Canadian Cascade volcanism: Subglacial to explosive eruptions along the Sea to Sky Corridor, British Columbia

J.K. Russell
Earth and Ocean Sciences, The University of British Columbia, Vancouver, British Columbia, Canada

C.J. Hickson
Geological Survey of Canada, Vancouver, British Columbia, Canada

Graham Andrews
Earth and Ocean Sciences, The University of British Columbia, Vancouver, British Columbia, Canada

ABSTRACT

Here we describe a two-day field trip to examine Quaternary volcanism in the Canadian Cascade arc, named the Garibaldi volcanic belt. Day 1 of the trip proceeds along the Whistler corridor from Squamish to Pemberton and focuses on Quaternary glaciovolcanic deposits. Interactions between volcanoes and ice in the Garibaldi volcanic belt have been common during the past two million years and this has resulted in a diverse array of landforms, including subglacial domes, tuyas, impounded lava masses, and sinuous lavas that exploited within-ice drainage systems. On Day 2, the trip heads northwest of Pemberton, British Columbia, along logging roads to see deposits from the 2360 yr B.P. eruption of the Mount Meager volcanic complex. This eruption began Plinian-style, generating pyroclastic fall and flow deposits and ended with the production of block and ash pyroclastic flows by explosive (Vulcanian) collapse of lava domes (e.g., Soufrière Hills). Many of the traits of the deposits seen on this two day trip are a reflection of, both, the style of eruption and the nature of the surrounding landscape. In this regard, the trip provides a spectacular window into the nature and hazards of effusive and explosive volcanism occurring in mountainous terrains and the role of water and ice.

Keywords: Cascades, Garibaldi volcanic belt, glaciovolcanism, Mount Meager, explosive, topography.

INTRODUCTION

This field guide was prepared in support of a two-day field trip to examine Quaternary volcanism in the Canadian Cascade arc informally named the Garibaldi volcanic belt. The field trip has two somewhat diverse goals. The first day of the trip proceeds along the Whistler corridor from Squamish to Pemberton and focuses on Quaternary glaciovolcanic deposits. Interactions between volcanoes and ice in the Garibaldi volcanic belt have been common during the past two million years. This style of volcanism has created a diverse array of landforms, including subglacial domes, tuyas, impounded lava masses, and esker-shaped...
lava that exploited within-ice drainage systems. The second day of the trip follows logging roads northwest of Pemberton, British Columbia, and explores deposits resulting from the 2360 yr B.P. volcanic eruption of the Mount Meager volcanic complex. This eruption began Plinian-style, generating pyroclastic fall and flow deposits; it ended with the production of block and ash pyroclastic flows by explosive (Vulcanian) collapse of lava domes (e.g., Soufrière Hills). What connects these two separate days of field trips is that many of the characteristics of these deposits are shaped by the style of eruption, in conjunction with the nature of the surrounding landscape. In this regard, the trip provides a spectacular window into the nature and hazards of effusive and explosive volcanism occurring in mountainous terrains and the role of water—both liquid and solid.

We have included most of the stops that we consider necessary to develop the ideas we present in this guide; however, not all of these stops can be incorporated into a single two-day trip. The guide includes extensive directions on how to reach each outcrop and abundant images that illustrate the critical elements of each stop. It is our hope that by including this material, we will encourage many others to visit this spectacular suite of volcanic deposits on their own.

The authors dedicate this guide to the memory and lasting scientific contributions of our friend and colleague, Nathan Green. Nathan made significant contributions to our understanding of Cordilleran volcanism in southwestern British Columbia, beginning with his Ph.D. thesis at the University of British Columbia. His professional career went on to delve deeper into our understanding of conditions of basalt and andesite genesis associated with subduction of the Juan de Fuca plate and quantification of differentiation processes (e.g., crystallization, contamination, and magma mixing) affecting magmas within the upper crustal reservoirs associated with High Cascade volcanoes of Oregon, Washington, and southwestern British Columbia. He will be missed.

GEOLOGICAL CONTEXT

This trip examines Quaternary volcanic deposits from several volcanoes that constitute the Garibaldi volcanic belt. The following primer of text and figures is intended to provide a greater context to this volcanic arc and is prepared from other sources (e.g., Monger and Journeay, 1994; Hart, 2002; http://www.nrcan.gc.ca/gsc/pacific/vancouver/earthsci/index_e.htm).

QUATERNARY HISTORY OF SOUTHWEST BRITISH COLUMBIA

Garibaldi Belt

The Garibaldi volcanic belt, situated in southwestern British Columbia, is the northern extension of the Cascade magmatic arc of the western United States (Mathews, 1958; Green et al., 1988; Guffanti and Weaver, 1988). Quaternary volcanism in the region is a result of the subduction of the Juan de Fuca plate beneath the North America plate (Green et al., 1988). The Garibaldi volcanic belt comprises mainly calc-alkaline volcanic rocks and extends from Watts Point, a small lava mass located near Squamish at the head of Howe Sound, northward through Mount Garibaldi, Mount Cayley, Mount Meager, and the Salal glacier volcanic complex, and ending at Silverthrone Mountain (Fig. 1). Volcanic deposits range from Miocene to Holocene in age and consist of at least eight separate volcanic complexes ranging in composition from high-alumina basalt to rhyolite, although intermediate compositions dominate.  Volcanic landforms (see Fig. 2) include stratovolcanoes (e.g., Mount Garibaldi), flows (e.g., Ring Creek), domes (e.g., Ember Ridge), spines (e.g., Black Tusk), cones (e.g., Bridge River cones), and tuyas (e.g., Ring Mountain). The most recent eruption within the Garibaldi volcanic belt occurred at Mount Meager at 2360 yr B.P. (Clague et al., 1995; Leonard, 1995).

The Garibaldi volcanic belt lies within the Coast Belt and cuts its northwesterly trending structures obliquely (Read, 1977; Green et al., 1988). The belt is segmented by the Nootka Fault (Fig. 1; Green et al., 1988), and this intersection coincides with the presence of alkaline mafic volcanic rocks at Salal Glacier. The Quaternary volcanic rocks are seen to mantle and intrude Coast Belt plutonic rocks and minor metamorphic rocks. The metamorphic basement includes metasedimentary and metavolcanic rocks, marble, schist, amphibolite gneiss, and migmatic. In the Meager Creek area, metamorphic rocks correlate with the Upper Triassic Cadwallader Group or, in a few locations, with the Lower Cretaceous Gambier Group. The intrusive rocks are Jurassic to Miocene in age and range in composition from quartz diorite to quartz monzonite.

Uplift Rates

The Coast and Insular Belts of southwest British Columbia have been characterized by high rates of uplift over the past 10 Ma (Fig. 3; Monger and Journeay, 1994) and especially rapid rates of uplift over the past 4 Ma (Farley et al., 2001). Green et al. (1988) suggest that the high rates of tectonic uplift are due to subduction of a relatively hot sea floor crust resulting from the proximity of the ridge system to the trench (Fig. 1). There is little time for off-axis cooling of the Juan de Fuca plate prior to its subduction. This increases the relative buoyancy of the subducting plate causing uplift of the overlying crustal column. Uplift rates have been estimated to be ~2–3 km over the past 10 Ma (Fig. 3).

These high uplift rates have been contemporaneous with the volcanism that defines the Garibaldi volcanic belt. This coincidence serves to explain some of the major morphological differences between the calc-alkaline stratovolcanoes that make up the Cascade volcanic belt and those found in southwest British Columbia. Volcanic landforms are an expression of the balance between relatively rare constructional events and gradual continuous mass wasting. The high uplift rates of this region, however, support accelerated erosion rates. Consequently, most of the volcanic edifices within the Garibaldi volcanic belt are highly
dissected. For example, a good portion of the Mount Meager volcanic complex is made up of the Plinth volcanic formation, which is 100 ka. Despite this young age, the edifice is sufficiently dissected to expose shallow-seated plutonic rocks that correspond to this volcanic system. Furthermore, the Garibaldi volcanic belt volcanoes are presently perched well above the present day base levels of erosion. In the case of the Mount Meager volcanic complex, for example, the peaks of the remnant are at elevations of 2500–2700 m and the base of the edifice is at 1100–1200 m elevation. The current erosion surface is marked by the Lillooet River and is situated at 400–500 m elevation.

(De-)Glaciation

The number of glaciations to have affected the Coast Mountains is uncertain. One site in the interior plateau records a major 1.2 Ma glaciation event (Mathews and Rouse, 1986); a second site to the east records a similar event, as well as several older glaciations. Three glaciations are recognized in the Fraser Lowland near Vancouver; only the latest event, the Fraser glaciation, is within the range of radiocarbon dating. Within the Coast Mountains, the record of glaciation events predating Fraser time is almost completely lacking.

0 Fraser glaciation (Clague, 1981) began somewhat later than 28.8 ka in the northern Strait of Georgia. The ice sheet reached Vancouver, depositing Coquitlam drift by 22.7–21.56 ka. Approximately 20 km south of Whistler the regional ice at its climax covered land to a thickness of 2200 m. At this point in time there were only a few scattered summits standing above the ice (e.g., Mount Garibaldi, Atwell Peak). A few kilometers south of Squamish, glaciation affected elevations up to 1700 m; south of Squamish all mountain tops show a degree of rounding.

At this point in space and time, Fraser ice withdrew an uncertain distance; conditions were sufficient to permit growth of mature forest. The ice then advanced quickly after 17.8 ka and reached its southern “Vashon” limit, 250 km to the south, slightly after 15 ka. Ice retreat was equally dramatic and remains of the Fraser ice were almost gone by 10 ka (Fig. 4). Isostatic depression of the land at the climax of Fraser glaciation may have reached 400 m (Mathews et al., 1970) in the vicinity of the Strait of Georgia which was under the influence of 1500 m of ice load. This depression was contemporaneous with a eustatic sea level of perhaps 75 m below present. Recovery of isostatic depression was probably well under way before ice retreat admitted marine waters to the Strait of Georgia ~13 ka, but here salt water reached the modern 175 m contour along the southern front of the Coast Mountains.
DAY 1: GLACIOVOLCANISM IN THE GARIBALDI VOLCANIC BELT

Glacial events in southwestern British Columbia are contemporaneous with volcanism in the Garibaldi volcanic belt and have affected several aspects of the volcanic history of the region. The advance and retreat of Fraser ice has substantially modified the landscape and has preferentially eroded and/or removed young volcanic deposits. This is especially true of un lithifi ed pyroclastic deposits. Many edifices appear to have erupted in the presence of large ice sheets (Mathews, 1958; Mathews and Souther, 1987; Kelman et al., 2002b). In these situations, the style of volcanism and resulting landforms has been influenced by these ice sheets (e.g., tuyas, subglacial volcanic domes, etc.). Thick, valley-fi lling ice sheets also serve to buttress volcanic edifices. The result is that ice retreat events have been accompanied by relatively high rates of edifice collapse. The apparent spatiotemporal coincidence of glacial events and volcanism suggests that the two processes may be coupled. The Garibaldi volcanic belt may be partly a manifestation of glacial pumping of a magma-charged crust (cf. Edwards and Russell, 1999).

Throughout Quaternary time, the Garibaldi volcanic belt (Figs. 1, 2) has experienced numerous volcanic eruptions and has been subjected to repeated continental-scale glaciations. Consequently, interactions between volcanoes and ice have been common throughout the past two million years (e.g., Mathews, 1947, 1951, 1952a, 1952b, 1958; Souther, 1980; Green et al., 1988; Hickson, 2000; Kelman et al., 2002a, 2002b). Examples of volcanic landforms that have been shaped or modified by ice include subglacial domes such as Ember Ridge, tuyas such as the Table, lavas impounded against ice, such as the Barrier, and flows that have traveled some distance in tunnels or trenches within ice, such as the Cheakamus basalts (Fig. 5). There are also numerous enigmatic, poorly exposed or preserved deposits having features indicative of quenching by ice (e.g., the Southeast Tricouni flows; Fig. 5).

Indicators of eruption in contact with ice include fine-scale jointing (columnar, fl aggy, irregular, or other) indicating rapid cooling, rapid changes in joint orientation and size over small distances, joint orientations and edifice morphologies not explained by apparent paleotopography, and features formed by subaqueous eruption (e.g., pillow lavas, hyaloclastite; Fig. 6).

The majority of studies on glaciovolcanism have focused on basaltic volcanoes, resulting in the development of a “classic” model for tuya-forming subglacial eruptions (Fig. 7; Mathews, 1947; Jones, 1969; Werner et al., 1996). Tuyas begin with a growing pile of pillow lava forming within a subglacial, meltwater-fi lled vault. As the eruption progresses, the vault enlarges and the lava pile grows upward, eventually grading into subaqueous to emergent fragmental deposits (pillow breccias and hyaloclastites); layered hyaloclastites may form delta-like strata on the volcano’s flanks (mimicking classic “Gilbert” style deltas in “normal” sediments). If the vent breaches the surface of the ice, fl at-lying subaerial lavas form a cap to the sequence. Otherwise, a subglacial mound remains. Fluctuations in effusion rate, changes in ice thickness, and accumulation or draining of water result in complex edifices with variants on this basic form.

Intermediate to silicic lavas in contact with ice, however, show differing eruptive behavior and produce landforms that are different in internal stratigraphy than basaltic subglacial features. This is due to the fact that composition controls most important lava properties, including liquidus temperature, viscosity, volatile content, heat capacity, and glass transition temperature. Ultimately, these properties control effusion rates and eruption style, thus resulting in a variety of volcanic landforms and deposits. Subaerial flows of rhyolite and dacite, for example, typically have smaller areal extents and higher aspect ratios than do basaltic flows. The heat budgets attending the eruption of mafic and felsic magmas beneath ice can be substantially different (Höskuldsson and Sparks, 1997; Kelman et al., 2002b); magmas with higher silica contents typically have lower eruption temperatures and smaller intervals between their eruption and glass transition temperatures, resulting in reduced abilities to crystallize, releasing
latent heat. Thus, felsic magmas are likely to generate less heat during subglacial eruptions and have a reduced ability to generate meltwater (Kelman et al., 2002b).

Lavas of intermediate composition in the Garibaldi volcanic belt tend to form flow-dominated tuyas (e.g., the Table, Ring Mountain), comprising almost entirely flat-lying lava flows, few or no pillows, and little or no hyaloclastites. Another type is subglacial domes, which comprise steep-sided, domelike piles of intensely jointed flows. In the Garibaldi volcanic belt, the steep topography and high altitude of many vents are additional influences on the styles of glaciovolcanism. The topography inhibits the ability of many edifices to accumulate significant amounts of meltwater generated from melting of overlying ice during eruptions. Impoundment features result from lava erupting from high altitude vents and flowing downslope to pond against ice that fills valleys during the waning stages of large-scale glaciations (e.g., the Barrier; Fig. 8). The Garibaldi volcanic belt also contains a number of landforms that, though their local morphologies and lithologic characteristics are strongly suggestive of eruption in contact with ice, are difficult to classify with other edifices (e.g., “esker-like” Cheakamus basalts, Southeast Tricouni flows, Monmouth Creek Complex).

Figure 3. Amounts of uplift in southwestern British Columbia in the past 10 m.y. and present rates of uplift in mm/yr (from Monger and Journeay 1994).

Figure 4. Decay of the Cordilleran Ice Sheet in southern British Columbia and northern Washington during the terminal phase of the Fraser Glaciation. Approximate glacier margins at 15,000, 13,500, 12,500 and 11,000 yr BP are shown (from C.J. Hickson, 1996 unpublished guide).

1GSA Data Repository Item 2007028, Geology, geological hazards and Quaternary volcanic rocks of Howe sound drainage basin and vicinity (unpublished guide compiled and prepared for participants at the Pan Pacific Hazards Conference, Vancouver), is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA, editing@geosociety.org, or at www.geosociety.org/pubs/ft2007.htm.
Figure 5. Distribution of Quaternary volcanic deposits in the Mount Cayley volcanic field and showing locations of field trip stops for Day 1 (Whistler Corridor; Kelman 2005). Volcanic centers are identified in terms of recording interactions with ice sheets or not.
ROAD LOG TO START OF TRIP

The 2007 Cordilleran GSA field trip begins in Squamish. The trip will begin with a short retracing of our steps southward to a suitable location to provide a geological overview for this portion of the Cascade arc. Figure 5 shows the locations of each stop for Day 1 of the field trip against the backdrop of the Whistler corridor (Horseshoe Bay to Squamish to Whistler). NOTE: WE HAVE RETAINED THE ORIGINAL KILOMETERAGE TO FACILITATE FIELD TRIPPERS CARRYING OUT THE TRIP ON THEIR OWN.

Begin Road Log (km)

0 km Begin field trip near Horseshoe Bay, north of Vancouver. Mileage begins from EXIT 2 (Eagleridge) on Highway 99 (upper levels highway), which is ~15 km past the north end of the Lion’s Gate Bridge (Fig. 5). Continue north on Highway 99 past the Horseshoe Bay ferry terminal until you reach the Porteau Cove turnoff (on the west side of Highway 99).

36.6 km Pullout for Garibaldi Monument

We use the pullout along the west side of the road (Monument to General Giuseppe Garibaldi) to turn the vans around to prepare for Stop 1.

Garibaldi Mountain was named in 1860 by Captain George Henry while carrying out a survey of Howe Sound on board the Royal Navy survey ship HMS Plumper. Captain Henry was impressed by the towering mountain dominating our view to the northeast (weather permitting) and chose to name the 2678 m mountain Mount Garibaldi. At this time, Giuseppe Garibaldi (4 July 1807–2 June 1888) was close to the peak of his career and was much admired in England and other Protestant countries for his fight against the Pope, and the unification of Italy.

Much of the area to the north of us is within Garibaldi Provincial Park. In 1907, a party of six Vancouver climbers reached the summit of Mount Garibaldi. The views from the peak inspired the establishment of summer climbing camps at Garibaldi Lake. This early interest led to the creation in 1920 of a park reserve. Garibaldi Provincial Park was legislated as a Class A park in 1927, a 195,000 ha mountain wilderness just 64 km north of Vancouver.

Head back SOUTH on Highway 99. Prepare (~0.5 km) to turn right off the highway and onto the first gravel road. After taking the turn drive 0.9 km along the gravel road and take the fourth right turn into the Upper Quarry. The quarry is active so drivers must exercise caution.

STOP 1: (35.9 km) Watts Point Upper Quarry

What is there: We will use this stop (Fig. 9) to give an overview of the day’s itinerary and an introduction to the geology of the Canadian Cordillera. After the overview we will then take a short walk from here through the quarries to Stop 2.
STOP 2: (35.9 km) Watts Point Upper Quarry

Where: The Upper Quarry at Watts point immediately below a microwave station (Fig. 10).

What is there: The Watts Point volcanic center is the southernmost volcanic center in the Garibaldi volcanic belt. It comprises a sequence of sparsely porphyritic, intensely jointed, variably glassy, hornblende pyroxene dacite lava and lava breccia (Bye et al., 2000; Kelman, 2005) that is locally overlain by glacial and postglacial sediments. K-Ar dating of two whole-rock samples yielded ages of 0.09 ± 0.03 and 0.13 ± 0.03 Ma (Green et al., 1988). The Watts Point lavas are interpreted as having erupted in a subglacial to englacial environment (Bye et al., 2000).

Figure 7. Classical model for formation of basaltic tuya (Jones, 1969) showing: (A) initial eruption of pillowed basalt into melt-water ponded at base of glacier, (B) continued eruption produces hyaloclastite and melting of ice and culminates in breaching of ice surface, (C) eruption products (pillowed basalt and hyaloclastite breccias) build up tuya until the edifice is emergent from water but below ice surface, (D) final eruption produces subaerial lava that caps the lower succession of pillowed basalt and hyaloclastite and gives rise to the relatively flat-topped shape of tuyas.

Figure 8. Schematic portrayal of lava being impounded by ice sheets at elevations below the volcanic vent (Mathews, 1952a). Retreat of ice leaves steep near-vertical walls of lava that commonly feature horizontally oriented cooling joints.
At the Watts Point Upper Quarry, well-developed, small (<30 cm) columnar joints may be observed in the lava flows that form its wall and floor. Depending on recent quarrying activities, different features may be visible. Excellent chisel marks may be evident in the northwest wall. At the northeast margin of the quarry, lavas have an irregular fracture pattern overlain upon columnar jointing. Hyaloclastite fragments have been found in the rubble on the quarry floor, although their precise source has not been located; it may be that the hyaloclastite occurs as small pods that are quickly excavated by quarrying activities.

Return to Highway 99 and continue north (left) toward and through Squamish. Caution must be used when rejoining the highway traffic.

64.7 km A bright orange bridge crosses Culliton Creek. We drive 9.7 km past this bridge.

74.4 km Chance Creek turnoff. Take the Chance Creek Forest Service road turnoff on the west side (left) of the highway. It consists of an unpaved pullout leading to a wooden bridge on the other side of which lie railroad tracks. This road may or may not have active hauling by logging and quarry trucks, so proceed with extreme caution. Continue along the gravel road across the railroad tracks and take the first right; the road immediately begins to wind uphill. At 1.6 km from Highway 99 is a prominent switchback with a pullout and a wooden building. Park here, far enough off the road not to impede turning trucks, and walk up the road a few hundred meters to examine the outcrop (Stop 3), a prominent, intensely jointed lava cliff.

STOP 3: Southeast Tricouni Ice-Contact Lavas

Where: Outcrop exposed on Chance Creek Forest services road, east of Freeman Lake.

What is there: This stop lies at the southern end of the Mount Cayley volcanic field (Fig. 5 and inset). The Mount Cayley volcanic field consists of Miocene to Pleistocene volcanic deposits of basaltic andesite to rhyolite composition, and comprises at least fifteen centers, most of which do not overlap spatially. All but two of these centers show evidence for eruption in the presence of ice.

The Tricouni Southeast unit is a sequence of porphyritic to microporphyritic plagioclase-hornblende-bearing dacite flows. In many locations these flows show evidence for eruption in contact with ice. Along this several-hundred-meters-long stretch of road (Figs. 11A, 11B) the southeastern margin of this gray (fresh) to yellow-gray (weathered) flow crops out with prominent columnar joints. The jointing occurs in locally radiating patterns with orientations that vary significantly over distances of only a few meters. Column diameters are generally 20–40 cm, with sizes increasing slightly toward column bases. This flow margin is interpreted as having been cooled against ice due to the joint orientations, which indicate irregular, locally vertical, cooling surfaces (that are not explained by apparent paleotopography), and the small joint sizes, which indicate rapid cooling.

From Stop 3, continue driving up the gravel Forest Services road ~1 km and take the turnoff to the north (right), which leads to a flat area large enough for several vehicles to park. Overlooking the parking area is a prominent, near-vertical cliff at least 50 m high (Stop 4).

STOP 4: Southeast Tricouni Lavas

Where: Outcrops overlooking Freeman Lake, 2.6 km from Highway 99.

What is there: This location is upslope of Stop 3 but still within the same dacite flow (Fig. 5 inset). Several features are of interest here. The eastern shore of Freeman Lake consists of low mounds featuring irregularly oriented, small-scale columnar joints (Fig. 12). A highly weathered, steeply southeast-dipping
contact with the underlying basement occurs a few meters above the level of the road. Proximity to the base of the flow may explain the high abundance of till or basement xenoliths at this outcrop relative to elsewhere within the same map unit.

Continue driving uphill from Stop 4 for another 0.4 km. Turn right (north) (at 3 km from Highway 99) and go north on the Roe Creek Road for another 0.7 km. Turn right. There is a short section of road beyond which is an open flat area where several vehicles can park.

STOP 5: Southeast Tricouni Lava, Breccia, and Outwash Sediments

Where: On Forest Services road ca. 3.7 km from Highway 99; plus ca. 250 m walking.

What is there: This site is still within the same Southeast Tricouni unit as Stops 3 and 4 (Fig. 5 inset); the northern side of the cliff-sided knob viewed at Stop 4 lies just southeast of the parking area. To the north (left) of the pullout is a pale gray, coarsely columnar-jointed lava with a weak perpendicular planar jointing superimposed on it (Fig. 13A).

To the southeast (right) of the pullout, separated from the coarsely jointed lavas by rubble and a small lake, is a short stretch of road. Here the lower contact of the lava meanders over till (Fig. 13B); distally, the lava eventually degrades into breccia and weathered hyaloclastite. At the very end of the road are finely laminated sediments containing rare larger rounded basement fragments and very rare angular fragments of the adjacent lava flow; these are most likely glacial dropstones. Rare till balls are also present. This is interpreted as a flow margin in close proximity to ice; the fine laminations in the sediment suggest a relatively stagnant meltwater pool into which ice fragments were calving.

Return to vehicles and return to the Chance Creek Road by turning left (south) and driving ~0.7 km. Turn right. Stay on the main road and drive west for 4.1 km, then turn right (north).
Drive up the hill past the first switchback until you see the small knob that appears to the east of the road (1.7 km from where you turned off the Chance Creek Road). You can park on the road or on the short section of road to the south of the knob.

**STOP 6: Southeast Tricouni Ice-Contact Lavas**

*Where:* High-elevation exposure of ice-contact lavas on Chance Creek Road 8.8 km from turnoff at Highway 99.

*What is there:* This exposure of lava (Fig. 14A) is within the same map unit (the Southeast Tricouni flows) is of similar composition and lithology to the previous three stops, and is probably of similar age and source; the lack of continuity of outcrop makes tracing individual flow units difficult. The knob to the east of the road is interpreted as having cooled in contact with ice, based on small column sizes and extreme local variations in their orientations. The lava along the road is interpreted similarly, but has large variations in glass content over a short distance. Note the abrupt change in joint orientation from near-vertical to near-horizontal about two-thirds of the distance up from the base of the rock face.

Note that at several of the stops along this portion of the trip you get excellent views to the east. You are looking across the Cheakamus River Valley to the Garibaldi area. Mount Garibaldi, The Table, Mount Price and Clinker Peak, and the Barrier are all visible.

Return to vehicles and drive south until you are back on the Chance Creek Road. Follow the road east, back the way you came, cross the bridge and prepare to return to Highway 99 by resetting the trip odometer to 0.0.

0 km Chance Creek Forest Services road turnoff. Turn north (left) onto Highway 99. Note the dead trees in the river bed as the road skirts close to the river. Along the road large boulders form the forest floor. These features are a result of the 1855–1856 collapse of the Barrier.

1.5 km Rubble Creek Bridge.

1.6 km Unsigned turnoff to the east (right). Take this northeast-trending road and follow it uphill for 2.7 km until you reach the Rubble Creek parking lot.

**STOP 7: The Barrier**

*Where:* Day-use recreational area at head of hiking trail to Barrier on Rubble Creek.

*What is there:* The Barrier is one of the best-described and most accessible impoundment features in the Garibaldi volcanic belt (Fig. 5). This is partly due to the area being embroiled in a land-use dispute (see below). Located northeast of Mount Garibaldi, near the Mount Price complex, it consists of an oxidized, rubble-topped, red to gray andesite lava terminating in a 200 m cliff surrounded by debris in the upper reaches of the Rubble Creek Valley (east and uphill of the Rubble Creek parking lot). Although upper reaches of the lava have normal gradients and surface characteristics, the flow terminus is precipitous, locally concave, unusually thick, and subject to major landslides.
It formed when lava from the Clinker Peak vent on the western side of Mount Price flowed downslope to pond against the waning Cordilleran ice sheet that still filled valleys 8000–10,000 yr B.P. (Mathews, 1952a; Fig. 8). A similar cliff, formed contemporaneously by another Clinker Peak lava, occurs in the upper reaches of the Culliton Creek Valley. The current face of the Barrier is a scar from a major landslide during the 1850s (Mathews, 1952a). The waters of Garibaldi Lake are impounded behind the Barrier, and the region immediately below the Barrier is considered hazardous due to the potential for future landslides. Thus, camping is not permitted in the valley below it.

The Barrier lava may be examined by entering the Rubble Creek streambed adjacent to the parking lot. The streambed is filled with debris from the nineteenth century landslide and from continued mass wasting of the Barrier. Mount Garibaldi is behind and to the right of the Barrier, its summit often obscured by clouds.

This area is one of the few places in British Columbia where there has been successful use of geological information for land-use decisions. In the 1960s a town was planned near the confluence of Rubble Creek and the Cheakamus River. Recognition of the landslide hazard led to an inquiry headed by Justice Berger. Ultimately the board of inquiry deemed the area too dangerous for habitation. Property owners were given land a bit farther north in exchange for their properties here. Land exchange combined with zoning was at that time a relatively little-used method for solving inappropriate land-use decisions. Today, research is being carried out to test the economic viability of land exchange and zoning in areas where engineering works are too costly or impossible to design to protect the land base. This type of nonstructural mitigation is seen as increasingly important for protecting people and infrastructure but meets with tremendous opposition from landholders, developers, and politicians. A pilot study is being carried out with the District of Squamish to explore various risk reduction options as the community faces enormous growth pressures in the face of the 2010 Winter Olympic Games.

Return to Highway 99 by driving west from the Rubble Creek parking lot.

7 km Highway 99. Turn north (right) and continue on Highway 99 for 7.9 km.

14.9 km Brandywine Falls Provincial Park. Exit here to the left into the parking lot. Lock vehicles, pay the parking fee, and prepare for a brief 200–300 m walk.

STOP 8: Cheakamus Basalt Esker-Like Lavas

Where: Brandywine Falls Provincial Park (Fig. 15).
What is there: Walk along the marked path toward Brandywine Falls for several hundred meters until you reach the point where the railroad crosses the path. Here, turn left and walk along the tracks a few meters to where the railway cuts through an 8- to 10-m-high mass of basaltic lava (Fig. 15B). This outcrop represents a perpendicular section through one of the youngest lavas of the Cheakamus Valley basalts, and consists of an elongated lava mass ~8 m high and 15–20 m wide that is transected.
Canadian Cascade volcanism

by the opening for the railroad tracks. Prominent columnar joints and a layer of hyaloclastite (just above track level) are present. It is one of a number of laterally extensive, sinuous, anastomizing lavas that stand out as isolated ridges above the glaciated surface of the older Cheakamus Valley basalts and were described as “esker-like” by Mathews (1958).

The Cheakamus Valley basalts are a sequence of lavas produced by episodic eruption from an unknown vent. Wood in lacustrine sediments beneath the youngest Cheakamus Valley flows is dated at 34,200 ± 800 yr B.P. (Green, 1981); this date correlates with the Olympia Interstade, the nonglacial interval that preceded the Fraser Glaciation (Fulton et al., 1976). Throughout the esker-like lavas, columnar jointing is ubiquitous, and is horizontal along the steep sides of the lavas and vertical beneath the blocky flow tops. At several locations, pillows or wide pillow-like features are present in the basal parts of lavas, and some portions are underlain by hyaloclastite breccia. Mathews (1958) hypothesized that these esker-like lavas were erupted subglacially and flowed some distance from the vent within tunnels or trenches melted in the ice sheet. He based this on the age of the underlying till, the presence

by the opening for the railroad tracks. Prominent columnar joints and a layer of hyaloclastite (just above track level) are present. It is one of a number of laterally extensive, sinuous, anastomizing lavas that stand out as isolated ridges above the glaciated surface of the older Cheakamus Valley basalts and were described as “esker-like” by Mathews (1958).

The Cheakamus Valley basalts are a sequence of lavas produced by episodic eruption from an unknown vent. Wood in lacustrine sediments beneath the youngest Cheakamus Valley flows is dated at 34,200 ± 800 yr B.P. (Green, 1981); this date correlates with the Olympia Interstade, the nonglacial interval that preceded the Fraser Glaciation (Fulton et al., 1976). Throughout the esker-like lavas, columnar jointing is ubiquitous, and is horizontal along the steep sides of the lavas and vertical beneath the blocky flow tops. At several locations, pillows or wide pillow-like features are present in the basal parts of lavas, and some portions are underlain by hyaloclastite breccia. Mathews (1958) hypothesized that these esker-like lavas were erupted subglacially and flowed some distance from the vent within tunnels or trenches melted in the ice sheet. He based this on the age of the underlying till, the presence
of pillows near the bases of some lavas (indicating subaqueous eruption), the horizontal jointing at the margins (indicating vertical cooling surfaces), the fine scale of jointing (indicating rapid cooling), and the lack of apparent paleotopography to explain these features. The Cheakamus Valley lavas appear to have been highly fluid, based on their low aspect ratios and thin termini (commonly less than a meter in thickness) where not impounded.

There is no recognized analogue for these esker-like lavas elsewhere. Their morphology and outcrop patterns may result from relatively rare events where special conditions for ice thickness, effusion rate, lava properties, and slope are met. Conversely, the absence of these flow features in the literature may be a reflection of their fragility, for the Cheakamus Valley lavas are relatively thin, and the fine-scale jointing that pervades much of the lava makes it easily erodible.

Return to park path and proceed to Brandywine Falls viewing platform.

STOP 9: Brandywine Falls

Where: Wooden platform overlooking falls.

What is there: At least four basalt lavas, ranging in age from nearly 34,000 yr B.P. to synglacial, are visible in the vertical walls surrounding the 70-m-high Brandywine Falls (Fig. 15A). A thin layer of fluvial gravel is visible at the top of the lowermost flow. The sequence is believed to have been exposed by backcutting during a major flood event, and the present chasm is much broader than the river flowing through it.

The flood event that carved the canyon is the subject of research by Hickson and Andree Blais-Stevens (who is mapping the surficial deposits in the valley). As you proceed along the path, you can see that the surface is worn and large boulders are rounded. This is not typical of glacially polished flows, but rather suggests water erosion. Additionally rounded, internally draining potholes can be seen along the edge of the highway as we drive north. These have the appearance of large scale scour pockets. It is suggested that there may have been large floods at the end of the ice age as drainage in the valley to the north was blocked by the surfi cial deposits in the valley. As you proceed along the path, you can see that the surface is worn and large boulders are rounded. This is not typical of glacially polished flows, but rather suggests water erosion. Additionally rounded, internally draining potholes can be seen along the edge of the highway as we drive north. These have the appearance of large scale scour pockets. It is suggested that there may have been large floods at the end of the ice age as drainage in the valley to the north was blocked by residual ice. It is also possible that the subglacial eruptions were creating massive amounts of meltwater that was scouring the surface of the older flows.

14.9 km Return to Brandywine Falls parking lot and continue north on Highway 99.

19.5 km Prominent bluff of basalt lava (Fig. 15C) in abandoned British Columbia Railway Company quarry occurs on the east side of the highway, behind a chain link fence and railroad tracks. Pull over into small pullout on left side of highway. Access is by walking through gate 20–30 m north of the pullout.

STOP 10: Cheakamus Basalt Lavas

Where: British Columbia Railway quarry on Highway 99 south of Whistler.

What is there: Within the British Columbia Railway quarry, several of the youngest Cheakamus Valley basalt lavas crop out; these olivine basalts are chemically and temporally similar to those at Brandywine Falls. A number of intriguing features are visible at this site: scoriaceous undersides to lavas perhaps resulting from passage over a wet substrate; locally irregular and radiating columns (Fig. 15 D) indicative of irregular transient cooling surfaces; and horizontal columns indicating vertical cooling surfaces.

End of Day 1: Closing Thoughts

Volcanism in association with large quantities of ice results in a variety of landforms (Fig. 6) whose shapes and lithological characteristics depend upon both the characteristics of the lava (e.g., composition, temperature, effusion rate, total eruption volume) and the physical conditions in which eruption occurred (the amount, thickness, location, and permeability of the associated ice, the nature of the underlying topography, and the amount of trapped melt-water). Where these deposits are preserved, they can serve as an important paleoclimatological tool, because they indicate the past presence of ice. Additionally, an understanding of how volcanoes and ice interact is important for hazard assessments, since subglacial eruptions have the potential to release large volumes of water catastrophically (as jökulhlaups) due to rapid, large-scale melting of ice. Glaciolvonic deposits have been recognized and studied in Iceland, Antarctica, the United States Cascades, Alaska, Hawaii, Chile, and other parts of British Columbia.

DAY 2: THE 2360 YR B.P. ERUPTION OF MOUNT MEAGER

The Meager Creek volcanic complex is located ~150 km north of Vancouver, at the northern end of the of the Garibaldi volcanic belt. The Mount Meager volcanic complex is situated between the Lillooet River and Meager Creek; it comprises a number of deeply eroded volcanic centers that have been active during the past 2.2 Ma (Read, 1978, 1990). The corresponding volcanic rocks directly overlie basement rocks of the southern Coast Belt including Triassic metamorphic supracrustal rocks, and Tertiary monzonite intrusions (Read, 1978). The geology of the Mount Meager volcanic complex (Fig. 16) is well-described by Read (1977, 1978, 1990), Anderson (1975), Stasiuk and Russell (1989, 1990), Stasiuk et al. (1996), Hickson et al. (1999), and Stewart et al. (2001, 2002). Volcanism at the Mount Meager volcanic complex both pre-dates and post-dates the major, recognized glacial periods in southern B.C. (Salmon Springs Glaciation, 50,000 yr B.P., and Fraser Glaciation, 10,000–26,000 yr B.P.). Hotspring activity inspired B.C. Hydro to investigate the area for geothermal energy potential in 1974 and 1975 (Read, 1977).

Read (1977, 1978) subdivided the volcanic stratigraphy of the Mount Meager volcanic complex (Fig. 5) into four separate volcanic stages: a Tertiary (Pliocene) stage and three Quaternary stages (Fig. 16). The Pliocene stage is represented by intermediate to felsic pyroclastic rocks. Basal breccia, believed to be an
exhumed vent, underlies andesite and dacite tuffs, flows, domes, and breccia, all belonging to the Devastator Complex.

The Devastator Complex was followed by the first Pleistocene stage of rhyodacite tuff, breccia, lavas and domes. The second Pleistocene stage produced the Pylon Complex of flow-laminated andesite (1.0–0.5 Ma). The third major eruptive stage is represented by rocks of the Plinth assemblage (unit PL, <100 ka, Fig. 16). The Plinth assemblage comprises the northern flanks and includes rhyodacite flows, domes, breccias and subvolcanic equivalents. The Mosaic assemblage (unit P7, <90–140 ka, Fig. 16) was also produced at this time and includes isolated small-volume alkali olivine basalt flows and pyroclastic breccias located on the outer margins of the main complex (Fig. 16). The fourth and final stage of volcanism is represented by Recent rhyodacite deposits on the west side of Plinth Mountain (see Pebble Creek Formation; Figs. 16, 17).

PEBBLE CREEK FORMATION

The Mount Meager volcanic complex also produced the youngest eruption in the Garibaldi volcanic belt which resulted in a series of volcanic deposits (unit R1, Fig. 16; Read, 1977) dated at 2360 yr B.P. (Clague et al., 1995; Leonard, 1995). The corresponding ash fall deposit (Bridge River tephra) to this eruption was originally mapped, sampled, and studied by Nasmith et al. (1967).

The Pebble Creek Formation (Figs. 18 and 19; previously known as the Bridge River Assemblage) is defined to include all of the eruptive products of this youngest eruption of the Mount Meager volcanic complex, as well as, two (associated?) rock avalanche deposits. The volcanic rocks are dacitic in composition and contain phenocrysts of plagioclase, orthopyroxene, amphibole, biotite and minor oxides in a glassy groundmass. The deposits of the Pebble Creek Formation are the focus of this field trip.

ROAD LOG TO START OF TRIP

The field trip begins in Pemberton, British Columbia. Pemberton is reached from Vancouver by driving north across Burrard Inlet, and along the Sea-to-Sky Highway (Highway 99), through Squamish and Whistler. Pemberton is 133 km north of the Horseshoe Bay Ferry Terminal (intersection of Highway 1 and Highway 99).

Our next leg of driving starts at the Petro-Canada gas station situated at the junction of Highway 99 and the Lilooet Valley road. The Petro-Canada station serves as a convenient rest stop. Set your odometer to zero.
Begin Road Log (km)

0 km  Turn left and drive west along main road to Pemberton. Turn left at the round-about (0.7 km) and cross railway tracks (0.8 km). Continue straight ahead until stop sign at the T-intersection (0.9 km).

0.9 km  At stop sign, turn right and follow this road northwesterly up the Pemberton Meadows valley. The fertile Lillooet River valley has an economy built on seed potatoes, tourism and more recently, as a bedroom community for Whistler. Note that houses are built on artificial knolls to mitigate effects of regular spring floods.

2.8 km  Stop sign at T-intersection. Take sharp left and continue northwesterly up the valley for 20 km or so. The flat valley bottom, now protected by dykes for farming (e.g., 5.5 km), is the broad floodplain of the Lillooet River. The river’s source is the Lillooet Glacier, and drains into the Fraser River via Lillooet Lake.

24.0 km  Watch for signs for turnoff to Gold Bridge, Meager Hot Springs, and the Hurley road.

24.4 km  Turn right onto secondary Lillooet Forest Road. Sign for Gold Bridge, Hot Springs, etc. 

ROAD LOG FOR FIELD TRIP

Driving Instructions: DRIVE WITH CAUTION; you are driving on roads that support active logging. This network of logging roads features a number of one-lane bridges and rough and variable road conditions. Furthermore, boulders commonly roll onto the road from the many unstable slopes. KEEP YOUR SPEED DOWN. One last element is the many tourists who are attracted to the hot springs; many have little experience on such roads, others tend to drive too fast for the road conditions. The logging roads are marked with “kilometerage” markers; we will use these distances throughout the guidebook.

Figure 18. Geologic map showing the distribution of Pebble Creek formation units in the Mount Meager area (from Stewart et al. 2001). This map is based on work by Read (1978), Stasiuk and Russell (1990), Stasiuk et al. (1996), Hickson et al. (1999) and Stewart et al. (2001). Stops of field trip are denoted by numbered dots.

Figure 19. (A) Cross sections showing the stratigraphy and distribution of members of the Pebble Creek formation (from Hickson et al., 1999). (B) Sections showing stratigraphic details at several points along the Lillooet River. Units are the same as in Figure 21 and include: (a) air fall pumice deposits and reworked equivalent (tf); (b) pyroclastic flow deposits associated with Plinian-style phase of eruption (pf1,2); (c) welded equivalents of Merapi-type block and ash flow deposits (bx1,2,3); (d) lava flow (vd); (e) hot, jointed, block lahar deposits (la); and (f) rock avalanche deposits dominated (>90%) by Plinth formation material.
0 km Turn off from Pemberton Meadows Road onto Lillooet Forest Road.

0.1 km Single-lane bridge. A few hundred meters farther along we can look west (left) up the valley where the open fields afford us our first view of the Mount Meager volcanic complex on a clear day.

1.5 km Single-lane bridge over Lillooet River. Pavement ends; gravel roads for the rest of the trip. CAUTION FROM HERE ON.

8.8 km IMPORTANT TURN OFF. Gravel road branches at Hurley River Road. Take LEFT (south) fork to Meager Hot Springs.

24 km The Lillooet River is directly to our left. Note the sediment-choked nature of the drainage attesting to the high rates of mass wasting at the headwaters of the river valley.

27.8 km Immediately after this gentle curve in the road, pull over to the clearing on the right.

STOP 1: (27.8 km) Overview of Mount Meager Volcanic Complex

Where: The road makes a right turn as it climbs a small ridge. Pull over immediately to the right shoulder at the top of the ridge. On a good day, this position affords us our first close-up view of the Mount Meager volcanic complex.

What is there: From this vantage point we can view the entire Mount Meager volcanic complex (Fig. 17). The shallow ridge in the foreground leads directly to the summit of Meager Mountain and conceals Mount Job. To the right (north) is Plinth Peak. Both Plinth and Meager are topped by intrusive rhyodacites (Plinth Formation), thought by Read (1977) to be dissected vents. The flanks of both peaks are composed of rhyodacite lavas. The ridge up to the peak of Meager also has two separate andesite lavas and two pyroclastic units on it (Fig. 16). To the left (south) is Capricorn Mountain, then Pylon Peak. Capricorn is composed of rhyodacite lavas, and Pylon is made of andesite lavas.

Continue driving west along main forestry road.

36 km BC Recreation and Parks Service campsite to serve visitors of the Meager Hot Springs.

37 km Major intersection. We continue straight on by taking the right branch which follows along the north side of the Lillooet River. The road to the left used to cross the Lillooet River and lead to the Hot springs and the base of the Mount Meager volcanic complex, however the bridge is presently washed out.

37.5 km Along the left side of the road are the sorting grounds for Great Pacific Pumice Inc. (http://www.pumice.ca). This mining operation exploits pumice deposits resulting from the 2360 BP eruption (see STOP No. 4).

37.7 km To the left is the old BC Hydro camp, which was the base camp for the geothermal energy drilling project of 1974 and 1975. Geophysical surveys and water geochemistry studies were carried out to determine the potential of the area. A total of 2523 ft (~770 m) of diamond drilling was completed in both the Meager and Lillooet valleys. The government has since shelved the project, and the Hydro camp was purchased by people interested in developing the area and using the available geothermal power.

39.2 km Clearing on the left (south). We will stop here later in the day for STOP 8.

40–41 km After crossing several kilometers of flat valley fill, the road descends down to the level of the Lillooet River—USE CAUTION. The bedrock exposed on the north side of the road consists of greenstone and meta-greywacke of the Upper Triassic Cadwallader Group which forms a large pendant within the Coast Plutonic Complex (Mathews and Souther 1987). The river valley is made quite narrow at this point because of the proximity of bedrock exposures on both sides of the river.

42 km The road cuts up and through a unit that was called a lahar or landslide deposit by Read (1977). We will stop here later at Stop 7.

42.8 km The road begins to climb steeply. Drive across the flats for 5 km or so. The road veers to the right and then turns sharply left to head up the valley wall via a series of switchbacks—USE EXTREME CAUTION. The first switchback enters a clear cut. Pullover to the left (inside portion of road) for Stop 2.

Synopsis of 2360 yr B.P. Eruption

Each of the volcanic deposits in the Pebble Creek Formation is indicative of a specific type of eruptive activity (Figs. 18, 19). Based on mapping by Stasiuk and Russell (1989, 1990), Stasiuk et al. (1996), Hickson et al. (1999), and Stewart et al. (2001), field relationships in the Pebble Creek Formation suggest that individual units were emplaced quickly, implying little to no hiatus in the supply of magma to the surface. Thus, the sequence of events is best described as a single but multiphase volcanic eruption: simply termed, the 2360 yr B.P. eruption. Each phase behaved in a physically distinct way. The presence of banded pumices suggests mingling of mafic and dacitic magma prior to eruption and perhaps represents the trigger mechanism for the Recent volcanism. Much of the stratigraphic complexity evident in the Pebble Creek Formation results from deposition in a narrow, steep-sided mountain valley containing a major river (Figs. 18, 19).

The eruption began explosively, producing a 14–18 km high, convecting pyroclastic column (Plinian-style) from which a mantling air fall pumice layer was deposited (unit tf). Partial and final collapse of the column produced several small volume pyroclastic density currents and their deposits (unit pf). The explosive phase of the eruption cycle was followed by production of lavas and domes (unit vd). A remnant of a 30–40 m thick lava can be found on the lower slopes immediately below the vent area (Figs. 18, 19). Effusion of lavas and domes was contemporane-
ous with the generation of numerous block and ash pyroclastic density currents. These hot Soufriére-style avalanche deposits probably resulted from the explosive collapse (e.g., Vulcanian) of oversteepened domes and lavas.

The production of these block and ash avalanches has resulted in a unique series of welded breccias (unit bx) which filled the Lillooet River valley (Fig. 19). These welded lava avalanche deposits ultimately dammed the Lillooet River. Damming of the Lillooet River caused a lake to form upstream, which may have episodically overtopped the natural dam. A major collapse of the dam (most likely while magma was still being erupted from the vent) triggered a flood that carved back a U-shaped valley through the welded breccias to partially recover the original Lillooet drainage. The deluge had an estimated total volume of \( 10^9 \) m\(^3\) and inundated the Lillooet Valley to a depth of at least 30 m above the paleo-valley floor 5.5 km downstream of the blockage.

Rock avalanches consisting mainly of blocks of Plinth Assemblage volcanic rocks (an older formation making up part of the Mount Meager volcanic complex) underlie and overlie the primary volcanic units of the Formation. Both rock avalanches appear to be unrelated to the 2360 yr B.P. eruption, although the post-eruption avalanche may have its origins in the oversteepened slopes created by the explosive phase of the eruption.

**STOP 2: View of Vent and Fallout Deposit**

**Where:** The stop is in the middle of a pair of switchbacks on a south-facing slope. The road has exposed 6–8 m of pyroclastic fallout. The clear-cut also affords an opportunity to view the area of the field trip and, especially, the area of the vent (now buried) for the 2360 yr B.P. eruption (Fig. 20).

**What is there:** Directly across the valley, if the weather is appropriate, the tallest peak in the complex is visible. Plinth Peak (2679 m, 8790 ft) is a dissected vent, as are three areas on its shoulder (Fig. 16) and Meager Mountain. Through the trees, across and up the river valley, the Fall Creek waterfall can be glimpsed. The proposed vent area for the most recent flow is located at the head of Fall Creek.

**Fall Deposit**

The 2360 yr B.P. eruption sustained a Plinian-style eruption column that reached 14–18 km in height based on measurements of maximum lithic clasts and pumice. The column may have intersected the jet-stream which caused a strongly northeast-trending plume to develop. The plume deposited pumice and ash at least as far east as Jasper National Park in Alberta. The distal air fall is well-described by Nasmith et al. (1967).

In the field area, the fallout deposit forms a well-sorted, topography-mantling deposit (Fig. 21A, 21B) that varies considerably in thickness and grain size. Large pumice clasts are pervasively fractured and surface “breadcrust” textures are common. Infrequent, exceptionally large blocks occur, up to 50 cm in long dimension. Some pumice clasts (1%–5%) exhibit compositional heterogeneity in the form of banding.

Accidental lithic clasts are mainly fragments of Plinth lavas (1%–2%). Other clasts (<1%) include (a) slightly inflated, bread-crustated gray vesicular clasts (accessory); (b) breadcrusted, inflated clasts of welded pyroclastic material (accessory; Fig. 21C) containing flattened to rounded white pumice lapilli; (c) accidental clasts of well-rounded cobbles of quartz monzonite; and (d) rare accidental clasts of baked clay-rich soil.

Much of the fall deposit was deposited onto very steep rock faces, talus slopes and steep, sparsely vegetated alpine slopes. Erosion rates in the area are high. As a result of this environment, the fall deposit has been heavily eroded by creep, slope wash and stream dissection. Most commonly, where the deposit is not completely removed by erosion, these processes have resulted in centimeter-scale laminations in the top quarter or third of the deposit. These can be clearly seen in the exposure at this stop.

**STOP 3: Stratigraphy in the Lillooet River Valley**

**Where:** Turn vehicles around and head back the way you came; continue downwards until you reach a flat terrace. After reaching the flats, you will stop immediately after the first sharp left—USE CAUTION. On your right you will see a narrow track to a small clearing within a stand of old growth cedar. We will park here. Additional parking is found 100–200 m along the main road until you see another tight and partly overgrown road off to the left. You can park another 3–4 vehicles on this road bed.

We leave from the clearing in the stand of old growth forest. It takes at least 20 minutes to get to the site and you will probably spend 1–2 hours at the site. Therefore you should take your day pack with rain gear, water, lunches etc. Follow the path that leaves from the south end of the clearing and cross 100–200 m of low growth (brambles, alder, etc.) until you reach the edge of a steep embankment. Descend the embankment moving always to
the right until you reach a lower terrace. You are walking through a section of hot lahar or debris flow deposit which will be seen at Stop 8. Continue to the northwest (right) until you reach another embankment; you should be able to see the Lillooet River from here. Go down the embankment and walk upstream through the older 200–300 m to the base of a large cliff face with a small waterfall on the upstream side.

What is there: This outcrop is ~2 km downstream from part of the Lillooet River that lies directly below the vent (see Figs. 18, 19). This stratigraphic section (section B in Fig. 19) records the sequence of volcanic events that were captured by the Lillooet River valley. The stratigraphic units and features to note here are (from bottom to top):

1. Old forest floor: water-laid beds of sand and gravel capped by silt-clay rich sediment.

2. Pumice fall deposit (unit tf): 1.5–2 m of well-sorted, lapilli-sized (but up to 30 cm), pumice bed unconformably blanketsing paleo-soil horizon and surrounding uncharred tree trunks (see Fig. 22). When this section was first described (Read, 1977), the upright remains of at least six large trees were preserved at this site, however, all but one have been removed by subsequent flooding and failures of the cliff face. The stumps are firmly rooted in fluvial sand beneath unit tf and project up into the base of the welded block and ash flow (Fig. 22). Carbon from one of the stumps yielded a 14C date of 2490 ± 50 yr B.P. More recent dating by Clague et al. (1995) gives an age of 2360 yr B.P.

3. Pyroclastic flow deposit(s) (unit pf): The pumice is overlain by 6–10 m of unconsolidated material. The deposit is completely unsorted and weakly structured pyroclastic material ranging in size from ash to meter-sized blocks of pumiceous dacite clasts. Pumiceous blocks are substantially less vesicular than blocks in the fall deposit; 5% of blocks show mingling textures between dacite and minor basalt. Locally, larger pumice blocks appear to be concentrated at the top of the depositional unit. This interval represents a pyroclastic flow deposit probably resulting from collapse of the Plinian column. A 0.3–0.5 cm layer within this unit may suggest that there are two separate pulses of pyroclastic flow. The pyroclastic flow(s) surround, bury, char, but do not knock down, large trees (Fig. 22).

4. High-energy water-laid deposits. Minor interlayers of well-sorted, rounded coarse sediments dominated by volcanic clasts deriving from the 2360 yr B.P. eruption are found within this stratigraphic interval. Although not exposed at this locality, such deposits are found nearby along strike. Many clasts are identical in composition and texture to the breccia deposit (unit bx1,2,3) found to overly the pyroclastic flow deposits. This unit is indicative of periods when the lake resulting from damming of the Lillooet River must have overturned the growing and unstable natural dam. During deposition of these relatively high-energy water-transported sediments, there were probably still eruptions of lavas and domes.
(5) Welded Block and Ash Flow Deposits: The upper 15 m of this section comprises a densely welded volcanic breccia, featuring an ash-rich vitreous matrix (Figs. 23, 24). Most blocks are rhyodacite lava that has lost all primary vesicu-
larity; light pink to white accidental clasts of quartz mon-
zonite (Fall Creek stock) are common. The unit as a whole shows crude layering which may indicate that the 15 m accu-
mulation results from a series of smaller individual deposi-
tional pulses. The breccia is generally matrix-supported and, locally, the matrix is foliated. The clasts may show some alignment and have been slightly flattened (Figs. 23, 24).

The most spectacular features of this map unit are the intense welding and the columnar jointing which extends more or less through the entire breccia unit. This indicates that the deposits were emplaced well above their glass transition temperature and that they were deposited sufficiently quickly that they cooled as a single unit. Tree and branch molds can be found throughout this deposit. The tree molds have vertical orientations indicating that the block and ash avalanches were sufficiently fluid to sweep around the trees. The deposits quenched against the tree prior to causing them to burn.

STOP 4: Pumice Mining and Sorting Operation

Where: Turn the vehicles around again and proceed along the logging road in a northwest direction again. Continue through the switchbacks (CAUTION) and past Stop 2. The drive takes you gently uphill and looking south (left) you can catch glimpses of the vent area and Plinth Peak on the other side of the Lillooet River. The road is cutting across a giant post-eruption rock avalanche deposit (Avbx2) that derives from Plinth Peak. The road heads down hill; after a relatively steep decline there is a major intersection. We take the LEFT fork and cut back sharply toward the Lillooet River. This road takes you to Keyhole Falls (Stop 5); cross the bridge and head up the steep hill. Continue on this road for several kilometers until reaching another fork. There will be signs advertising the open pit pumice mine. Take the right hand road which immediately heads downward into the pumice pit.

What is there: Proximal pumice fall deposits situated on the steep slopes northwest of Plinth Peak have been reworked by downslope movement (Fig. 25A). The entire slope has been affected resulting in a complex, channelized accumulation to create a 60 m thick pumice fan at the level of the Lillooet River. The operation (Fig. 25B) is made economical by the thickness of the deposit, the size distribution within the deposit and the properties of the pumice. Great Pacific Pumice Inc. mines this deposit and has Geolite® as its commercial product which is sold as con-
struction fill, aggregate, agricultural and horticultural fill, and as cosmetic abrasives.

Time permitting we will also stop at the sorting yard which we passed on our way in. Drive out of the pit and proceed back to the bridge at Keyhole Falls.

STOP 5: Bridge over the Lillooet River at Keyhole Falls

Where: This stop is marked by the bridge that crosses the Lillooet River at its narrowest point: Keyhole Falls (Fig. 23A). We will park on the north side of the gorge where there is a fairly large pullout. At this stop, we will spend some time at the bridge. Then we will take a 5 min walk downstream to Keyhole Falls following a path that parallels the north side of the gorge.
Figure 23. Field photographs of welded block and ash pyroclastic flow deposits (bx1-2). (A) Schematic representation of stratigraphic units exposed at Keyhole falls and view of Keyhole Falls looking northwest, showing overall shape of canyon carved by cataclysmic deluge. Cliff-forming unit (100 m) comprises densely welded breccia; upper succession (>75 m) is poorly consolidated, well-layered pyroclastic, fluvial and rock avalanche deposits. Elsewhere the block and ash flow deposits are: (B) incipiently welded, (C) nonwelded, and (D) densely welded.
At this stop, we are immediately downslope of the vent to the 2360 yr B.P. eruption. The break in slope on the south side of the bridge may be the catalyst for spawning block and ash avalanches from the fronts of the advancing dacite lavas. We are ~150 m away from and 30–50 m below the front of the last dacite lava. We are also standing on more than 100 m of block and ash avalanche deposits that accumulated in the Lillooet River valley (Figs. 18, 19, 23A, 26). This mass of hot material accumulated rapidly enough that it is welded from top to bottom. The mass represents numerous individual flows and has welded in several cooling units (defined by columnar joints).

On top of this densely welded surface are another 75 m of unconsolidated to weakly welded block and avalanche deposits interbedded with fluvial sediments and reworked volcanic material (Fig. 23A). This succession is well exposed on both sides of Keyhole Falls and is a direct indication of the competitive interactions between the body of water building up behind this natural dam and the waning phases of the eruption.
At some point the natural dam was overtopped and the upper un lithified portion failed cataclysmically causing a massive deluge. The flood soon swelled and swept away the upper surface then began to cut back into the lower portions of the welded block and ash flow, rapidly migrating upstream and creating a flow of water sufficient to carry 5 m blocks 3 km downstream. This event occurred when the core of the deposit was still hot as evidenced by the preponderance of clasts of breccia in the debris flow deposit that show prismatic, radially oriented cooling joints (Stop 8). The deluge resulted in the horseshoe-shaped canyon (Fig. 23A); when the flood waters subsided, the valley was cut through the welded breccia unit virtually to the present location. Note the fanning cooling joint patterns on the face of the bluffs below Keyhole Falls: the presence of these joints tell us two things: (a) the deposit was above the glass transition temperature (Tg) when the deluge carved through the breccias and caused the rock face to cool and joint; and (b) these cliff faces are virtually the same quench surfaces that formed 2360 yr B.P. The narrow gorge, > 25 m deep, represents gradual erosion of the welded breccia unit by the Lillooet River over the past 2360 yr.

Next stop: Return to vehicles and drive back up road toward Stops 1 and 2.

STOP 6 Pre-Eruptive and Post-Eruptive Rock Avalanche Deposits

Where: From the bridge at Keyhole Falls you keep to the north side of the Lillooet River and drive up the gradual slope until reaching a flat portion of the road. Continue on road to major intersection. Stop and pullover by small knoll containing massive to stratified fallout deposit.
What to see: This small but well-exposed outcrop shows primary fall deposit draped over a pre-eruptive rock avalanche deposit (unit Avbx; Fig. 27) and overlain itself by a younger rock avalanche (unit Avbx.). These two rock avalanche deposits are very difficult to distinguish because blocks of Plinth dacite dominate both. Both events probably originated from Plinth Peak (e.g., Read, 1977; Evans, 1992). This is one of the few localities where the three units can be seen in stratigraphic order. Unit Avbx can be distinguished from unit Avbx, where the former can be seen to overlie the air fall pumice deposit. Additionally, the older rock avalanche deposit has a thin soil horizon developed on it where it is overlain by the Pebble Creek Formation air fall pumice. The younger rock avalanche overlies air fall pumice, other Pebble Creek Formation deposits and basement rock. There is no evidence of a paleosol developed on the surface of unit Avbx, nor are Pebble Creek Formation rocks incorporated into the debris.

STOP 7: (42–42.8 km) Hot Debris Flow Unit (la)

Where: Drive back east along the main trunk. Kilometer distances refer to points passed earlier en route to Stop 2. You will cross the flats and begin to descend to the Lillooet River at ~42.8 km. Pull over at the pullout at the bottom of the grade on the river side of the road. The outcrop of interest is the road cut on the slope and on the opposite side of the road from where we parked.

What to see: The loosely stacked vitroclastic blocks exposed at this stop are deposited from a debris torrent that swept down the valley after failure of the breccia dam 3 km upstream of this point. The unit (la, Fig. 18) contains clasts which range in size from less than a millimeter to more than 15 m in diameter (Fig. 28), are subrounded and have the same composition and texture as the welded breccia unit. The larger clasts are composite aggregates of densely welded vitreous and aphanitic dacite fragments. Many exhibit a crude radial jointing perpendicular to their outer rims, suggestive of quenching of hot clasts after deposition (Figs. 28A, 28B, 28C). Clasts typically show no evidence of sorting but local lenses of graded finer material are clearly water lain.

Figure 27. Primary pumice lapilli fallout deposit from 2360 yr B.P. eruption of Mount Meager overlying a paleosol developed on an older rock avalanche deposit and overlain, itself, by a younger rock avalanche deposit derived from Plinth peak.

Figure 28. (A) Large vitroclastic block (10 m) in poorly sorted, unstructured debris flow deposit. (B) Debris flow deposit with metersized blocks showing radially oriented jointing. (C) Detail of radially oriented jointing in glassy block.
STOP 8: (39.2 km) Distal End of Pyroclastic Flow Unit (pf)

Where: Continue driving eastward on logging road. Immediately past Stop 7, the road descends to the level of the Lillooet River and then climbs again cutting through pyroclastic flow. The road then reaches a flat terrace (40 km). Continue eastward and pull over at ~39.2 km; there should be a small clear-cut on your right (south side of road). Look for flagging tape; our traverse starts there. Park and follow the northern edge of the clear cut to a point ~500 m from the road where a profusion of flagging tape shows where to enter the forest. At this point, following the flagging into the forest toward the west (the Lillooet River). About 10–15 min of walking should bring you to the top of a 25-m-high cliff. Follow the cliff to the south and descend where flagging marks the route through the trees. Walk to the north (upstream) and look first under the large tree roots.

What is there: This distal exposure is shown as Section D (Fig. 19) 8.5 km from the vent area. The section contains a pumiceous pyroclastic flow deposit (Fig. 29A) overlain by the distal facies equivalent of the hot debris torrent seen at Stop 8 (Fig. 29B).

The pyroclastic flow (unit pf) is 6 m thick, contains pumice blocks up to 2 m in diameter and numerous large tree trunks up to 50 cm in diameter and 3 m long (Fig. 29A). The pumice shows distinctive breadcrust surface textures and even the large blocks are highly inflated. Both the pumice blocks and charred tree trunks are crudely concentrated near the top of the pyroclastic flow unit. Walk about halfway along the base of the cliff to view a particularly spectacular concentration. The pumice blocks are commonly banded.

Closer to where you descended, the base of the unit can be viewed. Under the tree roots it is a 40-cm-thick, structureless, fine ash layer that rests directly on a thin organic layer on top of fluvial bedded sand and gravel or diamicton. Nowhere was fallout tephra seen at the base. The overlying fine-grained ash layer contains entrained reddish oxidized clots and pebbles from the underlying soil horizon. The entire unit pinches out abruptly downstream from the point where you descended. At the point of pinch out, a slightly charred dead tree remains standing and protrudes through the pyroclastic material.

Overlying the pyroclastic flow unit is bedded fluvial material (unit la). This material contains a large concentration of welded breccia blocks and some are radially jointed. It is most likely that these represent the deposits of the later catastrophic debris flow. This flow is the waning flood stage of the catastrophic debris flow as it is the only known flood which could overtop this terrace.

END OF TRIP

Closing Thoughts: Implications for Hazards and Risk in the Region

Probability distributions for geologic events are requisite for hazard and risk assessment (e.g., Figs. 30, 31). Methods for establishing occurrence probabilities for natural events (eruption, rock fall, etc.) include (a) collection and analysis of data from historical events,(b) analysis of deposits related to prehistoric events, or (c) reliance on computational forward models (e.g., prediction of slope failure). Prehistoric activity can only be gauged by “process-oriented” field mapping in landscapes such as those that surround the Mount Meager volcanic complex and the Lillooet River valley.

Although fieldwork has become somewhat unfashionable in recent years, the data extracted from such studies (e.g., hot versus cold avalanches) are absolutely critical to assessing the longer term recurrence intervals of these natural events. This is especially true for volcanic events associated with stratovolcanoes. These edifices are characterized by long periods of dormancy punctuated by intense and short lived eruption cycles. Each cycle is comprised of numerous individual volcanic events such as the growth of a lava or the formation of a block and ash avalanche. Thus, although historical events alone may provide reasonably well-constrained frequency distributions for mass wasting events (e.g., rock avalanches); reliable frequency distributions for volcanic events require extensive mapping and dating of older (prehistoric) successions.
Figure 30. Preliminary hazard distribution map for this portion of the Lillooet River valley based on mapped pyroclastic flows, rock and volcanic avalanches (Stewart et al., 2004). Probable source regions of the avalanche deposits are indicated. These areas are currently unstable and regularly shed material onto lower lying slopes. The head of the avalanche zone represents the inferred vent source for much of the volcanic material. The surge hazard represents the area at risk from decoupling of a fluidized surge flow with a 10% greater angle of reach than the avalanche events. Surge flows have been known to travel even greater distances, as much as 10 times the distance of parent volcanic flows.
Figure 31. Conceptual diagram for discussing relative risks associated with rock avalanches and volcanic eruptions in the Mount Meager region (Stewart et al. 2004). Risk magnitudes (shaded areas) derive from the product of probability (P) of an event within a fixed time interval and vulnerability of the system (V) to the same event. (A) Risk profile \( R^* \) resulting from the interpretation that all avalanche deposits represent mass wasting events (e.g., cold rock avalanche deposits). This interpretation results in a maximum estimate of \( P \) and a moderate value of \( V \). (B) Revised risk profile resulting from proper discrimination of hot volcanic avalanche deposits from rock avalanche events. Probability of rock avalanche events is reduced (e.g., \( \Delta P \)). Recognition of contemporaneous volcanic events creates a new risk profile. The probability of a volcanic event is small relative to rock avalanche events, however, the range of values of \( V \) are substantially larger depending on style of eruption (e.g., effusive versus explosive). This leads to a non-trivial risk factor \( R_\text{vol} \). An additional outcome is that there is an ancillary risk of overlapping independent events: rock avalanche and volcanic eruption \( (R_{\text{vol+}}) \).

ACKNOWLEDGMENTS

This field guide is an amalgamation of the work of many people. The reference list is long, reflecting the studies undertaken in the area, and our indebtedness to a vast number of people. Much of the information for the first day’s sites on the west side of the highway results from the Ph.D. thesis work of Melanie Kelman; her input into an earlier version of this guide is deeply appreciated.

The Mount Meager story has been expanded by the M.Sc. thesis work of Martin Stewart. We anticipate having their field work published shortly as Geological Survey open-file maps. We have tried to interpret the findings of others, but if we have failed to convey the author’s true intent, we apologize, the fault is ours. Each new trip offers insights, each new pair of eyes a differing perspective; we welcome your thoughts and comments.

REFERENCES CITED


**MANUSCRIPT ACCEPTED BY THE SOCIETY 1 FEBRUARY 2007**