The Geological Society of America
Field Guide 15
2009

Snowpack data collection in the Mount Hood area using SNOTEL and geomorphic events related to snowmelt

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ABSTRACT

This field trip guide describes a one-day loop from Portland eastward around Mount Hood and returning through the Columbia River Gorge. The purpose is to visit a SNOTEL (SNOwpack TELemetry) site to observe processes and instrumentation applied in automated snowpack data collection, as well as observe geomorphic features related to snowmelt in the western United States. Annual snow accumulation in the higher elevations in the western United States provides a critical source of water for irrigation, hydroelectric power generation, municipal water supplies, and recreation. Snowmelt, however, also can cause various hydrogeologic hazards, such as floods and debris flows.

OVERVIEW

The field trip is a one-day loop beginning in Portland, driving east and stopping at a SNOTEL site south of Mount Hood. The trip ultimately encircles Mount Hood as it continues east of the mountain, stopping at a debris flow and on to the Columbia River and back to Portland.

SNOWPACK DATA COLLECTION

The Natural Resources Conservation Service installs, operates, and maintains an extensive, automated system (SNOwpack TELemetry or SNOTEL) designed to collect snowpack and related climatic data in the western United States and Alaska. In 1935, the Soil Conservation Service (presently the NRCS),

Strobel, M.L., Lea, J., Brunengo, M.J., and Pedone, P.F., 2009, Snowpack data collection in the Mount Hood area using SNOTEL and geomorphic events related to snowmelt, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to Vineyards: Geologic Field Trips through the Dynamic Landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 1–XXX, doi: 10.1130/2009.fld015(22). For permission to copy, contact editing@geosociety.org.

established a formal cooperative Snow Survey and Water Supply Forecasting Program to conduct snow surveys and develop accurate and reliable water supply forecasts. The Program operates under technical guidance from the Natural Resources Conservation Service National Water and Climate Center.

With 50 to 80 percent of the annual water supply in the West derived from snow, snowpack information is critical to decision-makers and water managers throughout the West. SNOTEL provides a reliable and cost effective means of collecting snowpack and other meteorological data needed to produce water supply forecasts and support the resource management activities of the Natural Resources Conservation Service and others.

The Snow Survey and Water Supply Forecasting Program has grown into a network of more than 1,000 manually measured snow courses and over 760 automated SNOTEL stations in 13 western states, including Alaska (Fig. 1). The Program provides streamflow forecasts for over 740 points in the West. The data, as well as related reports and forecasts, are made available—in near real time from the SNOTEL sites—to private industry; to federal, state, and local government entities; and to private citizens through the Internet and other distribution channels.

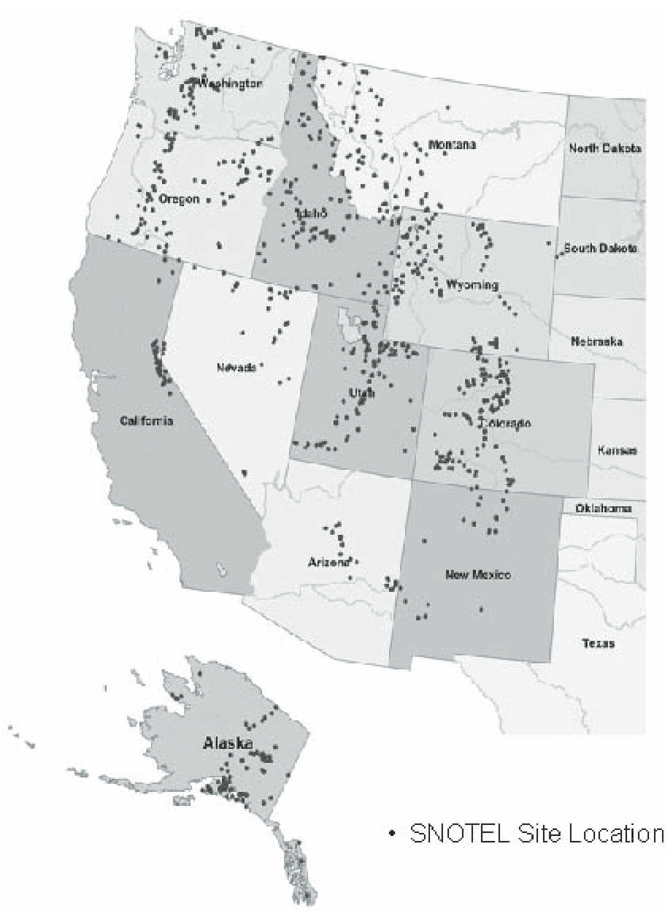

Figure 1. Map of western United States showing locations of Natural Resources Conservation Service SNOTEL sites.

The SNOTEL network, which began in the 1970s and continues to expand every year as new sites and existing manual snow courses are converted to automated SNOTEL sites, also provides data for climate studies, air and water quality investigations, and endangered species habitat analysis. The high-elevation watershed locations, broad coverage, and real time operation of the network supports researchers, river and reservoir managers, emergency managers for natural disasters such as floods and droughts, recreational area managers, and power generation companies.

SNOTEL uses meteor burst communications technology to communicate data in near real time. Radio signals are reflected at a steep angle off the ever-present band of ionized gases in the trails of meteors existing from ~80–120 km above the earth. SNOTEL sites generally are located in remote high-mountain watersheds where access is often difficult or restricted. They are designed to operate unattended and without maintenance for a year or longer with batteries charged by solar panels. Access for maintenance can involve hiking, snowmobiles, skiing and snowshoeing, and/or helicopters.

Six Natural Resources Conservation Service Data Collection Offices monitor daily site statistics. Three meteor burst master stations are the central collection points for all transmitted remote station data. These master stations are located near Boise, Idaho; Ogden, Utah; and Anchorage, Alaska. When the data are received, they are converted to digital unit values and screened for errors, then stored in a database and made available to the public via the National Water and Climate Center Web site (www.wcc.nrcs.usda.gov).

The basic SNOTEL station provides snowpack water content data via a pressure-sensing snow pillow. It also collects data on snow depth, all-season precipitation accumulation, and air temperature with daily maximums, minimums, and averages (Table 1). Many of the enhanced SNOTEL stations are also equipped to take soil moisture and soil temperature measurements at various depths, as well as solar radiation, wind speed, wind direction, and relative humidity (Fig. 2). The snowpack, atmospheric and, where installed, soil moisture and soil temperature measurements are reported hourly for most stations, with some stations reporting only a few times per day due to power limitations necessary for data transmission.

This field trip examines the precipitation and snowpack records from SNOTEL sites as related to recent debris flows. Because SNOTEL provides data in near real time, the information could be utilized as a tool in assessing potential risk from geomorphic events.

PRECIPITATION

Orographic effects from mountain ranges in the western United States strongly influence the distribution of precipitation, and especially so in the field trip area of Portland, Mount Hood, and the Columbia River Gorge (Fig. 3). Moisture laden storms often travel to the west end of the Columbia River Gorge,

TABLE 1. PARAMETERS MEASURED AND SENSOR TYPE FOR SNOTEL (SNOWPACK TELEMETRY) SITES

Parameter measured	Data sensing
	SNOTEL Site-Standard Configuration
Air temperature	Shielded thermistor
Precipitation	Storage type gage
Snow water content	Snow pillow device and a pressure transducer
Snow depth	Sonic sensor
	SNOTEL Site-Enhanced Additions
Barometric pressure	Silicon capacitive pressure sensor
Relative humidity	Thin film capacitance-type sensor
Soil moisture	Dielectric constant measuring device. Measurements are taken at standard depths of 5 cm, 20 cm, and 50 cm with some at 5 cm and 100 cm.
Soil temperature	Encapsulated thermistor. Typical measurements are taken at standard depths of 5 cm, 20 cm, and 50 cm with some at 5 cm and 100 cm.
Solar radiation	Pyranometer
Wind speed and direction	Propeller-type anemometer

where they impinge upon the western Cascade Range foothills. The Columbia River Gorge also can influence precipitation distribution and storm events can move towards the west down the gorge. Locally, the Cascade Range is highlighted by Mount Hood, the highest point in Oregon and rising 3426 m above sea level, and Mount St. Helens, which after the catastrophic eruption in 1980 was reduced to the height of 2549 m. The orographic effect of the Cascade Range, as illustrated in Figure 3 and documented in Table 2, results in large increases in annual precipitation between Portland and the Cascade Range and sharp decreases in precipitation to the east in the rainshadow of the Cascade Range. The average annual precipitation changes

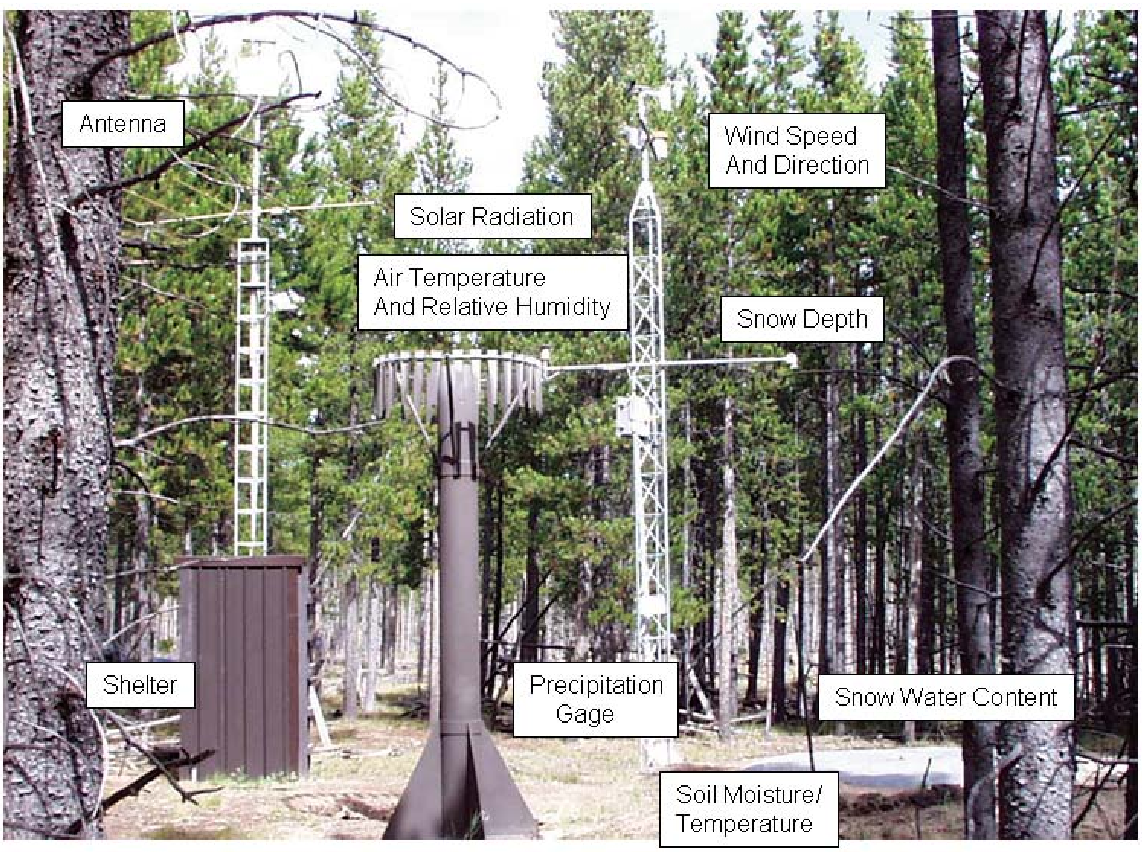

Figure 2. Typical SNOTEL site with sensors and equipment identified.

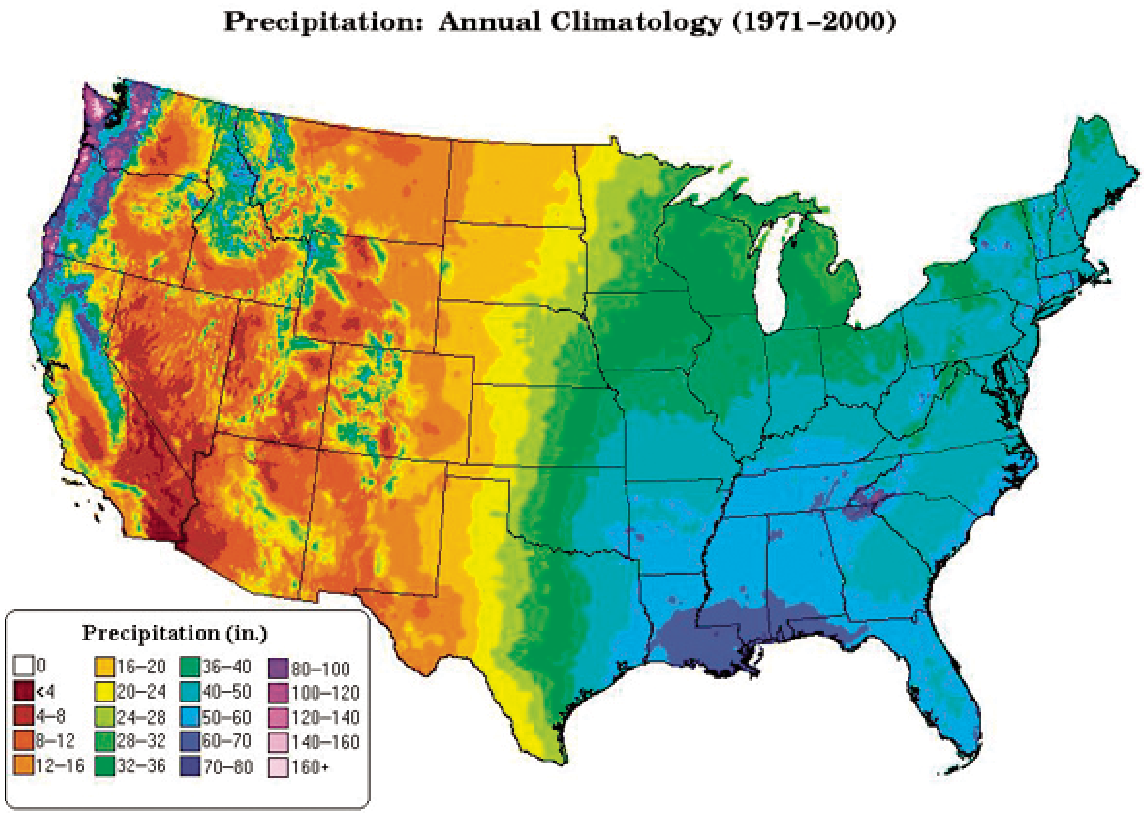

Figure 3. Precipitation map of the United States for 1971–2000 produced from PRISM (from PRISM Group at http://www.wcc.nrcs.usda.gov/climate/prism.html).

TABLE 2. AVERAGE ANNUAL PRECIPITATION AND AVERAGE MAXIMUM SNOW WATER EQUIVALENT AND DATE MEASURED FOR SITES IN THE MOUNT HOOD AREA

Elevation (m)	Site name	Annual precipitation (mm)	Average maximum SWE (mm)	Date of SWE measurement
6	Portland Airport	940	15	15 Jan
9	Troutdale	1131	13	15 Jan
21	Bonneville Dam	1969	46	15 Jan
30	The Dalles	368	46	15 Jan
49	Portland Water Bureau	1095	5	15 Jan
152	Hood River Experimental Station	800	71	15 Jan
229	Headworks	2035	14	15 Jan
405	Dufur	340	36	15 Jan
463	Parkdale	836	155	15 Jan
933	North Fork*	3751	399	1 Apr
1009	Greenpoint*	1997	445	1 Apr
1049	June Lake*	4451	907	1 Apr
1113	Blazed Alder*	3175	815	1 Apr
1162	Clear Lake*	1196	335	1 Mar
1198	Lone Pine*	2583	935	15 Apr
1213	Government Camp	2254	777	1 Mar
1216	Sheep Canyon*	3414	960	1 Apr
1241	Mud Ridge*	1775	617	1 Apr
1308	Surprise Lakes*	2636	1184	15 Apr
1345	Red Hill*	2931	1171	1 Apr
1637	Mount Hood Test Site*	2826	1623	1 May

Note: SNOTEL (SNOwpack TELemetry) indicated with *; other site data provided by the National Weather Service. Snow water equivalent (SWE) at non-SNOTEL sites estimated. Average annual precipitation and average maximum snow water equivalent based on period 1971–2000 or fraction of this period for records less than 30 years.

with elevation from the Portland Airport (elevation 6 m) with an average annual precipitation of 940 mm to 2035 mm of precipitation ~26 km to the southeast at the Headworks, Portland Water Bureau, near Sandy, (elevation 229 m) (Fig. 4). Farther up in elevation ~40 km due east from the Portland Airport along the Columbia River Gorge, the SNOTEL site at North Fork (elevation 933 m), has an average annual precipitation of 3751 mm, and across the river on the flanks of Mount St.. Helens, the June Lake SNOTEL site at an elevation of 1052 m and ~72 km to the north of the airport has an average annual precipitation of 4451 mm. East of the Cascade Range, precipitation stations at The Dalles (368 mm) and Dufur (340 mm) show the strong rainshadow effect.

GEOLOGY

The field-trip route loops through or near three physiographic provinces with a geologic history spanning most of the Cenozoic Era, though the features of interest are dominantly Miocene or younger, and many have been formed within the past few million years.

On the west side of the route, the Portland metropolitan area is situated within the Puget-Willamette Trough, a north-south structural basin lying between the Coast Ranges to the west and the Cascade Range to the east. The Portland Basin, a major component of the Willamette Trough, was formed in a complex structural regime involving large-scale plate movement and

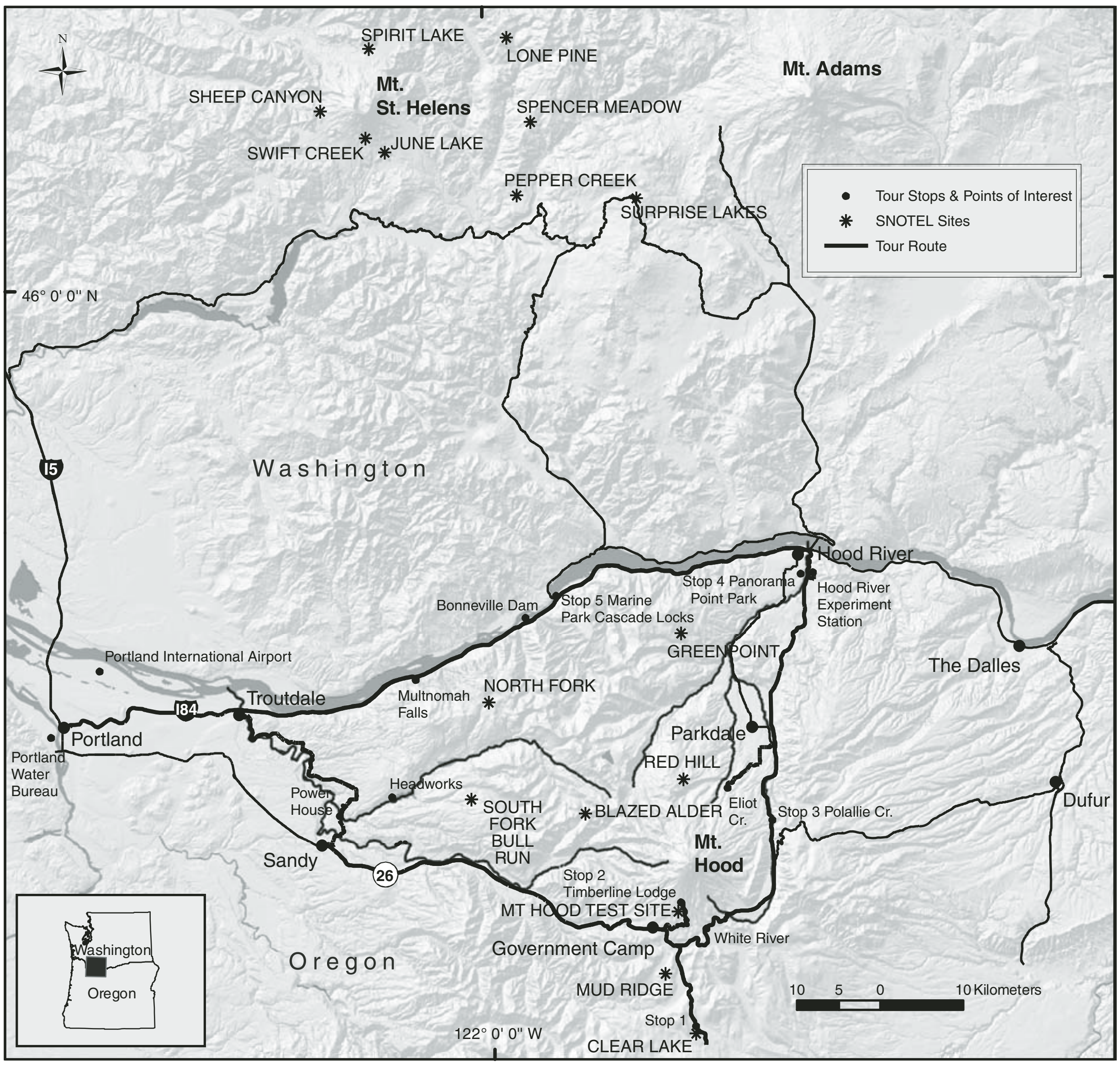

Figure 4. Map of field trip route, stops, SNOTEL sites, and precipitation stations.

subduction along western North America, causing right-lateral extension along a series of faults reaching from central Oregon, across the Cascade Range and into the lower Willamette Valley (for general discussion, see Burns, 1998; Orr and Orr, 1996). The subsided lowland of the Portland Basin is bounded on the east and southeast by the Cascade Range.

On the east edge of the route, in the Hood River Valley, we glimpse the Deschutes-Umatilla Plateau, part of the Columbia Plateau province that extends into central Washington (Galster et al., 1989; Burns, 1998). Although this trip does not travel through this region, it is important to the story of the Cascade Range and the Columbia River Gorge because it was the source and major repository of the voluminous Columbia River Basalts (Miocene). These lavas were erupted from fissures far to the east (near the Oregon-Washington-Idaho boundaries), chiefly between 17 and 14 Ma but extending to ca. 6 Ma (Tolan et al., this volume, Chapter 28). Many of the flows ponded against the east side of the ancestral Cascade Range, and dozens moved through an earlier, wider "Columbia" valley into the Willamette Trough, with some flows making it all the way to the coast. Representatives of these basalts are exposed in the walls of the Columbia River Gorge and in the Portland area, and underlie the Cascade Range southward past the Clackamas River. Also, the Hood River Valley sits at the southeast corner of the Yakima Fold Belt, a region of compressional folds and thrust faults that extends across the Columbia Plateau; we see some manifestation of these structures in the walls of the Columbia River Gorge.

Most of this trip travels within the Cascade Range. In Oregon and southern Washington, the Cascade Range is underlain chiefly by Tertiary-age (Oligocene to Quaternary) volcanic, volcaniclastic, and shallow-intrusive rocks that were produced by eruptions within the range, along with the Columbia River flood basalts that erupted far to the east. The ancient Columbia River and other streams deposited gravels, sands, and silts over the volcanic rocks, which were partly lithified as the Troutdale Formation (late Miocene to Pliocene). These older volcanic rocks, Columbia River basalts, and Troutdale sedimentary strata are exposed on the up-arched flanks of the Cascade Range, around the Columbia River Gorge east of Troutdale, and underlie most of the Portland Basin.

Over the past 4 million years, continued erosion in the rising Cascade Range led to deposition of more fluvial sediments in the basins. These formed an irregular piedmont surface sloping gently to the west and southwest from the mountains into the lowlands. Concurrently, volcanoes erupted in the High Cascade Range, producing the lavas that cap the slopes rising eastward from the Sandy River toward Larch Mountain and over to the Hood River–White Salmon area. Some of this volcanism extended westward across the Portland Basin, and short-lived eruptions from dozens of vents formed the many small cones and shields of the Boring Lavas (Conrey et al., 1996; Evarts et al., this volume).

The most prominent feature along the fieldtrip is Mount Hood, which is the highest mountain in Oregon at 3426 m. This volcano is more than 500,000 years old and has had two significant eruptive periods in the recent past, one ca. 1500 yr B.P. and the other in the 1790s, not long before the Lewis and Clark expedition visited the region (Gardner et al., 2000; Pierson et al., this volume). Mount Hood has snow cover for much of the year, and there are 11 glaciers that feed streams radiating away from the volcano. Glacial and fluvial erosion and deposition strongly influence the surficial geology along most of the field trip route.

The other prominent feature along the field trip is the Columbia River Gorge. The most recent major geologic events to shape the region were tremendous floods down the Columbia River, caused by the repeated collapse of glacial dams and drainage of a large lake in western Montana (Allen et al., 1986; O'Connor and Burns, this volume). Many dozens of these Missoula Floods occurred between ca. 15,500 and 12,500 yr B.P. (and perhaps during earlier glaciations). Flood waters up to 300 m deep swept through the Columbia River Gorge and over the lowlands of the Portland Basin, reshaping the landscape by erosion and deposition of coarse sediments in mega-fluvial pendant bars, and mantling back-flooded side valleys with silt and scattered ice-rafted erratics.

SNOWMELT AND GEOMORPHIC EVENTS

Although 50 to 80 percent of the western water supply is provided by snowmelt, on the west side of the Cascade Range both rainfall and snowmelt contribute to runoff. Snowmelt-runoff generates flow at the higher elevations, and rainfall-runoff at the lower elevations. In the Mount Hood area, most of the precipitation occurs during the fall and winter months. Because the Mount Hood area is influenced by a maritime climate, many of the large winter storms are rain or rain-snow mixed storms which can produce rain-on-snow precipitation events with potentially large runoff.

Storms in the Pacific Northwest can deliver days of heavy rains and warm winds in autumn, winter, and early spring. Seasonal snowmelt can be rapid and deep in some years, especially when warm rains combine with snowmelt. In such events, the region experiences major episodes of flooding, landslides, and debris flows, as in 1948, 1964, 1996, and 2007. Mount Hood poses additional hazards: (1) exposed unstable debris on steep slopes that can feed debris flows and muddy floods during storms, especially as snowpacks decline; (2) volcanic eruptions and associated lahars (volcanic debris flows), potentially flushing large amounts of sediment into the Hood, White, and Sandy Rivers, and ultimately the Columbia River (Pierson et al., this volume). The lack of storms can also cause problems; winters with low precipitation cause water-supply problems for municipal, irrigation, and hydropower users, as well as for environmental needs. Many of these practical issues—and the means adopted to help monitor and forecast flows and geomorphic hazards in the Mount Hood–Columbia River Gorge region—are the main topics of this field trip.

Although there have been no major eruptive events on Mount Hood since 1830, there have been various releases of steam and tephra. The potential for large lahars small during these quiet times, but the likelihood of future eruptions and large lahars remains. Within the past 2000 years, there have been three periods where lahars resulted in extensive deposits; (1) between 200 and 600 AD, (2) between 1400 and 1600 AD, and (3) between 1740 and 1830 AD (Cameron and Pringle, 1986; Swanson et al., 1989). A more recent example of these types of events are the lahars associated with the 18 May 1980 eruption of Mount St. Helens, where the rapid melting of snow and ice resulted in several lahars that were responsible for the damage of 27 bridges and approximately 200 homes and that reduced channel depth in the Columbia River from 12 m to 4.5 m, stranding 31 ships upstream (Brantley and Myers, 2000).

On this field trip, we will view effects of debris flows not specifically related to volcanism, such as the 30 September–1 October 2000 debris flows along the White River and Newton Creek (U.S. Geological Survey, 2000), the 25 December 1980 debris flow along Polallie Creek (Gallino and Pierson, 1984), and the November 2006 debris flows on the White River, Clark Creek, Newton Creek, Eliot Creek, and Sandy River (Pirot et al, 2007). SNOTEL data on precipitation, temperature, and snow water equivalent at sites near these debris flows provides insight to conditions producing the events. Each will discussed further in the road log section below.

ROAD LOG

The drive is an ~320 km loop around Mount Hood that leaves from Portland and follows the Historic Columbia River Highway and U.S. 26 (Mount Hood Highway) eastward, then north on State Route 35 to Hood River and back to Portland on Interstate 84 (Fig. 4). The first leg of the loop follows part of the Barlow Road, which was a main route for the Oregon Trail. Continuing around Mount Hood, the route follows what is known as the "Fruit Loop" because of the number of orchards along the route near Hood River, Oregon. The trip returns to Portland via the Columbia River Gorge, the only "sea level crossing" from the interior to the Pacific Coast in the entire western United States.

Cumulative miles	*(km)*	*Directions*
0.0	(0.0)	Leave the Oregon Convention Center and head east on Interstate 84.
14.1	(22.7)	Exit off of Interstate (exit 17) onto frontage road. Turn right on Graham Road.
15.0	(24.1)	Turn left onto Columbia River Highway (historic highway through the Columbia River Gorge predating present interstate). Route proceeds through Troutdale along the Sandy River Valley.
15.8	(25.4)	Crossing the Sandy River (single lane bridge) at Broughton Bluffs. There is the option to pull off at a historic marker once over the bridge.

Lewis and Clark called the Sandy River the Quicksand River, for the then-recent volcanic debris from Mount Hood that choked the river with debris.

The namesake of Bull Run Road is the Bull Run River, which is crossed in a few kilometers. The Bull Run River or more specifically, the Bull Run Watershed, is the major drinking water source for Portland, Oregon, or nearly 25 percent of the all the residents of Oregon. The watershed is ~380 km^2, 95 percent owned by the U.S. Forest Service, and 5 percent by the City of Portland. The Bull Run Watershed ranges in elevation from 229 m at the municipal headworks near the second Bull Run Dam, to 1433 m. It is not connected to the glacial-fed streams draining Mount Hood. Because much of the watershed is below the transient snow zone, most of the runoff is derived from rainfall, with snowmelt providing ~5–10 percent of the annual flow (Portland Water Bureau, 2005). Rainfall in the Bull Run watershed averages ~3300 mm annually (PRISM Group, 2006). Despite being mainly a rainfall-affected watershed, the city of Portland supports their analyses of annual water conditions with three SNOTEL sites within the watershed.

Cumulative miles	*(km)*	*Directions*
18.7	(30.1)	Dabney State Park.
20.1	(32.3)	Turn right on Hurlburt Road.
22.2	(35.7)	Turn right on Gordon Creek Road.
23.5	(37.8)	Overview of Sandy Creek.
30.2	(48.6)	Turn right on Bull Run Road.
32.6	(52.4)	Bull Run Rim (Case Headworks Building).
33.2	(53.4)	Turn left on Ten Eycks Road. Around mile 34.7 (kilometer 55.8) the route begins to follow the Oregon Trail–Barlow Road route. This continues for much of the remainder of the trip past Mount Hood.
36.7	(59.1)	Turn left (east) onto U.S. 26 near Sandy, Oregon. Head toward Mount Hood.
60.5	(97.4)	Stop at pull-off at Barlow Trail and the Salmon River overlook.
61.4	(98.8)	Laurel Hill (considered one of the most difficult parts of the Oregon Trail).
63.7	(102.5)	Government Camp.
67.1	(108.0)	Road splits with Oregon 35. Stay on U.S. 26.
69.1	(111.3)	Mud Ridge SNOTEL site about 2 kilometers west of here.71.7 (115.4) Frog Lake.
74.1	(119.3)	Stop 1. Park near the access road and walk in ~0.4 kilometers to site. After stop, head west (left) on U.S. 26.

Stop 1. Clear Lake SNOTEL Site

The Clear Lake SNOTEL installation was completed on 21 August 1978, near a preexisting manual snow course, which was first measured on 8 March 1931. A portion of the now-abandoned snow course is right in front of the door to the instrument shelter. The early snow course was used to make volumetric water supply forecasts on the Hood River, the White River, and the Clackamas River. The snow course was discontinued in the mid 1980s after a 5-year statistical analysis between the snow course and SNOTEL site showed no significant difference between the manual and automated measurements at this site. The Clear Lake SNOTEL site was installed as a part of the first generation SNOTEL Stations in the west. SNOTEL sites have superseded many manual snow courses because they provide near-real-time data for climatic conditions and snow depth, as well as reducing the hazards of sending personnel into harsh and potentially dangerous conditions to make the required monthly measurements. For the first few years of operation of the Clear Lake SNOTEL site, data could not be telemetered because of equipment problems. The first successful site to transmit data on the SNOTEL network was one of Clear Lake's sister sites, Mud Ridge (note road log for kilometer 111.3) for which the first transmission was during the summer of 1979. Since Clear Lake SNOTEL was first installed, the site has gone through a number of upgrades, with all such changes described in metadata available by request from the local Natural Resources Conservation Service Data Collection office in Portland. Currently, SNOTEL sites typically transmit data every hour and the information is served on the National Water and Climate Center Web site in Portland, Oregon. Primary uses of these data are for near real time monitoring of climate and snow conditions, and for Natural Resources Conservation Service forecasts of volumetric water supplies for basins in the western United States. SNOTEL data can be used to remotely monitor changing weather and snowpack conditions in the mountains and potentially identify situations where flooding and debris flows may occur.

Cumulative miles	*(km)*	*Directions*
83.2	(133.9)	Turn right onto Timberline Highway.
88.7	(142.7)	**Stop 2. Timberline Lodge.**
94.0	(151.3)	Turn left (east) on U.S. 26.
95.9	(154.3)	Turn onto Oregon 35, southeast toward Hood River.
99.0	(159.4)	Cross White River.

Debris flows on the White River and other nearby creeks draining Mount Hood have caused substantial damage to property and infrastructure, including this highway. Some of these have been entirely rain events, whereas others were a combination of rain and snowmelt. The debris flow of 30 September–1 October 2000 along the White River and Newton Creek resulted from intense rainfall (U.S. Geological Survey, 2000). SNOTEL data from the Mount Hood Test Site, Mud Ridge, Clear Lake, and Blazed Alder SNOTEL sites indicate there was no snowpack at this time. The National Weather Service measurements at Government Camp recorded 118 mm of precipitation over the period of 29 September through 1 October 2000. The rainfall triggered landslides and debris flows in several drainages, with the largest in White River and Newton Creek (U.S. Geological Survey, 2000). Debris flows in November 2006 occurred in the White River, Clark Creek, Newton Creek, Eliot Creek and Sandy River drainages, resulting from 340 mm of precipitation in six days (Pirot et al., 2007). SNOTEL data show that from 2 November through 8 November 2006, total precipitation was 323 mm at Mount Hood Test Site, 267 mm at Mud Ridge, and 203 mm at Clear Lake—three stations within a few kilometers of each other but at different elevations. The precipitation at Blazed Alder on the west side of Mount Hood was an incredible 615 mm for this period. Combined with the rainfall was snowmelt in the higher elevations. The only SNOTEL site reporting snow during this period was Mount Hood Test Site, which went from 38 mm of snow water equivalent on 2 November to essentially zero snow water equivalent on 7 November. Warm winds and rain-on-snow contributed to this rapid snow melt, which added to the precipitation in November 2006.

Cumulative miles	*(km)*	*Directions*
100.6	(161.9)	Pull-off for White River Snow Park East
112.4	(180.9)	Stop 3.

Stop 3. Polallie Creek

An intense rain-on-snow event on 25 December 1980 triggered a debris flow that moved rapidly down the Polallie Creek Valley. The debris flow killed a camper and temporarily dammed the East Fork Hood River. The resulting floods and debris flows caused more than $13 million in damages, including destruction of 3 km of highway, three bridges, and a State Park (Gallino and Pierson, 1984; Gardner et al., 2000). Polallie Creek lies about half way between the Mount Hood Test Site and Red Hill SNOTEL sites. The Mount Hood Test Site SNOTEL station recorded precipitation amounts of 107 and 84 mm on 24 and 25 December 1980, respectively. However, there was not a large change in snow water equivalent over this period, indicating that snowmelt did not contribute to runoff in this location. At the Red Hill SNOTEL site, there were 114 and 140 mm of precipitation on 24 and 25 December 1980, respectively. However, different from the Mount Hood Test Site SNOTEL station, snow water equivalent at the Red Hill SNOTEL site went from 117 mm on 23 December 1980 to 71 mm on 24 December 1980 to 8 mm on 25 December 1980. All snow was gone by 26 December 1980. The contribution of an additional 110 mm of water from snowmelt to the precipitation over this period must have contributed to the resulting debris flows. These measurements also highlight the spatial variations in precipitation and snowmelt in the Mount Hood area.

Cumulative miles	*(km)*	*Directions*
116.1	(186.8)	Excellent views of basalt features, viewed from the road, near Dog Creek Trailhead.

118.6	(190.9)	Turn-off for Eliot Creek (site of multiple debris flows).
132.5	(213.2)	Turn right at exit for Panorama Point.
133.6	(215.0)	Turn left into Panorama Point Park.
133.8	(215.3)	Stop 4.

Stop 4: Panorama Point Park

Viewed to the north is the Columbia River. This 1930-km-long river drains ~673,000 km^2, including most of Oregon, Washington, Idaho, large portions of Montana, and some of Wyoming and Nevada and much of Southern British Columbia. As measured at The Dalles, the average annual flow is ~1.7×10^{11} m^3 and the average discharge is 5380 m^3/s (U.S. Geological Survey, 2007). The U.S. Geological Survey gage at The Dalles is one of the oldest in the country, beginning operation in 1857 with continuous measurements since 1878. This river system has seen a tremendous change from the 1930s to present. There is now nearly 5.3×10^{10} m^3 of storage for flood control, hydropower generation, irrigation, navigation and fish and wildlife. Water supply forecasts derived in part from SNOTEL data are critical for managing water resources and water use in the Columbia River and throughout the western United States.

The remainder of the field trip follows the Columbia River Gorge. This canyon is up to 1220 m deep and over 130 km long, forming the boundary between Washington and Oregon. The Columbia River Gorge has its origins as far back as the Miocene Era, although many of the present features owe to Quaternary events and processes. Further discussion and descriptions can be found in Benito and O'Connor (2003) and O'Connor and Burns (this volume), including Pliocene and Pleistocene uplift, concurrent river incision, and pervasive landslides that shape and influence the Columbia River Gorge.

Cumulative miles	*(km)*	*Directions*
134.0	(215.7)	Turn left (north) toward Hood River. Stay left onto East Side Road.
135.5	(218.1)	Turn right onto Oregon 35.
136.1	(219.0)	Turn left onto Interstate 84 heading west toward Portland.
155.3	(249.9)	Exit right into Cascade Locks/Bridge of the Gods.
156.3	(251.5)	Turn right into Marine Park, then right on Portage Road.
156.5	(251.9)	Stop 5: Marine Park at Cascade Locks. Early lock on the Columbia River located at this site exit. Park to the right and drive through Cascade Locks.

Stop 5. Marine Park at Cascade Locks

Cascade Locks is located at the site of the Bridge of the Gods, presently a manmade bridge spanning the Columbia River but also the location of Native American legend of river blockage. The cause of this blockage was almost certainly Bonneville landslide (O'Connor, 2004), which covered more than 14 km^2 and created a temporary lake and dam in this area, probably about 1450 A.D. The former rapids at this site (now drowned by the pool behind Bonneville Dam) are the remnants of the landslide following erosion of the dam and drainage of the lake (O'Connor and Burns, this volume).

Throughout the next 32 km of the tour, the highway passes numerous waterfalls along the Oregon side of the gorge. These waterfalls, and most notably Multnomah Falls, occur where streams cascade over steep walls in part created by the scouring of the basalt during the floods associated with Glacial Lake Missoula.

Cumulative miles	*(km)*	*Directions*
169.3	(272.5)	Multnomah Falls.
197.9	(318.5)	Exit Interstate 84 at Lloyd District (exit 1).
199.0	(320.3)	End field trip at Oregon Convention Center.

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Manuscript Accepted by the Society 20 July 2009