric fractionation of basaltic parental magmas (Green, 1981). However, erupted basalts and calc-alkaline lavas cannot be related by fractionation processes as the basaltic andesites and andesites contain more magnesian olivine and clinopyroxene phenocrysts than the basalts (Figure 3).

The individually coherent calc-alkaline eruptive groups evolved by either hydrous (pl±hbl±ol+cpx±opx±bt+mag±ilm) or anhydrous (pl±ol+cpx+opx±chr+mag±ilm) crystallization of chemically distinct parental magmas. Co-existing Fe-Ti oxide and pyroxene compositions and thermodynamic calculations involving both phenocryst and cognate xenolith mineral assemblages (Green, 1981, 1989) suggest that their distinctive phenocryst assemblages reflect systematic differences in temperature (805°-1025°C), log $f_{O_2}$ (-10 to -15), equilibration pressures (2-6 kbar), and water contents (<1-5 wt.%). Geochemically, the different crystallization paths are represented by "high-Sr" and "low-Sr" series characterized by higher F, K, Rb, Sr and Ba and generally lower Zr, Nb and HREE abundances in amphibole-bearing lavas (Green, 1981, 1982a, 1989; Green and Henderson, 1984). These geochemical differences become less well defined in lavas of dacitic composition.

The basaltic and andesitic lavas have similar $^{87}Sr/^{86}Sr$ ratios, suggesting that their primary magmas were derived from a common (mantle) source, and both probably interacted in a similar manner with crustal material (Figure 4). The low Rb contents (4-18 ppm) of these magmas suggest that their source region was depleted in large-ion-lithophile elements as a result of previous melt extraction

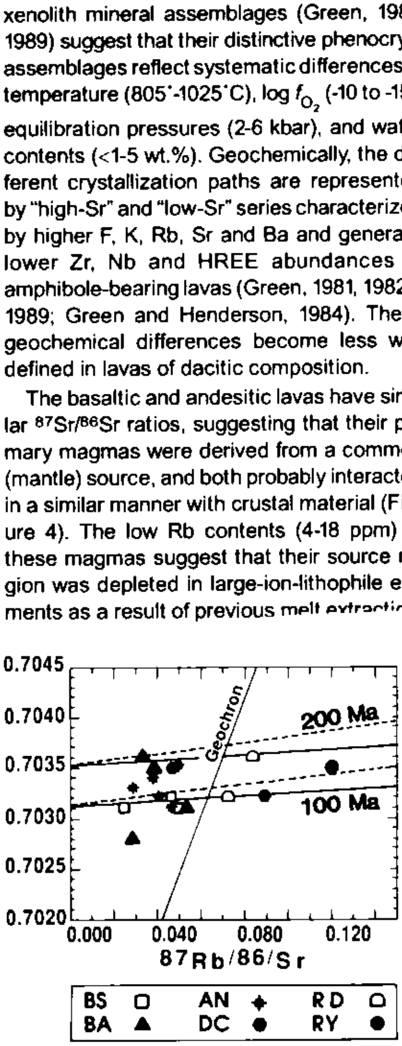


**Figure 4** *Rb-Sr systematics of Mount Garibaldi and Garibaldi Lake basalts (**BS**), basaltic andesites (**BA**), andesites (**AN**), dacites (**DC**), rhyodacites (**RD**), and rhyolites (**RY**). Note that the basalts, basaltic andesites, and andesites lie to the left, whereas more siliceous lavas generally plot to the right of the Geochron (4600 Ma isochron through BABI [Basaltic Achondrite Best Initial]). The Mount Garibaldi and Garibaldi Lake rocks define an array between 100 Ma (solid) and 200 Ma (dashed) reference isochrons which are compatible with K-Ar, Rb-Sr and U-Pb dates for basement Coast Plutonic Complex rocks (Mathews, 1972; Woodsworth, 1977; Armstrong, 1988).*

In contrast, Mount Garibaldi dacite and rhyodacite lavas appear to contain a significant Rb-rich (crustal) component (Figure 4). These rocks, which have compositions that define a linear array between those of associated basaltic andesite and rhyolite, are characterized by oxide and pyroxene phenocryst compositions that yield unusually high (949°-1069°C) equilibration temperatures (Green, 1989), and locally contain olivine xenocrysts that are chemically similar to phenocrysts in the basaltic andesites (Figure 3). The groundmasses of some lavas contain sheared-out patches of red brown glass with high-silica rhyolite compositions similar to those of melts in partially fused granodiorite xenoliths. The dacitic magmas are therefore best interpreted as products of haphazard assimilation-fractional crystallization (AFC) processes acting on basaltic andesite and andesite precursor magmas. The contamination mechanism appears to have involved incorporation of both xenocrysts and anatectic melts derived through disaggregation of the mechanically weakened, partially fused margins of crustal xenoliths included in the ascending magmas. The pattern of AFC-related geochemical variations, however, was locally modified within subvolcanic plumbing systems by: (1) development of slight compositional and thermal zonations due to sidewall crystallization processes as suggested by disequilibrium relationships exhibited by two texturally and compositionally distinct amphiboles and associated ferromagnesian minerals in some lavas (Green, 1982b); and, (2) mixing of compositionally similar dacitic liquids as indicated by composite lava groundmasses containing light grey to black streaks and blebs with slightly different phenocryst populations (Green, 1989).

## Conclusions

Pleistocene-Holocene eruptions formed numerous calc-alkaline volcanic complexes during multiple periods of activity within the Mount Garibaldi and Garibaldi Lake volcanic fields. The calc-alkaline magmas evolved from chemically distinct basaltic parents which underwent varied polybaric crystallization paths, accompanied by assimilation of wall-rock melts and xenocrystic material in derivative andesitic and dacitic liquids. The andesitic and dacitic volcanism was accompanied by extrusion of basaltic lavas only during the last 100,000 years. The late eruption of basalts possibly reflects increasingly less hydrous conditions of magma production associated with reduced late Cenozoic convergence rates along the southwestern British Columbia continental margin.

## Acknowledgements

The author wishes to express his gratitude to C.J. Hickson, D.W. Peterson, and an anonymous reviewer for their helpful comments on the manuscript. This work has benefited considerably through discussions with W.H. Mathews, J.G. Souther, R.L. Armstrong, G.J. Woodsworth, G.T. Nixon and K. Muehlenbacks. In particular, the insightful interpretations of W.H. Mathews have contributed significantly to our present understanding of contemporaneous volcanism and glaciation in southwestern British Columbia.

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# Magmatic Unrest at Long Valley Caldera, California, 1980-1990

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## Summary

On May 25, 1980, the resort town of Mammoth Lakes, California, was shaken by a remarkable 48-hour-long earthquake sequence that included four M=6, two M=5 and 300 M=3 quakes. The nature of the precursory seismicity plus the unusual character of the May 25-27 sequence itself suggested that it was not typical of tectonic earthquakes in the region. Discovery of 25 cm of domical uplift centred on the resurgent dome within Long Valley caldera strongly implied that this activity was accompanied, if not caused, by influx of magma into the Long Valley magma chamber.

## Prologue

On May 25, 1980, one week after the May 18 eruption of Mount St. Helens and following by only a few hours its second major explosive eruption, the resort town of Mammoth Lakes, California, was shaken by a remarkable 48-hour-long earthquake sequence that included four M=6, two M=5, and 300 M=3 quakes (Sherburne, 1980). The largest of these quakes were located on the southern margin of Long Valley caldera and in the High Sierra immediately to the south. The known recurrence interval of tectonic earthquakes in this region, M=5.5 to 6 quakes every decade or two, suggested that this sequence was essentially tectonic in origin, yet the nature of the precursory seismicity along the entire length of the Sierra Nevada front during the preceding three years, plus the unusual character of the May 25-27 sequence itself, suggested that it was not typical of tectonic earthquakes in the region (Ryall and Ryall, 1980). Discovery of 25 cm of domical uplift centred on the resurgent dome within Long Valley caldera during a levelling survey in the summer of 1980 (Savage and Clark, 1982), together with the recognition of seismic P- and S-wave attenuation at depths of 7-8 km beneath the resurgent dome (Ryall and Ryall, 1981), strongly implied that this activity was accompanied, if not caused, by influx of magma into the Long Valley magma chamber. This interpretation was strengthened by continuing unusual seismicity in 1980-82, wherein seismic swarms characterized as spasmodic bursts were localized in a 4-km-diameter epicentral area in the south moat of the caldera at depths from 8 to 5 km (Ryall and Ryall, 1983). Spasmodic bursts are commonly recognized in active volcanic areas and are thought to be the result of rapid-fire brittle rock fracture driven by transient increases in local fluid (either magma or water) pressure. One of the strongest of these swarms, including a M=4.1 and several M=3 quakes, occurred on May 7, 1982, with hypocentres as shallow as 2 km. This activity suggested the upward injection of magma or the expulsion of vapour under high pressure from the magma chamber (Ryall and Ryall, 1983), and it prompted the United States Geological Survey to issue a "Notice of Potential Volcanic Hazard" and to mobilize an intensive monitoring effort in the Long Valley area (Bailey, 1982; Hill, 1984). The Notice, issued when visions of the devastation of Mount St. Helens were still fresh in the public's mind, evoked from the media and the public, particularly locally, the same range of emotional responses previously encountered at Mount St. Helens (Peterson, 1990), varying from disbelief to anger, and scientists were forced to learn anew some difficult lessons in public relations and tactful information dissemination.

## Nature and Chronology of Continuing Activity

Since this initial 1980-82 activity, seismicity and ground deformation in the vicinity of Long Valley have waxed and waned to the present time. After several months of relative quiescence in late 1982, the area was again shaken on January 6, 1983, by an intense earthquake sequence, which this time included two quakes of M=5.3 and thousands of lesser magnitude. This sequence, beginning in the south moat of the caldera at the 1982 main epicentral area, spread rapidly eastward along an 8-km-long, steeply dipping, planar zone, with hypocentres extending from 10 km depth nearly to the surface. It was accompanied by 7 cm additional rise of the resurgent dome and 22 cm right lateral slip along a rupture surface beneath the south moat. Modelling of the seismicity and ground deformation suggested that, in addition to influx of additional magma beneath the resurgent dome, magma also may have been injected as a dyke along the caldera ring fracture (Savage and Cockerham, 1983). This possibility increased concern for an eruption of greater magnitude and extent than was previously considered likely, and appropriate emergency-response plans were formulated by the California Office of Emergency Services, in co-operation with