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Field guide to Mount Baker volcanic deposits in the Baker River valley: Nineteenth century lahars, tephras, debris avalanches, and early Holocene subaqueous lava

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ABSTRACT

Holocene volcanic deposits from Mount Baker are plentiful in the low-lying Baker River valley at the eastern foot of the volcano. Tephra set SC (8850 yr B.P.), erupted from the nearby Schreibers Meadow cinder cone, is sporadically present. Exposures of both subaerial and subaqueous facies of the associated Sulphur Creek basalt lava flow are easy to access; the lava, the most mafic product known from the entire Mount Baker volcanic field, entered Glacial Lake Baker, invaded lacustrine sediments, and formed peperites as well as subaqueous block-and-ash flows. A volcaniclastic delta was deposited in the lake above the lava. The peperite and delta can be seen in the walls of Sulphur Creek, and in the banks of Baker Lake when the reservoir is drawn down in winter and early spring.

The best exposures of volcaniclastic flank assemblages from Mount Baker are found in the Baker River valley. The Boulder Creek assemblage formed a thick fan between the end of the Vashon glaciation and the deposition of the SC tephra. Now deeply trenched by Boulder Creek, lahar and block-and-ash diamicts can be seen with some effort by ascending the creek 2 km. A tiny vestige is exposed along the Baker Lake Road.

Much younger deposits are also accessible. In 1843, tephra set YP, erupted from Sherman Crater, was deposited in the valley. In ca. 1845–1847, the Morovitz Creek lahar swept down Boulder, Park, Morovitz, and Swift Creeks and inundated much of the current location of the Baker Lake reservoir. This lahar is an example of the most likely future hazard at Mount Baker as well as the most common type of lahar produced during the Holocene at the volcano—clay-rich or cohesive lahars initiated as slope failures from hydrothermally altered rock. They commonly increase in vol-

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ume by entraining sediment as they flow. When thermal emissions from Sherman Crater increased in 1975–1976, the level of the reservoir was lowered to accommodate inflow of lahars such as the Morovitz Creek lahar. Renewed activity at Sherman Crater will again trigger reservoir drawdown. In 1890–1891, and again ca. 1917–1932, debris avalanches from pre–Mount Baker lavas flowed down Rainbow Creek. The largest, which flowed 10.5 km, can be visited at the Rainbow Falls overlook. Here, the peak discharge of the flow, derived from reconstructed cross sections defined by well-exposed lateral levees and from reported velocities of equivalent modern flows, is estimated to have been greater than the peak discharge of any historic flood in the Mississippi River.

Keywords: Mount Baker, Holocene, tephra, lahar, debris avalanche, peperite.

INTRODUCTION

This field trip visits volcanic deposits on the lower eastern flank of Mount Baker, an active, ice-mantled, 3286 m (10,781 ft) Cascade arc volcano (Fig. 1). Many of the interpretations and much of the data in this guide are presented here for the first time. Some aspects of the geology have been presented in a number of abstracts by various combinations of the field trip authors (Scott and Tucker, 2003, 2006; Scott et al., 2003a, 2003b; Tucker and Scott, 2004, 2006; Tucker et al., 2007; Lewis et al., 2006, 2007). We selected the low-elevation field stops shown on Figure 2 with the early May timing of the 2007 GSA Cordilleran Section annual meeting in mind. Snow typically covers even the lowest meadows of the mountain at this time. The Baker River valley, on the east side of the volcano, affords the most diverse early season exposures of a variety of Holocene volcanic deposits anywhere around the mountain. Although this flank of the volcano is relatively well served by roads, serious examination of volcanic exposures requires hiking and considerable bushwhacking. No field trip to Mount Baker would be complete without at least a small sampling of these activities, which we are pleased to provide here.

A flurry of recent studies focusing on Mount Baker volcanism (e.g., Hill et al., 2006a, 2006b; Kovanen et al., 2001, McGee et al., 2001; Symonds et al., 2003a, 2003b; Warren et al., 2006) is indicative of the research attention this beautiful, but potentially destructive, volcano deserves. The 2007 GSA Cordilleran Section annual meeting included a symposium on recent research at Mount Baker (Baggerman and DeBari, 2007; Caplan-Auerbach and Huggel, 2007; Feeney and Linneman, 2007; Fountain et al., 2007; Hill et al., 2007; Hodge and Crider, 2007; Juday, 2007; Mullen and McCallum, 2007; Poland et al., 2007; Ryane et al., 2007; Tucker et al., 2007; Warren and Watters, 2007; Werner et al., 2007). Readers may be interested in Easterbrook et al. (this volume), who discuss Mount Baker tephras at Heather Meadows, northeast of the volcano. Note that these workers use different unit names for ash layers. The Mount Baker Volcano Observatory Web site, hosted by Western Washington University, features research updates and more information on the volcano. The URL is mbvo.wwu.edu.

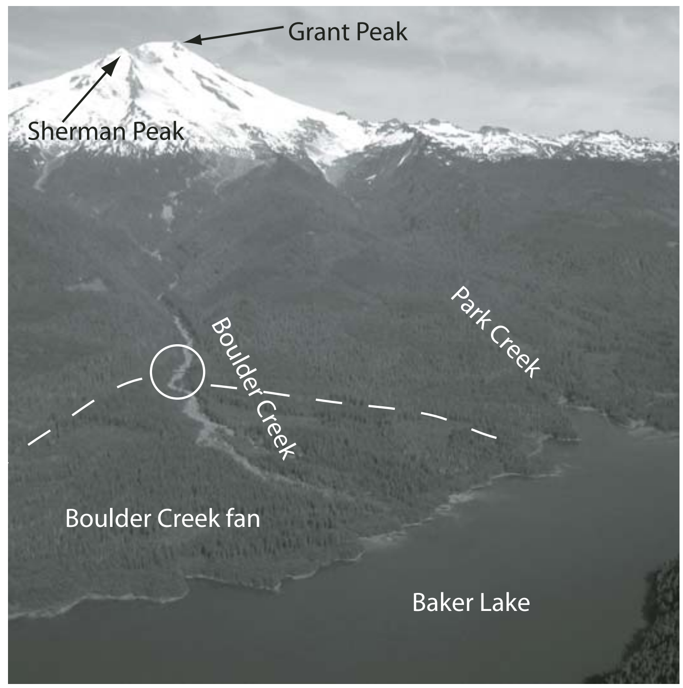

Figure 1. Mount Baker rises 3065 m (10,056 ft) above Baker Lake in this mid-July 2003 aerial view looking northwest. The Pleistocene vent, Carmelo Crater, underlies the summit ice cap; Grant Peak is the high point on this crater's rim, 14 km from the lake. The floor of Sherman Crater is 400 m below the summit on the left (south) skyline; pointed Sherman Peak forms the southeast rim of Sherman Crater. Dark cleavers emerging above the mountain's heavy glacial cover are Pleistocene lava flows. Boulder Creek is the prominent alluvium-filled valley. The bridge at Stop 4 is circled. Dashed line delineates the Boulder Creek fan (Stop 4). Park and Swift Creeks enter the bays at right. Aerial photo by J. Scurlock.

MOUNT BAKER ERUPTIVE PERIODS

Field investigations of surficial deposits by the authors, dovetailed with the bedrock history of Mount Baker (Hildreth et al. 2003), allow us to define four eruptive periods (Scott et al., 2003a). These are listed from oldest to youngest, and included in Table 1.

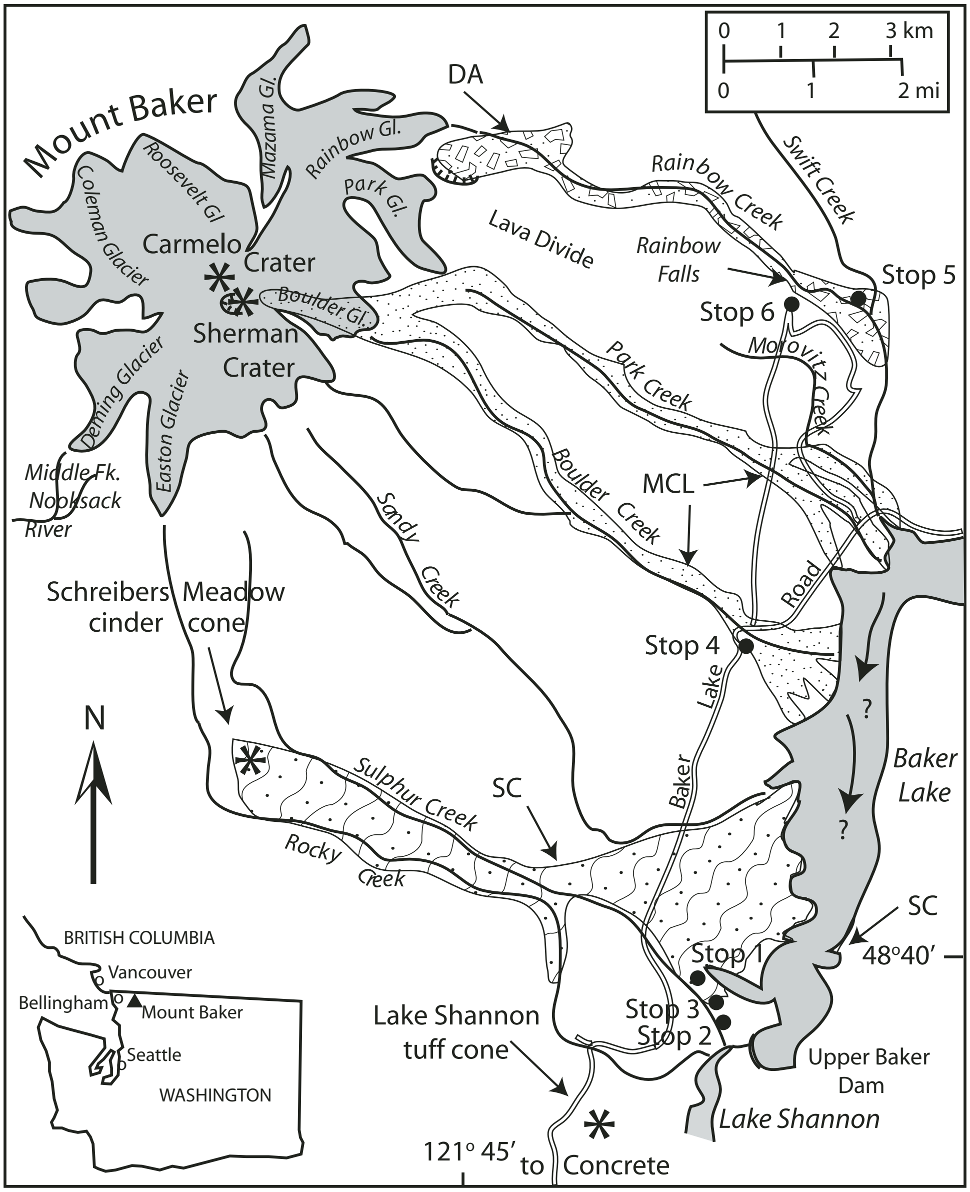

Figure 2. Map of Mount Baker volcano and drainages on the south and east flanks, showing the route and stops of the 2007 Cordilleran GSA field trip. Vents are shown as starred symbols. Selected Holocene flows are patterned. Units: SC—basalt of Sulphur Creek (after Hildreth et al., 2003); MCL—Morovitz Creek lahar; DA—Rainbow Creek debris avalanches. Note that the Sulphur Creek lava crops out on the east side of Baker Lake. Arrows in Baker Lake reflect uncertainties in downstream extent of lahars in the Baker River, now impounded behind Baker Dam. Adapted from Hyde and Crandell (1978).

Carmelo Crater Eruptive Period (ca. 12,200–15,000 yr B.P.)

The Mount Baker edifice, composed of andesitic lavas and breccias, was completed in the Late Pleistocene. Thick assemblages of block-and-ash pyroclastic flows, lahars and their distal runouts, and associated alluvium were emplaced in drainages on the south and southeast flanks of Mount Baker (Tucker and Scott, 2004). Flows originated from the now ice-filled Carmelo Crater at the mountain's summit (Hildreth et al. 2003). The best known of these assemblages is the Boulder Creek assemblage (Hyde and Crandell, 1978; Hildreth et al., 2003; Tucker and Scott, 2004), exposed 2 km upstream from the bridge over Boulder Creek (Stop 4). A cross-country day trip is required to visit these exposures. The most distal exposure known of the assemblage, though small, is visible in a road cut just north of the bridge at Boulder Creek.

A maximum limiting age of the eruptive period is based on the age of Vashon till, which underlies at least one of the assemblages, in Pratt Creek. Vashon ice arrived in the Baker River

TABLE 1. A SUMMARY OF MOUNT BAKER EVENTS THAT HAVE IMPACTED THE BAKER RIVER VALLEY

Event and age	Comment	Field trip stop
Recurrent small debris flows of volcaniclastic sediments leave terraces in tributary stream valleys	Destruction of trails, roads, and bridges; caused by heavy precipitation, often with rapid snowmelt	Boulder Creek, Stop 4; Rainbow Creek, Stop 5
Increased heat flux at Sherman Crater, 1975–1976	Levels in Baker Lake and Lake Shannon drawn down in preparation for inflows of lahars analogous to Morovitz Creek lahar	
1891; ca. 1917–1932	Two debris avalanches in Rainbow Creek	Stops 5 and 6
1845–1847—failures of east side of Sherman Crater	Morovitz Creek lahar flows down tributaries and reaches Baker River	Lahar deposits, Stop 4
1843 to present—Sherman Crater eruptive period	YP phreatomagmatic eruption ejects tephra and hydrothermally altered ballistic blocks	YP tephra, Stop 3
5740–5930 yr B.P. Mazama Park eruptive period	OP, BA tephras emplaced; lahars derived from flank collapses reach Puget Lowland	
8500 yr B.P. Mount Baker flank collapse	Schreibers Meadow Lahar surrounds cinder cone at Schreibers Meadow	
8500–8850 yr B.P. Schreibers Meadow eruptive period	SC tephra; Sulphur Creek lava flow enters Glacial Lake Baker; volcaniclastic sedimentation in impounded lake	Stops 1 and 2
ca. 12,200–15,000 yr B.P. Carmelo Crater eruptive period	Assemblages of lavas, block-and-ash flows, and lahars in radial valleys	Boulder Creek assemblage at Stop 4
Late Pleistocene impoundment of Glacial Lake Baker	Moraine on north wall of Skagit River valley impounds Baker River; volcaniclastic-free lacustrine deposits in Glacial Lake Baker	Outcrop examination requires reservoir draw down to low levels (mid-winter and early spring)
Late Pleistocene growth of Mount Baker by multiple eruptions	Andesite lavas and breccias	

valley via the Skagit valley, ca. 16,000 yr B.P. (Riedel, this volume). A minimum-limiting age for the Vashon, (12,200 yr B.P.) is the age of the Sandy Creek beds, volcaniclastic-free lacustrine deposits of Glacial Lake Baker which directly overly Vashon till (Scott and Tucker, 2006). The newly defined glacial lake (Scott and Tucker, 2006) occupied the Baker River valley after recession of Vashon ice. A minimum age for the Boulder Creek assemblage is given by overlying fine ash from the 8850 yr B.P. Schriebers Meadow cinder cone (see below).

Schriebers Meadow Eruptive Period (ca. 8500–8850 yr B.P.)

The main event of this eruptive period was the eruption at the Schriebers Meadow cinder cone, at 1122 m elevation (3680 ft) near the south base of Mount Baker (Easterbrook, 1975). The eruption initially produced basaltic tephra (51%–52% SiO_2; Hildreth et al., 2003; Tucker et al., 2007), followed by effusion of compositionally similar lava. Composition of the lava becomes andesitic closer to the cone (55%–59% SiO_2; Hildreth et al., 2003).

The lava (map unit SC, Fig. 2), flowed 12 km down Sulphur Creek valley eventually entering Glacial Lake Baker (Stops 1 and 2; Scott and Tucker, 2006). This lake was formed by the end of the Vashon glaciation, dammed by glacial deposits on the north side of the Skagit River. The lake flooded the Baker River valley; its northern extent was similar to that of modern Baker Lake reservoir (Fig. 2).

The final event of the period was a flank collapse from the upslope sector of Mount Baker that yielded the Schriebers Meadow lahar (8500 yr B.P.). The lahar crossed the interfluve separating the west-flowing Middle Fork Nooksack River (Fig. 2) and Sulphur Creek, flowing down both drainages, and surrounding the cinder cone in Schriebers Meadow.

Mazama Park Eruptive Period (ca. 5740–5930 yr B.P.)

This Middle-Holocene eruptive period shows evidence of a classic eruption cycle in which (1) the edifice is destabilized as magma is intruded at depth leading (2) to flank collapses, followed by (3) phreatomagmatic eruptions as rising magma in the edifice encounters meteoric water, and culminating in (4) a magmatic eruption. The magmatic BA tephra (Stop 5; Scott et al., 2001; Hildreth et al., 2003; Scott et al., 2003a; Tucker et al., 2007) has the greatest volume and most widespread distribution of any Holocene tephra from Mount Baker. A focus of our continuing work is to define the absolute time distribution of the initial 4–5 flank collapses and the eruptions recorded by the subsequent tephras by "wiggle matching" multiple dates from log cross sections. Two of these collapses transformed into the Middle Fork and Ridley Creek lahars, the largest lahars known from Mount Baker. The time relationship of flank collapse lahars and eruptions is crucial in deciding whether the former can be grouped with the volcanic hazards directly associated with eruptions, and can therefore be similarly predicted. Some emerging evidence suggests that large-scale collapses can be triggered with initial magma injection at depth well before an impending eruption (Scott et al., 2001).

Sherman Crater Eruptive Period (A.D. 1843 to Present)

The period began with at least one possible phreatomagmatic eruption at Sherman Crater (Scott and Tucker, 2003). The eruption was witnessed by Hudson's Bay traders at Fort Langley on the Fraser River and "covered the whole country with ashes" (Gibbs, 1874). Hydrothermally altered lapilli and ballistic blocks were ejected onto the glaciers and upper slopes of the mountain, and tephra set YP (Stop 3) was deposited on the surrounding landscape (Tucker et al., 2007). Those deposits, accreted to and inset against lateral moraines, define the configuration of the volcano's glacier mantle near the end of the Little Ice Age, ca. 1850, most notably in the case of the Chromatic Moraine of Coleman and Roosevelt Glaciers on the north flank (Fig. 2). A juvenile component of the 1843 activity is documented by prismatically jointed blocks on the rim of the Crater, vesicular lapilli and glass shards in tephra YP, and credible accounts of incandescent ejecta from smaller subsequent eruptions as late as 1880 (Tucker and Scott, 2006, Tucker et al., 2007). The YP tephra covered an area of at least 600 km^2 with at least 0.5 cm of ash up to 30 km southeast of the volcano (Tucker et al., 2007).

Hydrothermal alteration weakened the east side of Sherman Crater, which failed between 1845 and 1847 (Scott and Tucker, 2003; Scott et al., 2003b) to produce multi-branched Morovitz Creek lahar (Stop 4). The lahar descended Boulder Glacier and, because of more extensive glacial cover at the time, spilled over the divide into Park Creek and the lower reaches of Morovitz, Swift and Little Park Creeks. We name the lahar to honor pioneer miner and climbing guide Joseph Morovits (Morovitz when applied to geographic features; Fig. 3), who constructed his cabin on its deposits and who made important observations of nineteenth century geological events, including the debris avalanche we will see at Stops 5 and 6 (Lewis et al., 2006, 2007).

We suggest that the eruptive period continues today, based on the greatly increased heat flux in 1975–1976. Thermal activity has since decreased, but not to pre-1975 levels. Sherman Crater emits ~190 tons/day^{-1} of CO_2 and 5.5 tons/day^{-1} of H_2S believed to be derived from magmatic SO_2 by hydrothermal scrubbing (McGee et al., 2001; Symonds et al., 2003a, 2003b). Airborne monitoring of gas emissions continues. On the basis of activity in 1975–1976, scientists warned that Baker could be the site of the next eruption in the Cascade arc, a role usurped by Mount St. Helens five years later. Levels of the reservoirs in the Baker River valley, Baker Lake, and Lake Shannon were drawn down in preparation for inflows of lahars analogous to the Morovitz Creek lahar.

Figure 3. The legendary Joe Morovits homesteaded on the creek that bears his name in 1891. This self-educated miner and mountain guide provided original and accurate interpretations of Baker deposits. "Mighty Joe," the Hermit of Baker Lake, described the debris avalanche deposit in lower Rainbow Creek about 1 year after the event. He correctly estimated the nineteenth century lahar deposits in Boulder, Park, and Morovitz Creeks to have been deposited in ca. 1845, based on tree growth. His mention of a gorge eroded through the Sulphur Creek basalt in the Baker River, now drowned beneath the reservoir, provides the only account known to the field trip authors of the exposed thickness of the lava where it is cut through by the river. Joe also recognized that an "earlier Mount Baker" at one time existed in the headwaters of Swift Creek. Today we know this to be the 1.15 Ma Kulshan caldera. Photo courtesy Whatcom Museum of History and Art.

MOUNT BAKER'S LAHAR TEXTURES REFLECT THEIR ORIGINS

The chief volcanic hazard at Mount Baker is from lahars, in particular those that begin as flank collapses. Flank collapses are volcanic landslides confined to one flank of a volcano; they do not remove the summit, as would a sector collapse like that from Mount Saint Helens in 1980. Lahars that begin as flank collapses are known as cohesive lahars, and deposits have a relatively clay-rich matrix; a Mount Baker example is the Morovitz Creek lahar, seen at Stop 4. The clay content reflects the degree of hydrothermal alteration common to many stratovolcanoes. Cohesive lahars contrast with noncohesive, granular-textured lahars commonly described as syneruptive. Noncohesive lahars have an origin involving the entrainment of detrital sediment (from which much fine sediment has been previously winnowed) on volcano flanks by surges of meltwater resulting from hot volcanic flows or ash falls. Lahar deposits in the Boulder Creek assemblage (Stop 4) are examples. This textural dichotomy in lahars is a valuable tool in reconstructing volcanic history (see Scott et al., 2001. Copies are available for field trip participants). Both clay-rich cohesive and granular noncohesive lahars can greatly increase in volume as they flow downslope by "bulking" with alluvium and valley wall sediment.

FUTURE HAZARDS OF MOUNT BAKER

The Morovitz Creek lahar, not defined at the time of the 1975–1976 activity, is an example of the hazard that was both then and now the most probable and that causes the greatest concern. That hazard would be a collapse from Sherman Crater that would transform to a mobile lahar displacing water from Baker Reservoir. Downstream flooding as well as wave damage to developments around the shore of the reservoir could result. What occurred in the 1970s was the correct response—evacuating lakeshore developments and campgrounds and lowering the level of the reservoir to accommodate potential lahar inflow until the activity subsided. Drawdown will logically accompany any future increase in activity at Sherman Crater.

ROAD LOG

The field trip begins at the junction of Washington State Route 20 and the Baker Lake Road, a well-used paved road. This junction is 16 miles east of the town of Sedro Woolley and 6 miles west of the town of Concrete.

Mileage log *Inc.*	*Cum.*	
0.0	0.0	Turn north off SR 20 onto Baker Lake Rd.
1.6	1.6	Thick, Vashon-aged glaciolacustrine and outwash deposits on the right, across Grandy Creek.
3.2	4.8	Grandy Lake County campground.
1.8	6.6	Burpee Hill Rd, leads to Concrete in 4 miles.
2.8	9.4	High, conical hill ahead is the vent for the 94 ± 21 ka subglacial basalt of Lake Shannon (Hildreth et al., 2003), consisting of palagonitized hyaloclastite tuff. A few thin basalt lava flows are interbedded near the summit.
1.8	11.2	At the extreme north end of the outcrop on left, fragmental basalt of Lake Shannon lies against Cretaceous-Jurassic Nooksack Formation (Tabor et al., 2003). Gated road to right gives access to the vent area of the basalt.
0.9	12.1	At the T-intersection with FS 12, stay right on the paved Baker Lake Road. FS 12 gives access to Mount Baker hiking trails and the tree-covered early Holocene Schreibers Meadow cinder cone.
0.6	12.7	High cliffs of Nooksack Formation line the road on the left.
0.7	13.4	View ahead is of the south side of Mount Baker. The summit plateau is the ice-filled Carmelo Crater, site of Pleistocene eruptions; Grant Peak, the highest point on this crater's rim, is on the right. The slightly lower point on the left is Sherman Peak (3090 m; 10,140 ft), on the south rim of Sherman Crater.
0.4	13.8	Turn right on Baker Lake Dam Rd. After crossing Sulphur Creek, the road descends the fresh surface of the forested early Holocene Sulphur Creek lava flow. Fifty meters beyond the bridge over Sulphur Creek, a faint trail goes right (south) at a pullout through brush 100 m to a 10-m-high waterfall thundering over an eroded scarp in the Sulphur Creek lava flow.
0.6	14.4	Turn sharp left on a spur road (may be signed FS 1106–011) leading down toward an arm of Baker Lake.
0.1	14.5	Turn left into an old quarry and park for Stop 1. The quarry may be occupied by campers. Elevation ~241 m (790 ft).

STOP 1—Quenched, Glassy, Subaqueous Basalt of Sulphur Creek

Carefully scramble up the loose talus to the base of the wall of lava. Watch for broken bottles and rolling blocks. This is the ca. 8850 yr B.P. basalt of Sulphur Creek, the most mafic lava known from vents in the Baker volcanic field (51.64% SiO_2, sample MB 462 of Hildreth et al., 2003). The lava issued from a small cinder cone in Schreibers Meadow, elevation 1122 m (3680 ft), 10 km further up Sulphur Creek to the northwest (Fig. 2). Lava extends another 3 km to the east, to the far side of the Baker River. The lava invaded and displaced laminated clays deposited in Glacial Lake Baker (Scott and Tucker, 2006; Fig. 4). The eruption initially produced basaltic tephra and lava; the composition of the lava becomes andesitic closer to the cone (55%–59% SiO_2; Hildreth et al., 2003). A petrologic study by Green (1988) modeled magma mixing conditions to produce this lava.

The black, densely vesicular, glassy, plagioclase-phyric basalt lava at this stop is pervasively jointed. At its base, the lava displays concentric, steeply east-dipping, shell-like flow structures, 5–25 cm thick (Fig. 5). Dip faces on these structures are brown and somewhat pitted. "Tiny normal joints" (McPhie et al., 1993) with 1-cm-spacing radiate a few cm inward from the margins of the shells; the interior of the shells is more massive, jointed at 10 cm intervals. Pseudo-pillows (Walker, 1992) can be seen at the very base at the left end of the exposure. These are interpreted to form when water enters fractures in flowing lava. Closely spaced cooling joints develop normal to the quenched faces of blocks isolated by the fractures. Deep clefts separate some of the shells. Neither the concentric "shell" structures nor the pseudo-pillows are evident higher up on the 10-m-high lava face. The lava is overlain at the top by several meters of sandy alluvium consisting of basalt scoria and rounded blocks of lava

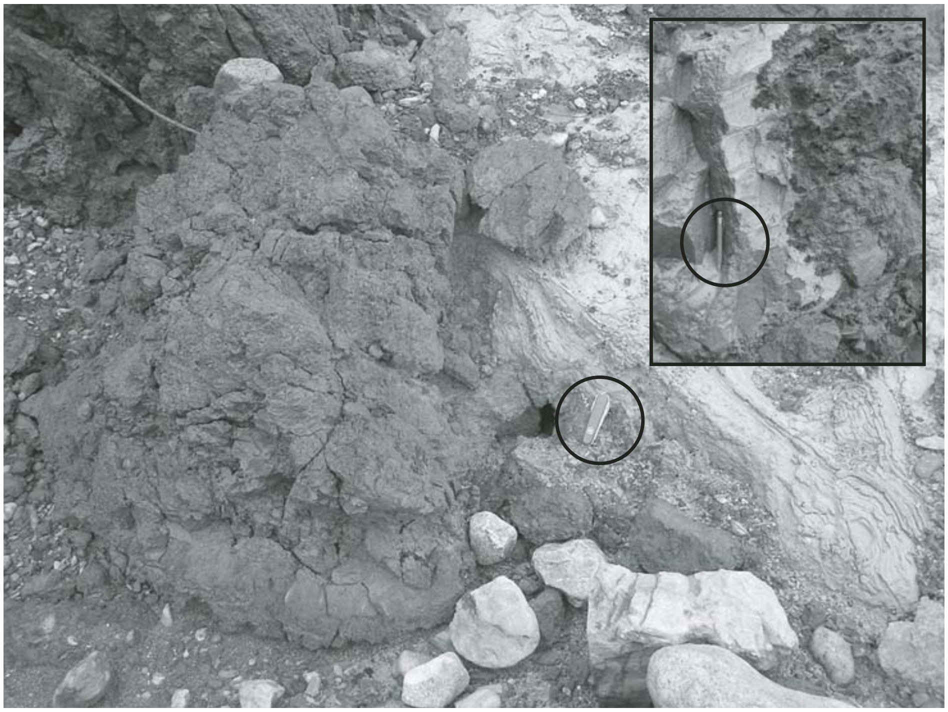

Figure 4. The dark mass is peperitic subaqueous Sulphur Creek basalt lava that invaded light colored lacustrine clays of Glacial Lake Baker. Clay laminae are deformed and baked near the margins of the lava, just above the circled 9-cm-long pocketknife. Inset: Margins of fluidal lava have penetrated lacustrine clay. Circled pen is 15 cm. The best exposures, and the site of the photo, are 10 m or more below the 220-m-elevation (722 ft) of full pool level of the Baker Lake reservoir.

up to several meters in diameter. The texture and structure of the lava at this location is markedly different from textures at exposures only a few hundred meters to the west, where the basalt is lighter colored, massive, and less glassy.

We interpret the base of the lava here to record the level at which it flowed into Glacial Lake Baker (Scott and Tucker, 2006), where it was quenched and then overflowed by itself, forming a partially fragmental and partially massive deposit. Hyaloclastite, expected to form at subaqueous lava flows, may have filled the deep clefts between the shells, but was washed out by later wave action at the shoreline.

Mileage log		
Inc.	*Cum.*	
0.1	14.6	Return to Baker Lake Dam Road, turn left (south).
0.1	14.7	Drive off the surface of the lava onto volcaniclastic sediments deposited into Glacial Lake Baker.
0.3	15.0	Turn right at the first gated entrance to Puget Sound Energy facility. Permission is required to proceed to Stop 2. Follow this road downhill toward Sulphur Creek, passing through another gate.
0.3	15.3	Small outcrop on left of rhythmically bedded clays of Glacial Lake Baker.
0.2	15.5	Road fork. Go right, along the bank of Sulphur Creek.
0.1	15.6	Steep, high south valley wall across the creek exposes lacustrine clay of Glacial Lake Baker.
0.2	15.8	End of road, elevation 155 m (510 ft).

Baker Lake is 750 m northeast; full pool elevation is 220 m (722 ft), well above our heads. The underground drainage tunnel collects seepage from Baker Lake percolating through lava and sediments. The upper part of the valley wall directly above the road end (Fig. 6) has wonderful exposures of Sulphur Creek basalt lava invading and displacing laminated lake sediments of Glacial Lake Baker. Higher in the section, east-dipping crossbedded volcaniclastic sands were deposited in a delta built into the lake (Fig. 7); the lakeshore must have been only a short distance west of here. The road crossed the top of this delta after descending off the lava flow surface.

Leave vehicles and walk 75 m toward Sulphur Creek on a forest trail. After crossing a tributary stream, leave the trail and head uphill through brush along the tributary ~50 m to the base of another high wall of sediments.

STOP 2—Lacustrine Sediments of Glacial Lake Baker and Subaqueous Fragmental Facies of the Sulphur Creek Basalt Lava

This field stop is beneath a high bank; there is a small swift stream flowing from its base. Please be careful.

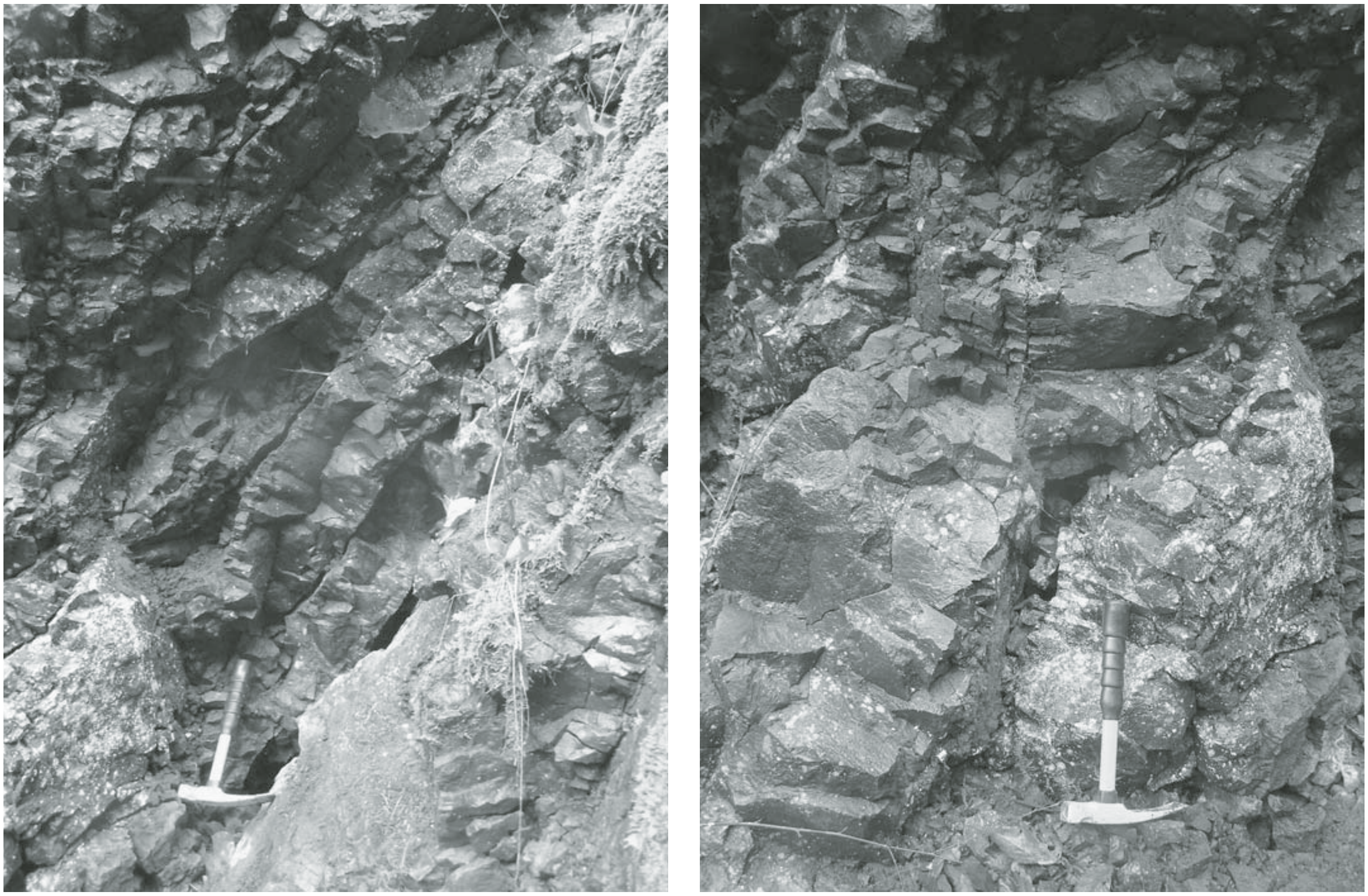

Figure 5. (A) Steep, east-dipping layers of glassy, vesicular basalt lava are seen at Stop 1. Margins of the layers are characterized by close-set joints; interiors are more massive. (B) Pseudo-pillows appear in basalt lava at the base of the exposure of Stop 1. These are nearly identical to structures photographed in Walker (1992).

Big Spring gushes out of the base of a 50-m-high bank. The basal unit is 3–4 m thick, poorly sorted, monolithologic basalt breccia (Fig. 8). Clasts are black, glassy and variably vesicular, ranging in size from sand to ~20 cm. No base is exposed. Nearby lava blocks gave 51.8% SiO_2 (sample MB 183 of Hildreth et al., 2003). Some blocks are coated with a thin brown film that may be clays percolated from sediments above. Alternatively, the clay may be an alteration product due to subaqueous deposition. The breccia is overlain by many meters of rhythmically bedded clay laminae and thin beds. There are usually fallen blocks of this at the base of the exposure, which permit close examination of this lacustrine sediment. These sediments were deposited on the nearly level upper surface of the breccia deposit; there is no evidence here for invasion of these lake sediments by lava. The highest part of the valley wall is cross-bedded volcaniclastic deltaic sands, deposited in the lake as Sulphur Creek reestablished flow into the lake.

We believe the breccia was deposited by a sublacustrine block and ash flow on the floor of Glacial Lake Baker. Perhaps the lava front collapsed or quench-shattered as it flowed into the lake close by to the west, near Stop 1. A 30-m-high wall of subaerial basalt is exposed up the valley less than 500 m away, just downstream from the waterfall at mile 13.8. The sediment overlying the basalt breccia indicates that Glacial Lake Baker persisted here long after the ca. 8850 yr B.P. lava. At Stop 2, only a few meters of laminated lacustrine clay were deposited on top of the lava before encroachment of the ancestral Sulphur Creek delta into this portion of the lake.

Return to vehicles, turn around and return to the Baker Lake Dam Road.

Mileage log		
Inc.	*Cum.*	
0.8	16.6	Pass through the Puget Sound Energy gate at the junction with the Baker Lake Dam Road. Turn left toward the paved Baker Lake Road.
0.2	16.8	Park beside a power pole numbered 450508. A very faint path from this pole goes south 30 m toward the brink of the valley wall of Sulphur Creek. At the first trees, angle to the right, and stop just short of the top of the precipitous overhanging bank. This is directly above the parking area for Stop 2.

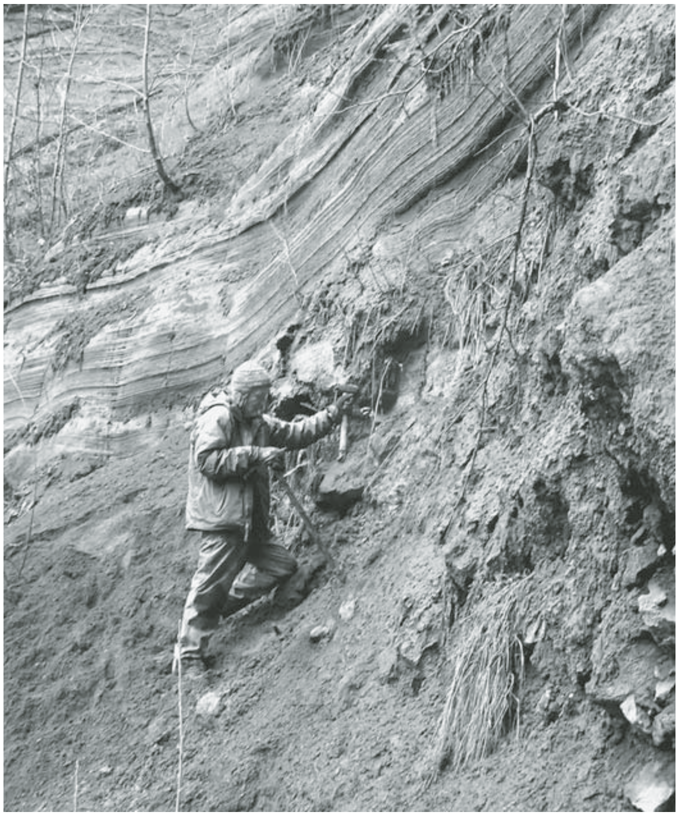

Figure 6. Kevin Scott stands beside 3 m-thick lava breccia of the Sulphur Creek basalt above the parking area for Stop 2. The breccia, deposited in Glacial Lake Baker, is overlain by 3 m of laminated lacustrine clay. Lake clays also underlie the lava here. A thick sequence of volcaniclastic deltaic sediments is faintly visible at the top of the photo.

Figure 7. Volcaniclastic deltaic sediments dip east 20°–30° near the top of the right valley wall of Sulphur Creek, above the parking area for Stop 2. A debris flow deposit truncates the delta sediments, and is in turn overlain by sand-silt alluvium. The YP tephra visited at Stop 3 was deposited at the very top of this section.

STOP 3—The YP Tephra, and a Volcaniclastic Delta in Glacial Lake Baker

The valley walls below you expose dipping alluvium forming a delta at the margin of Glacial Lake Baker. These sediments were laid down after the Sulphur Creek lava flowed down an ancestral valley of Sulphur Creek into the lake, and provide evidence that the lake persisted at this elevation (750 ft, 229 m) long after Vashon ice receded. The modern stream flows along the south margin of the lava flow.

Walk west through easy brush along the edge for 20 m, and step down into a small depression. Be very careful—there is not much room here, and there is a considerable drop beneath you!

The 1843 phreatomagmatic YP tephra is exposed in the bank you just stepped over, at the base of the humus mat (Fig. 9). The tephra varies from 0 to 3 cm thick. It is a poorly sorted ash composed of microscopic glass and sand-sized plagioclase, pyroxene, and lithic fragments. It also contains 1–4 mm black, vitreous, vesicular lapilli up to 4 mm. The presence of the lapilli may be evidence that the eruption had a magmatic component, though it can not be ruled out that they are remobilized older pyroclasts from the rim of Sherman Crater, entrained in a large, purely phreatic eruption column (Tucker et al., 2007). These pyroclasts are commonly coated with pale gray, silty glass and are often not immediately apparent. A water rinse will reveal them.

Return to vehicles, and continue to the Baker Lake Road.

Mileage log		
Inc.	*Cum.*	
0.9	17.7	Turn right (north) on Baker Lake Road
0.3	18.1	Koma Kulshan Guard Station. Lows mounds behind the buildings are vegetated tumuli of the Sulphur Creek lava flow.
0.9	19.0	Exposures of subaerial basaltic andesite Sulphur Creek lava flow (55.2% SiO_2; Hildreth et al., 2003) are on both sides of the road.
0.8	19.8	Bridge across Sandy Creek, draining the Squak Glacier. This creek flows along the northern margin of the lava flow.
0.9	20.7	FS 1124 goes left to Forest Divide. Remain on the Baker Lake Road.

Figure 8. Scoriaceous basalt breccia underlies lacustrine clay and volcaniclastic deltaic sediments at Stop 2. Shovel is 1.8 m long.

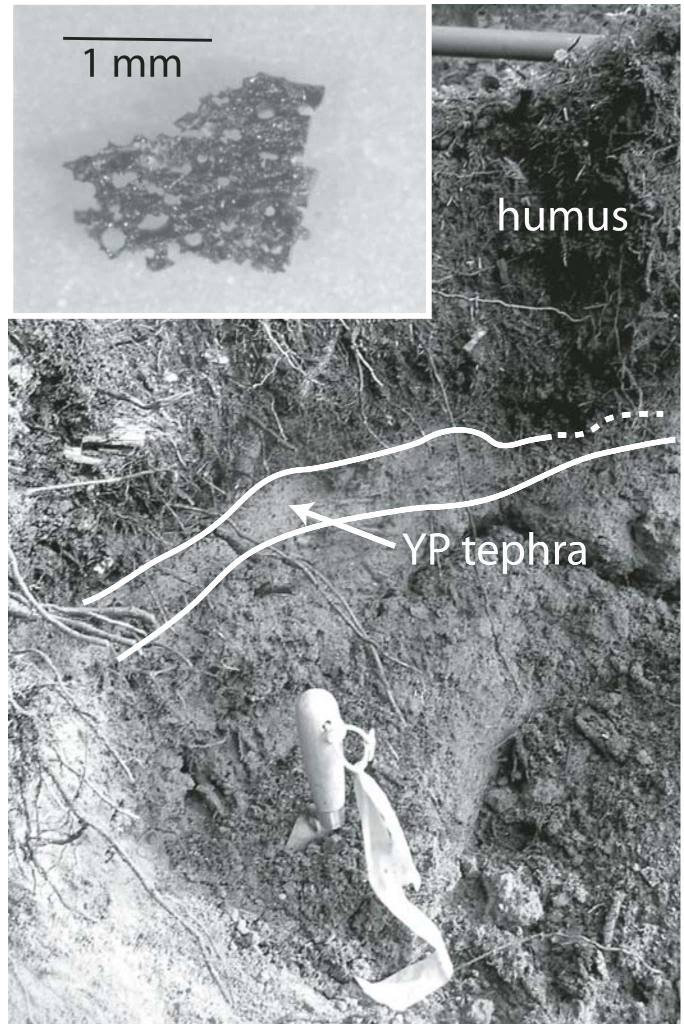

Figure 9. The nineteenth century YP tephra is typically found at or near the base of the organic layer, as it is at Stop 3. The pale gray ash was erupted during phreatomagmatic eruptions at Sherman Crater. The trowel handle is 11 cm long. Inset: photomicrograph of a vesicular, black vitric lapillus found in YP ash. Textures are indicative of juvenile material.

1.4 22.1 South end of the Boulder Creek Bridge. Park on the left at the bridge, or in a soggy pullout to the right. Stop 4 is a short walk through the campground.

STOP 4—Lahars of the Sherman Crater Eruptive Period

Examine the exposures in the high terrace along the right bank of the active braided channel of Boulder Creek by descending the cut bank adjacent to campsites 3–8 of the Boulder Creek campground. The campground is located at the head of the massive Boulder Creek alluvial fan, emplaced since withdrawal of Vashon ice from the Baker River valley. Trees in the campground are less than ~154 years in age on the surface of the Morovitz Creek lahar (map unit MCL; Fig. 2). The most prominent deposit in the terrace cut bank is diamict of the Morovitz Creek lahar. The matrix is highly altered. The rounded boulders of andesite that dominate the coarse or "dispersed" phase of the lahar are identical in size and composition to the bed material of Boulder Creek. At this site, the Morovitz Creek lahar deposit is composed of ~80% rounded clasts of Baker andesite, illustrating a common and dangerous behavior of lahars—their ability to increase in volume by entraining (bulking) additional sediment with distance from source. A much smaller lahar overlies the Morovitz Creek lahar. The two flows (Fig. 10) were initially described by Hyde and Crandell (1978), who interpreted them as lahars, but ascribed the matrix alteration to in situ weathering.

The 1843 YP tephra underlies flood plain deposits of the Morovitz Creek lahar, though it is not seen at this stop. A layer of wood and conifer needles separates the tephra layer from the lahar diamict. Analyses by several specialists in the composition of forest litter shed from trees killed by wildfire or insects (but in this case presumably by tephra) estimate that this layer represents an interval of least 2 years. Growth rings on logged stumps growing on the lahar surface date to 1847. Therefore, the lahars occurred between 1845 and 1847. The preservation of the woody layer is an example of how nonerosive a lahar can be during the

Figure 10. The contact between deposits of two nineteenth century lahars is knife-sharp in the stream bank at the Boulder Creek campground, 120 m below the highway bridge (Stop 4). Boulder-size clasts of Baker andesite dominate the coarse phase of the older and much larger Morovitz Creek lahar. Originating with the collapse of the east side of Sherman Crater, the lahar also entered Park, Little Park, Morovitz, and Swift Creeks and reached the Baker River. The matrix phase of the Morovitz Creek lahar consists of highly altered material ("Shermanite") like that forming nearly the entirety of the younger, paler, overlying lahar, which entered only Boulder Creek and yielded deposits confined to the head of the Boulder Creek fan. The relative proportions of matrix and entrained clasts in the Morovitz Creek lahar at this site illustrate a volume increase by a factor of four. The pencil at the contact is 15 cm long.

relatively passive emplacement of its flood-plain facies, which accounts for the vast majority of preserved lahar deposits. The channel facies is accompanied by intense tractive force that commonly results in large amounts of channel incision.

A smaller unnamed lahar locally overlies deposits of the Morovitz Creek lahar. The matrices of the flows are similar, and the younger flow contains a smaller proportion of entrained material (a lower "bulking factor"). The first written descriptions of deposits in the Baker River valley were made by prospectors who in 1858 reported fresh inundation of the Boulder Creek fan surface by "lava," which we believe refers to the lahars. The younger flow, present only in Boulder Creek, may have occurred from immediately to shortly after the Morovitz Creek lahar.

If weather permits, we can admire the spectacular view of Sherman Crater from the walkway on the bridge (Fig. 11). A small exposure of Boulder Creek assemblage (Hyde and Crandell, 1978; Hildreth et al., 2003; Tucker and Scott, 2004) deposits left by andesitic block and ash flows and noncohesive lahars of the Carmelo Crater eruptive period, crops out at the road junction just east of the bridge.

Mileage log		
Inc.	*Cum.*	
0.1	22.2	Continue across the bridge on the Baker Lake Road. Stay right at the junction with FS 1130, which climbs to the Boulder Ridge trailhead. The most distal exposure of debris flows of the Boulder Creek assemblage is found at this junction. The exposed deposit is only a few meters thick here, but is probably far thicker beneath the Boulder Creek fan, spreading outward from the mouth of the incised valley. At the type locality, 2 km upstream, the Boulder Creek assemblage is 85 m thick. The Baker Lake Road descends the Boulder Creek fan.
1.2	23.4	Cross Little Park Creek, at the junction of the Boulder Creek and Park–Swift Creek alluvial fans. Good views of the east breach of Sherman Crater may be had from the road; they are better if you park and walk toward Baker Lake.
0.6	24.0	The road crosses Park Creek. Just across the bridge, turn left on FS 1124, across from the turn-off to the Baker Lake Resort (open in summer). This graveled road is poorly maintained, perhaps to discourage traffic to Baker Hot Springs; the springs may be a disappointment for hot spring connoisseurs.
1.2	25.2	Cross Morovitz Creek. We are near the 1891 Morovits homestead, now completely reclaimed by the famous brush of the Pacific slope of the Cascade Range.
1.9	27.1	Park at the Swift Creek trailhead, elevation 415 m (1360 ft).

STOP 5—Debris Avalanches in Rainbow Creek

The stop is reached after a 1 km stroll along the Swift Creek trail through temperate rain forest where we examine the distal deposits of the largest debris avalanche in Rainbow Creek (map unit DA, Fig. 2). In 2006, this trail was brushed and locally reconstructed throughout the entire 11 km route to Artist Point. We will also see the impressive devastation left by 100 year floods in October 2003 and November 2006. The 2006 floods washed

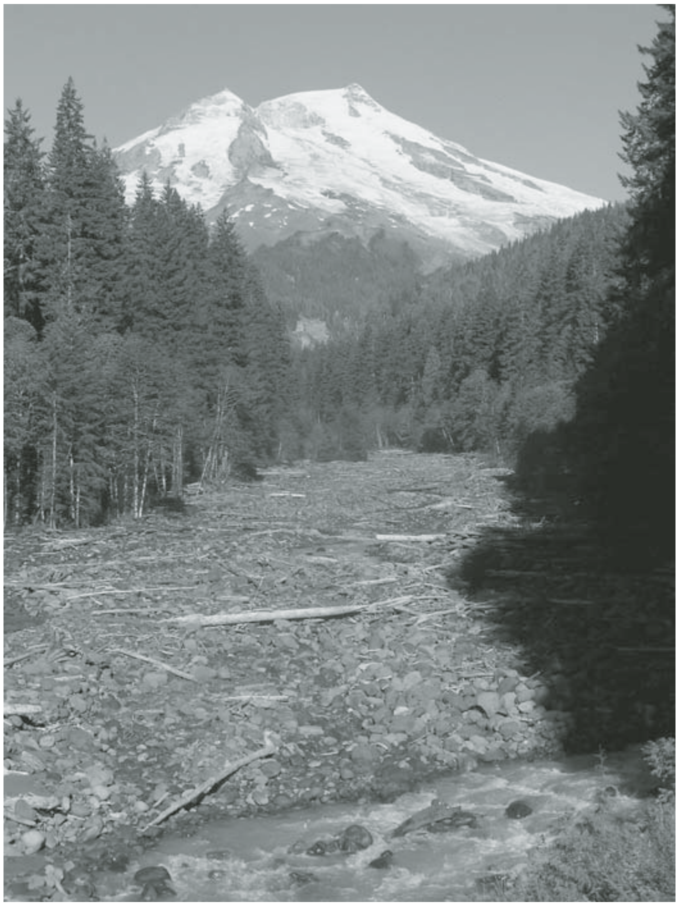

Figure 11. Boulder Creek descends east from Sherman Crater (the notch in the summit skyline). This view of Mount Baker is from the Boulder Creek Bridge, near Stop 4.

away an improved foot log built in 2004 that crossed Rainbow Creek, left gravel on the trail well over 100 m beyond the creek banks, deposited up to 3 m of bouldery alluvium in the stream channel, and then incised a new channel, leaving behind high terraces. The 2003 flood toppled the 1.5 m diameter tree we cored to determine the 1891 date; the 2006 floods carried it away.

About 100 m after leaving the road, reworked BA tephra is sporadically present in trail cuts. The trail crosses a swampy area resulting from disturbed drainage following emplacement of the 1890–1891 Rainbow Creek debris avalanche. Where the trail descends a steep bank, remobilized SC tephra (8850 yr B.P.) may be seen in a few places. The SC tephra here, ~12 km from its source at the Schreibers Meadow cinder cone, is bright orange-red fine ash. A short distance beyond, the forest floor changes dramatically as we encounter the avalanche deposit. The right margin of the flow is marked by a change in both tree age—from old growth to a post-1890–1891 forest, and in deposit texture—from soil developed on glaciofluvial deposits to the bouldery surface of the avalanche. Reach Rainbow Creek, with piles of logs and boulder bars and terraces emplaced by the recent flooding. If a log is available, we can cross Rainbow Creek to exposures of the first and largest of the two debris avalanches. After crossing, hike downstream on river gravels of the left bank until you are approximately opposite the point at which you first reached the creek. If there is no crossing, a similar exposure that was exposed in November 2006 is available on the right bank. Here, the avalanche deposit rests on a woody layer above till, rather than alluvium.

At the base of the forested cutbank, we can see the debris avalanche deposit, with its characteristically angular boulders, overlying a soil layer with alluvium below (Fig. 12). The flow was relatively passive as it spread across the interfluve between Rainbow and Swift Creeks. It only locally eroded the underlying deposits, similar to the manner in which the lahar flood plain facies we saw at Stop 3 was emplaced. Contrast this setting with our next stop, Stop 5, where a canyon was filled with the roaring, confined flow.

Approximately 15–20 million m^3 of andesitic lava and poorly consolidated lava-flow breccia fell from the north side of Lava Divide (Figs. 2 and 13) into the valley of Rainbow Creek, crossed the terminus of Rainbow Glacier, and ran 140 m up the opposite valley wall. The deposit extends 10.5 km through Avalanche Gorge to the confluence of Rainbow and Swift Creeks. The failure scarp is well defined in lava flows and breccia of the Pleistocene andesite of Lava Divide (Hildreth et al., 2003) overlying rocks of the Nooksack Group. The lavas are from a pre–Mount Baker volcanic center. The distance of vertical runup of the flow on the valley side opposite the failure site indicates an initial cross-valley velocity of ~50 m/s, in excess of 100 mph.

When the first settler in the area, miner Joseph Morovits, settled on the banks of Morovitz Creek in October 1891, he described its deposit as not supporting "a bush of any kind" (Easton, 1911–1931). This account indicates a probable age of

Figure 12. The distal end of the large Rainbow Creek debris avalanche is seen at Stop 5. Note the sequence of subrounded alluvium at the bottom, the prominent undisturbed soil layer (where Kevin Scott is pointing), and the poorly sorted debris avalanche deposit at the top.

Figure 13. This view looks southwest to the 750-m-wide failure scarp left by the Rainbow Creek debris avalanches on the north face of Lava Divide, at left center and now partially filled with glacial remnants. Arrows show path of the avalanches into the hidden valley of Rainbow Creek. The crag at the extreme west (right) end of the narrow ridge is the vent area for the east-dipping lava flows and breccias of the andesite of Lava Divide, contemporaneous with the Black Buttes center but erupted from a separate vent (Hildreth et al. (2003). Rainbow Glacier occupies a deep trough below the scarp, mostly hidden by the closer valley wall. Sherman Crater is in the deep notch left of Baker's summit, 5 km further southwest of the scarp.

1890–1891, since robust regrowth of bushes and alders would have begun to cover the surface within approximately two years. Dendrochronology also places the flow within this two-year period (Lewis et al., 2006). Although the deposit appears to be dominated by boulders, the nutrient-rich, fine-grained matrix supports extremely rapid revegetation relative to the more common granular flood deposits around the volcano and which we see around us in the active channel of Rainbow Creek. Like other debris avalanche and lahar deposits, the deposit texture is bimodal, with the dispersed or coarse phase of cobble and boulder-size clasts that are set, like plums in a plum pudding, in the fine grained matrix phase.

An unusual feature of the flow is that, although originating from relatively unaltered rocks, its mobility approaches that of volcanic debris avalanches readily mobilized by fine sediment resulting from hydrothermal alteration. Factors that result in this unusual mobility for an alpine debris avalanche include production of fine sediment by cataclasis that accompanied the steep initial fall of the mass, and bulking (entrainment) of soil and fine sediment from the valley-side slopes (Lewis et al., 2006, 2007).

Fieldwork encompassing the entire length of the flow involved grueling 3-day backpack trips in 2005 and 2006. During the most recent trip, in August and September 2006, we verified the presence of a second flow, as postulated by both Hyde and Crandell (1978) and Fuller (1980). The oldest tree we cored in the center of the course of this younger flow was 67 years old. Combining this observation with vegetation patterns from the first aerial photos taken between 1930 and 1935 (Fig. 14), we estimate that the younger flow occurred between 1917 and 1932.

Return to vehicles at the trailhead, and continue up the potholed road.

Mileage log *Inc.*	*Cum.*	
0.2	27.3	Baker Hot Springs parking area. The ca. 44 °C (111 °F) springs are reached by a flat, often soggy, 0.4 km (0.25 mile) trail. NOTE: the road was washed out in November 2006, leaving impressive 2-m-deep channels cut down its length. Until, or unless, it is repaired, it is necessary to walk the remaining mile to Stop 5. A higher road, FS 1130, that branched to the left at just beyond Stop 4, was also washed out and buried in rockslides. The route to Stop 5 via FS 1130 requires a one-mile walk at this writing.
0.6	27.9	Junction with FS 1130. Sharp turn to right.
0.4	28.3	Stop on the right at the sign for the Rainbow Falls overlook.

STOP 6—Peak Flow of the 1890–1891 Rainbow Creek Debris Avalanche

The Rainbow Falls overlook is constructed on the lateral levee of the debris avalanche above a steep slope. Please use caution in departing from the trail and the overlook area. The goal of this stop is recognition of the potential size and mobility of volcanic flows of this type and an appreciation of the devastation that can result (Lewis et al., 2006). Think of both debris avalanches and lahars as flowing rock moving interstitial water, and of a normal flood as flowing water moving entrained sediment.

This well-developed lateral levee, with a relief here of as much as 2 m, is characteristic of the flows described as debris avalanches, especially the more mobile examples. Its level closely approximates the peak stage of the flow. In contrast, the peak stage of lahars is less well marked, commonly only as a mud line on a valley-side slope that may remain visible for only a few years. At this location, we can be certain of the peak stage of the debris avalanche, which, when combined with an estimate of mean flow velocity, allows us to reconstruct the discharge.

For an idea of the damage and inundation of a flow of similar size, turn to Figures 4–7 of Scott et al. (2001), illustrating an earthquake-triggered flow (called "La Avalancha" but more accurately described as a lahar) that occurred in Colombia in 1994. Site of the almost instantaneous burial of the town of Toez, with a population of hundreds of people, is shown in Figure 5 of Scott et al. (2001). This flow occurred at the base of Nevado del Huila, the next large stratovolcano to the south of Nevado del Ruiz, source of the notorious 1985 eruption-triggered lahar that devastated the city of Armero and killed 23,000 people.

Depth of peak flow of the Rainbow Creek debris avalanche at this location is ~87 m (280 ft). We can estimate the cross-

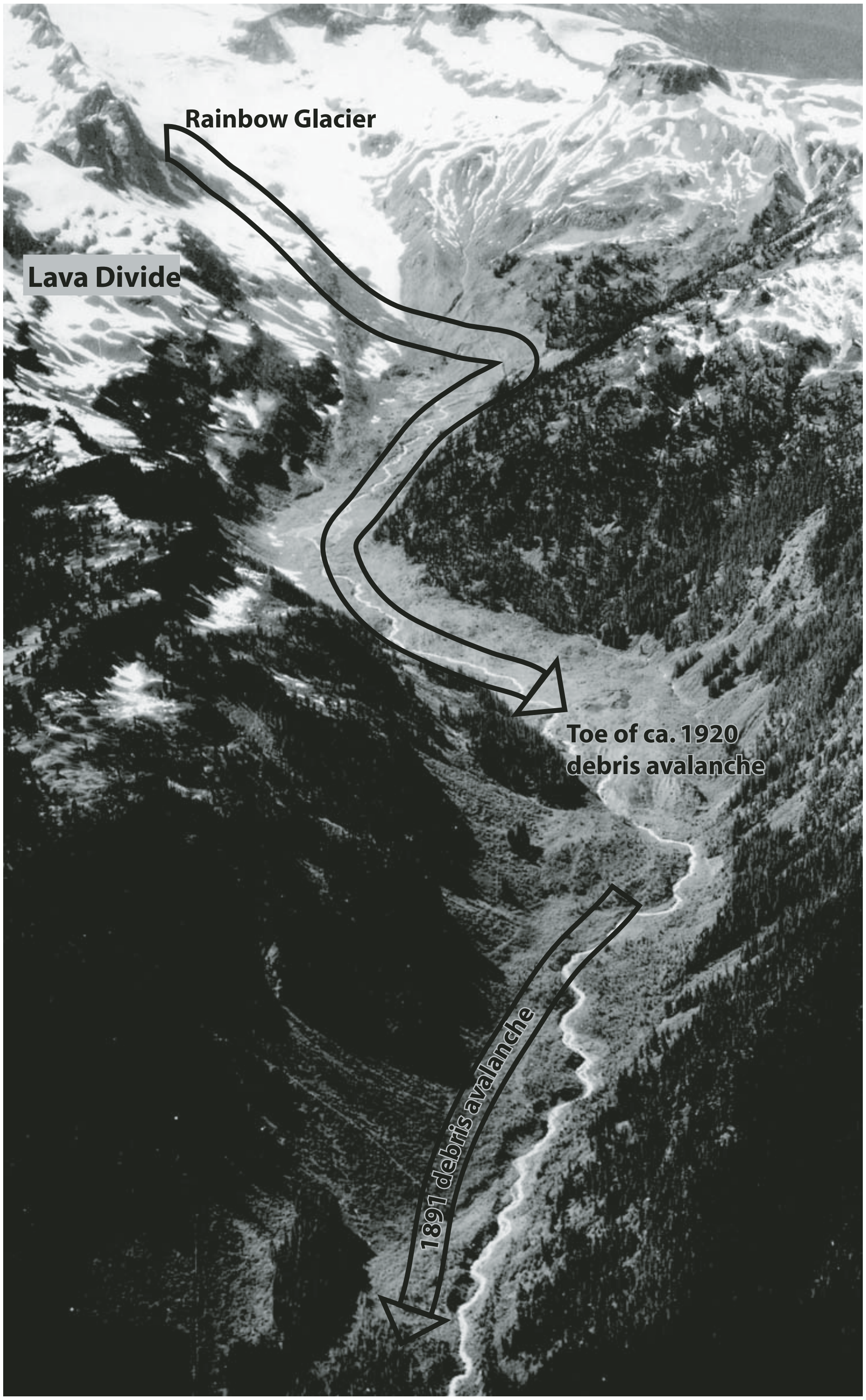

Figure 14. Aerial photo by Lage Wernstedt between ca. 1930 and 1935 shows Avalanche Gorge, in upper Rainbow Creek, and the track of huge Rainbow Creek debris avalanches. The field of view is ~6 km from the terminus of the Rainbow Glacier to the bottom of the photo. The debris avalanches began at Lava Divide (upper left), a stack of altered andesite lava and breccia that is mid-Pleistocene in age (Hildreth et al., 2003), falling down the south valley wall onto the terminus of the Rainbow Glacier; they then ran up the opposite wall over 150 m before falling back and continuing down the valley. The first avalanche, dated to 1891, continued another 3 km beyond the bottom of the photo. The steep terminal lobe of the second debris avalanche can be seen at the second large bend in the stream. The younger deposit appears to be entirely unvegetated, and covers parts of the Rainbow Glacier terminus. Photo courtesy of the U.S. Forest Service.

sectional area at ~4000–5000 m^2 (relative to the maximum cross section of 8000 m^2 for the flow in Colombia). Velocities of "La Avalancha" and the Rainbow Creek flows were probably similar, and the instantaneous peak mean velocity of the Rainbow Creek debris avalanche can be estimated conservatively in the range of 14–18 m/s, or 30–40 mph. Using the mean estimate of each value, we can approximate the discharge to have been 70,000 m^3/s. That flow rate is greater than the maximum instantaneous peak discharge ever recorded for the Mississippi River in over 140 years of measurement at St. Louis, including the record flood of 1993. Bear in mind that the cross-sectional area of flow of the Mississippi River in flood is many times that of the debris avalanche as it passed this point. Correspondingly, the mean velocity of the Mississippi River in flood is a small fraction of the flow rate of the debris avalanche at this site.

Note the old-growth cedar trees with their up-valley trunks scarred by the 1890–1891 debris avalanche (Fig. 15). These trees are markedly larger than the ones growing lower on the slope, and survived at the margin of the avalanche. Only these huge trees, with their supportive flared bases, could withstand the impact of several meters of flow of the debris avalanche. The old-growth forest impacted by the avalanche would have increased what hydraulic engineers call boundary roughness, acting to slow the flow. This factor has been incorporated in our estimate of velocity. We cut cross sections of three of these scars, and the clearest of these indicates an age of 1890–1891.

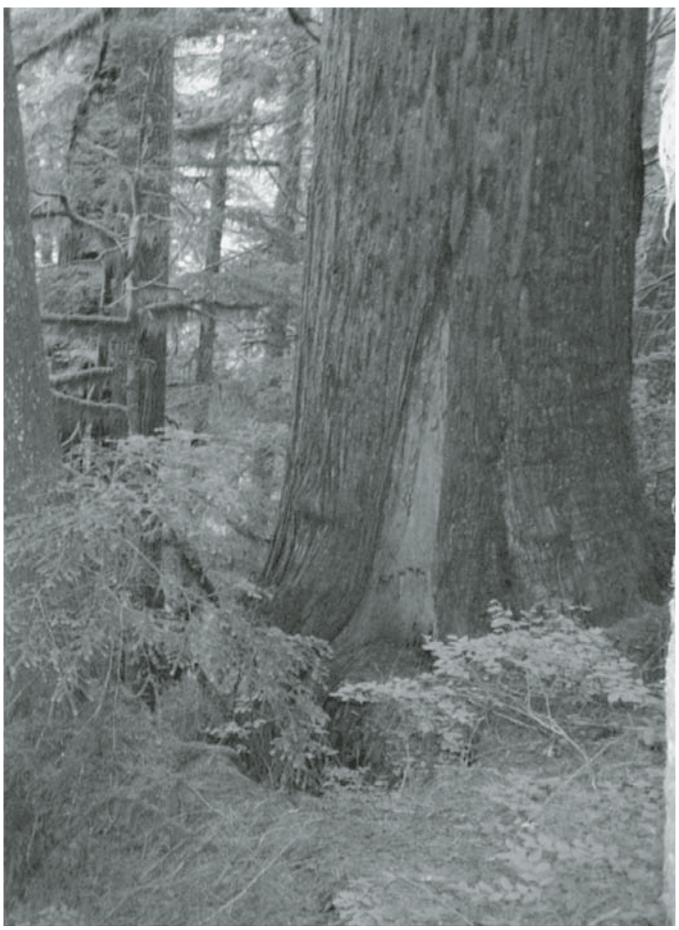

Figure 15. A prominent vertical scar marks the upstream side of one of several 1.5-m-diameter cedar trees, ~280 ft above the valley floor, near Stop 6. These surviving trees mark the peak flow level of the earlier of the two rainbow Creek debris avalanches. A scar on a tree similar to this dates to 1890 or 1891.

Had you been near here when the flow approached, the ground tremor would have been so strong you probably would not have been able to stand. However, you would probably have thought the tremor was an earthquake. Scott et al. (2001, p. 47–49) review cases where knowledge that tremor can signal the approach of a catastrophic volcanic flow would have saved tens of thousands of lives in recent decades. Signs with the warning, "In case of earthquake, go to high ground," are now posted at trailheads at volcanoes such as Mount Rainier.

This is the end of the field trip. Return to vehicles, and drive back to the paved Baker Lake Road. There are two possible routes. If you had to walk from the Baker Hot Springs parking area, drive back down FR 1124 and turn right when you reach the paved road. If you were able to drive beyond the washouts to Stop 6, it may be possible to return to the paved road via FR 1130, keeping right at the junction with FR 1124. This road rejoins the Baker Lake Road in ~3 miles (4.8 km), just north of the Boulder Creek bridge. Note that Road 1130 was cut by flooding and buried by a landslide in November 2006.

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