Portland, Oregon, geology by tram, train, and foot

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Overview: This field trip provides an introduction to the geology of the Portland, Oregon, area. Five field trip stops, all accessible by public transportation and walks of easy to moderate difficulty, provide opportunities to see outcrops of Columbia River Basalt, Troutdale Formation, Boring volcanic field flow and vents, Portland Hills Silt, and a small landslide.

INTRODUCTION

Residents of the Portland, Oregon, metropolitan area are proud of its scenery and its public transit system (also known as TriMet or MAX). Beneath both lies some fascinating geology, including Miocene flood basalt flows, Quaternary volcanoes, and deposits and landforms left by the great Bretz/Missoula Floods. This field trip provides an opportunity to see some of the geology of the Portland area by walking and using public transportation, starting from the Oregon Convention Center (777 NE Martin Luther King, Jr. Boulevard). A guided version of the trip will be offered during the October 2009 GSA meeting, but this guide is also intended for those who want to self-guide at their own convenience. Bus, streetcar, light rail, and tram fares can all be readily purchased at the Rose Garden Transit Center adjacent to the Oregon Convention Center.

This field trip guide is intended to provide a fun introduction to the geology of Portland area. It is not meant to be a definitive and comprehensive review of the subject. A list of references is provided at the end of this guide for those interested in more details.

REGIONAL SETTING

The tectonic and geologic setting of the Pacific Northwest (Figure 1) is dominated by the Cascadia Subduction Zone, where the Juan De Fuca plate is actively subducting toward the northeast beneath the North American plate at the rate of almost 4 cm/yr. Portland is located in the Portland Basin, a forearc basin that lies between the Coast Ranges and the active volcanic arc of the Cascade Range. The Coast Ranges are composed of Eocene to Miocene marine sedimentary rocks and Eocene intrusive and extrusive basalt deposited on the accreted Siletz terrane. The Cascade Range is composed of a sequence of Eocene through Holocene arc volcanic rocks, decorated with a chain of Quaternary stratovolcanoes.

The Portland basin is bounded on the east by the Cascade Range and on the west by the Tualatin Mountains, a faulted anticline that has been growing since the Miocene. The Portland Basin is traversed by the Columbia River which, at 2,000 km in length and with a drainage basin of 670,000 km^2, has had a major influence on the geology of the basin.

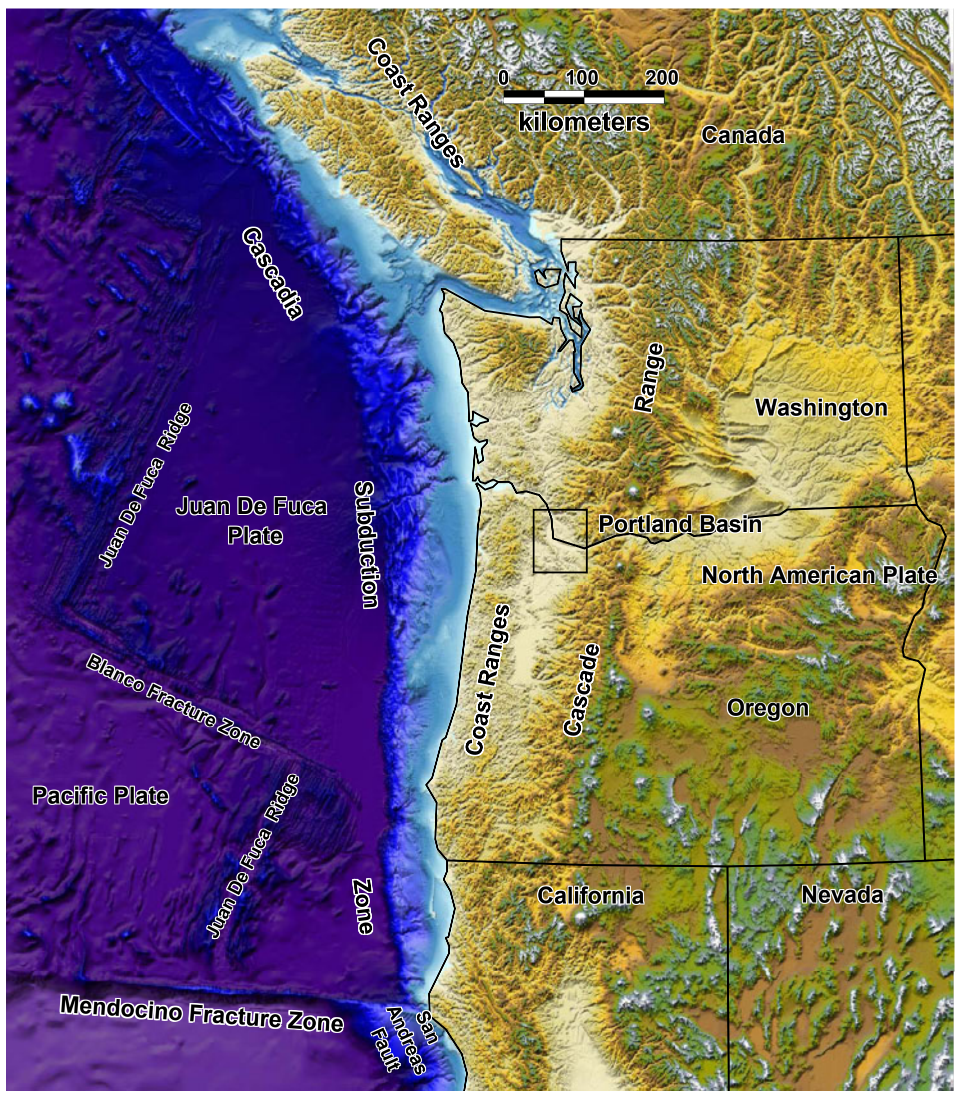

Figure 1. Regional tectonic setting of the Portland Basin within the Pacific Northwest.

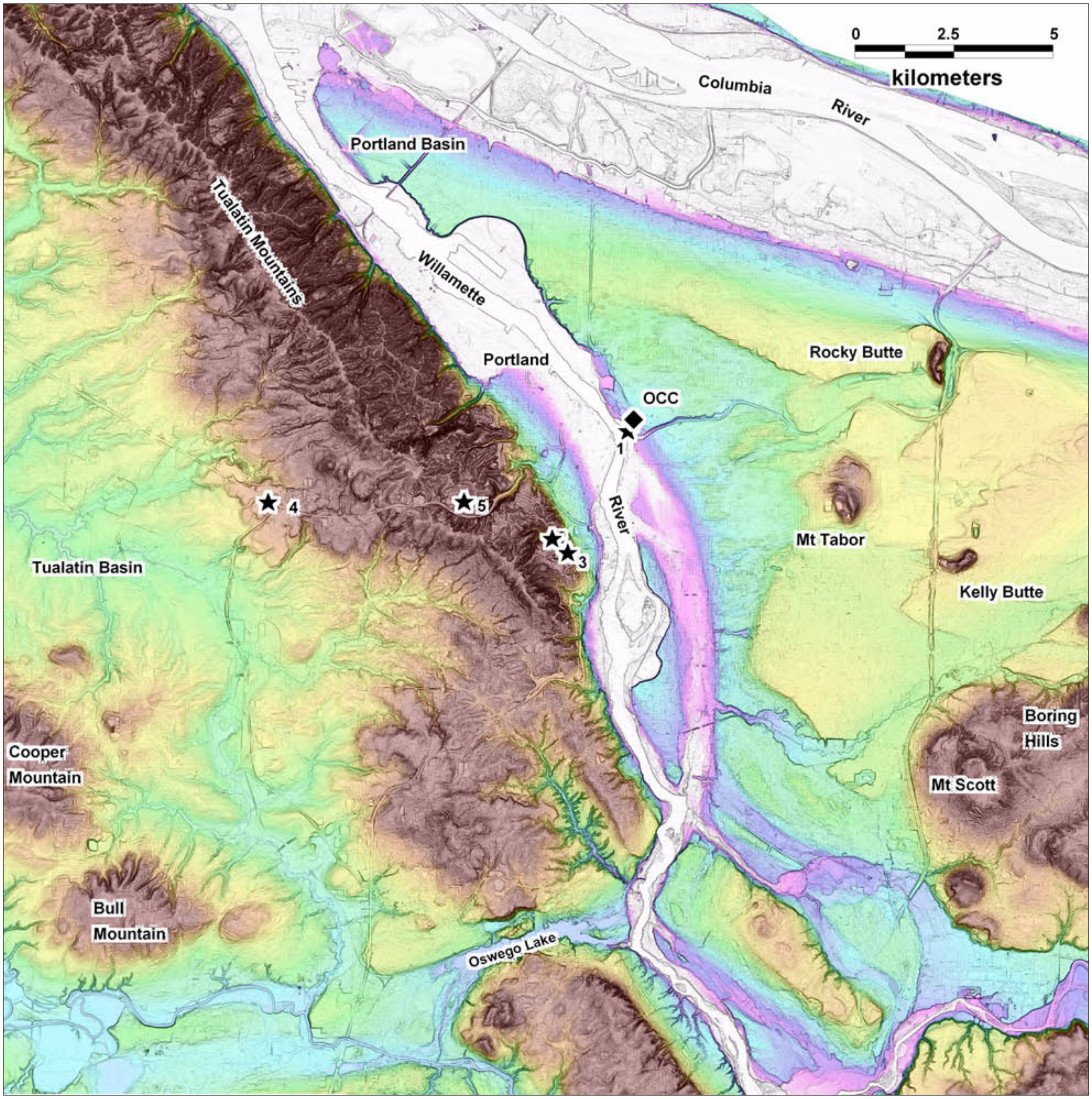

Figure 2. Lidar image of the Portland, Oregon, area, showing field trip stops (stars) and major geographic features. Image consists of an elevation color gradient over slopeshaded lidar. The peak elevation for Bretz/Missoula floodwaters was about 115 m, corresponding to the base of the brick red color. Elevation shown by color gradient: Brick red color indicates higher elevations up to 390 m; white color is sea level.

THE GEOLOGY OF PORTLAND

The City of Portland sits at the confluence of the Willamette and Columbia rivers and occupies the western half of the Portland Basin and much of the adjacent Tualatin Mountains (Figures 2 and 3). The flat floor of the Portland Basin is punctuated by several small buttes and the Boring Hills, a complex region where small volcanic cones mix with blocks uplifted by faulting. The Tualatin Mountains, a straight and narrow range with a sharp, fault-bounded eastern edge, separate the Portland Basin from the Tualatin Basin to the west.

The Tualatin Basin is generally flat, with a few faulted and folded highs in the center of the basin.

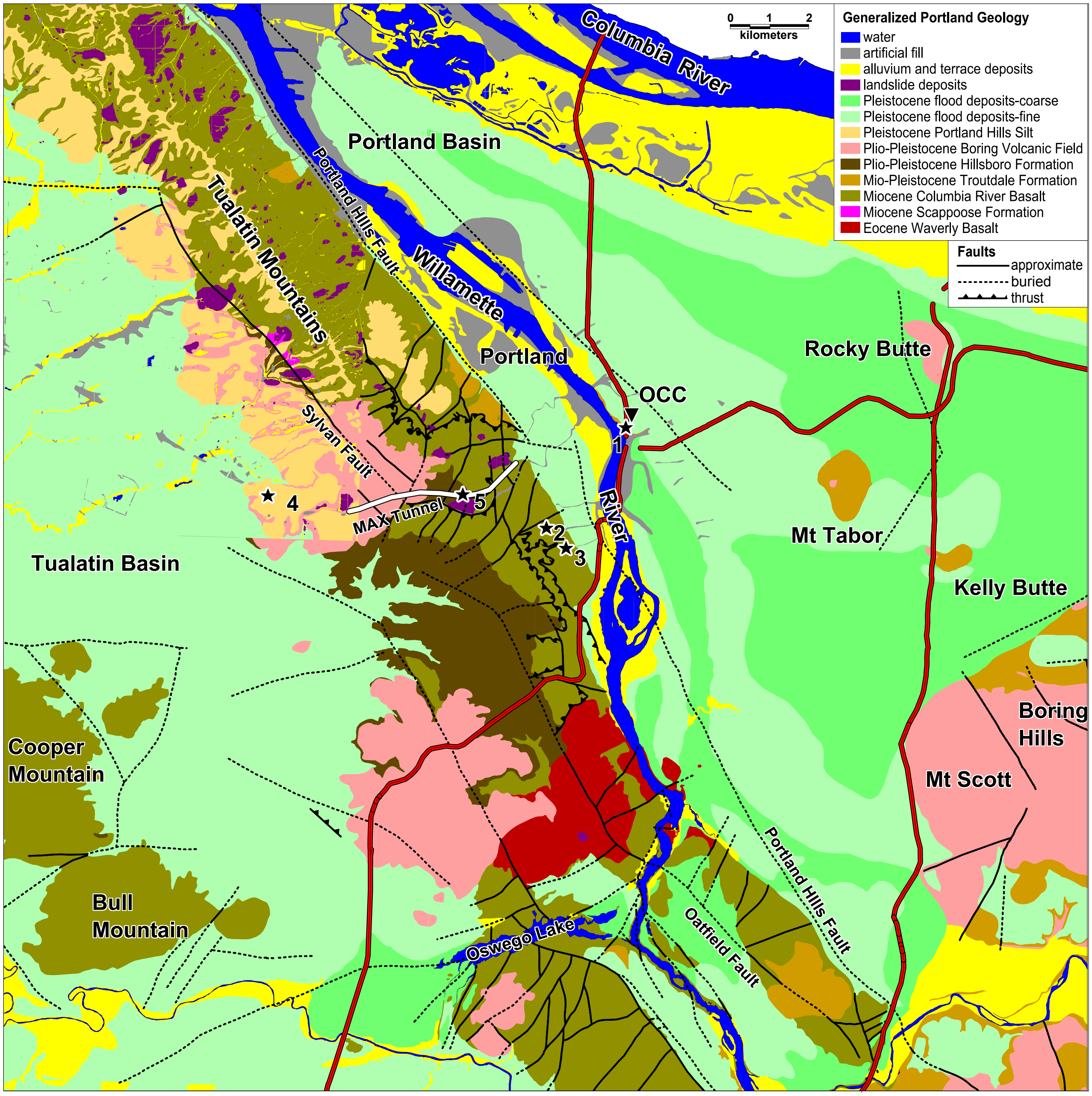

Figure 3. Generalized geologic map of Portland, Oregon. Map area is identical to Figure 2. Data from Oregon Geologic Data Compilation, release 5.

PORTLAND STRATIGRAPHY

- **Alluvium** — Holocene sand, silt, and gravel deposited in the channels and on the floodplains of the Columbia and Willamette rivers and their tributaries
- **Landslides**—Quaternary landslide deposits
- **Bretz/Missoula flood deposits** — Pleistocene (15–23 ka [thousands of years]) sand and silt (fine facies) and pebble to boulder gravel (coarse facies) deposits from repeated glacial outburst floods that originated in Montana
- **Portland Hills Silt** — Pleistocene loess deposited in the Tualatin Mountains (Portland Hills) during recent ice ages.
- **Boring volcanic field** — Pliocene to Pleistocene lava flows, tephra, and cinder cones produced by dozens of basalt to basaltic andesite eruptions
- **Hillsboro Formation** — Fine-grained fluvial sedimentary deposits of Coast Range provenance deposited in the Tualatin Basin
- **Troutdale Formatio**n — Fine- to coarse-grained fluvial sediments of Cascade Range and Columbia River provenance deposited in the Portland basin
- **Columbia River Basalt** — Miocene flood basalt flows that originated in western Idaho and eastern Oregon and Washington and entered the Portland Basin via an ancestral Columbia River channel (see Table 1, after References)
- **Scappoose Formation** — Miocene marine tuffaceous sandstone and siltstone
- **Basalt of Waverly Heights** — Eocene basalt flows associated with intense volcanism in the northwest Oregon Coast Range

The oldest rocks exposed in the Portland area are the basalt flows and interbedded marine sedimentary rocks of the Eocene Basalt of Waverly Heights. The age and chemistry of these poorly exposed rocks are similar to the Tillamook Volcanics of the northwest Oregon Coast Range that overlie the accreted Siletz terrane. This combination may explain why the crust beneath the Portland Basin is unusually strong, supporting crustal seismicity to depths of 20 km. The Basalt of Waverly Heights is locally overlain by very poorly exposed Scappoose Formation, which represents the easternmost edge of a thick wedge of marine sedimentary rocks that underlie much of the Oregon Coast Ranges. Both the Basalt of Waverly Heights and the Scappoose Formation are buried by voluminous flood basalt flows of the Columbia River Basalt Group (CRBG). These Miocene tholeiitic flood basalt and basaltic andesite flows were erupted from linear fissure systems in northeastern Oregon, eastern Washington, and western Idaho from ca. 17 to 6 million years ago.

Early flood basalt flows were diverted by a structural high where the Tualatin Mountains now stand, but eventually overtopped the high and spread to the southwest. Deformation continued after the flood basalt flows ended, and eventually the Portland and Tualatin Basins became separated.

The Portland Basin, traversed by the Columbia River, accumulated up to 500 m of Troutdale Formation fluvial mudstone, sandstone, and conglomerate. Some of the Troutdale Formation consists entirely of sediment brought in from the upper reaches of the Columbia; other parts are composed of sediment brought in by local streams draining the Cascade Range.

The Tualatin Basin meanwhile was filling with almost 300 m of Hillsboro Formation, fine-grained fluvial sediments derived from streams draining the Coast Range.

Starting about 3 million to 2.4 million years ago, small eruptions of olivine-rich basalt and basaltic andesite began to occur throughout the Portland Basin, forming the Boring volcanic field. Most of the eruptions produced small cinder cones and a few lava flows, although some produced small shield volcanoes, plugs, or flows that covered significant areas. The ages are distributed fairly evenly from the onset to the most recent, at about 120 ka.

Starting in the late Pleistocene, strong east winds through the Columbia River Gorge picked up glacial silt from the Columbia River floodplain and distributed it as loess across the Tualatin Mountains, forming the Portland Hills Silt. The Portland Hills Silt is up to 30 m thick. The presence of paleosols indicates that the silt accumulated during more than one glaciation.

Toward the end of the last ice age, the Portland Basin, Tualatin Basin, and Willamette Valley were swept by repeated colossal glacial outburst floods called Bretz, Missoula, or Ice Age Floods. These catastrophic events occurred between ca. 23–15 thousand years ago and dramatically reshaped the landscape of the Portland area.

The outburst floods ended while sea level was still at its glacial low stand, so the Columbia and Willamette rivers in the Portland Basin flowed through canyons graded to that lower sea level. During the Holocene sea level rise, the canyons rapidly filled with alluvium to their current level, and the water surface of the Columbia and lower Willamette River are just at sea level today. Despite being 175 km from the Pacific, the Portland harbor experiences small tides. Alluvium is as much as 70 m thick beneath the Portland airport. Deposits of ash from the ~7-ka eruption of Mt. Mazama in southern Oregon (Crater Lake) are typically found in the alluvium at a depth of about 17 m, giving an approximate rate of late Holocene alluvial sedimentation of 2.4 mm/yr.

Landslides, driven by the combination of heavy rainfall, steep slopes, and an abundance of weak deposits like the Portland Hills Silt, are abundant in the Portland area. Recent acquisition of high-resolution lidar over all of the Portland area has revolutionized the mapping of landslides of all scales, leading to the discovery of literally hundreds of previously unknown landslides. Large bedrock landslides are also common in the Tualatin Mountains, where Columbia River Basalt flows slide on sedimentary interbeds.

Unfortunately, good outcrops demonstrating Portland's dramatic geologic history close to public transportation routes are rare. Fortunately, outcrops of Columbia River Basalt, Troutdale Formation, Boring volcanic field flow and vents, Portland Hills Silt, and a small landslide do exist along the routes. Let's ride!

Stop 1. Bretz/Missoula floods and the Troutdale Formation

Exit the Oregon Convention Center through the Holladay Street lobby, turn left, and walk west on NE Holladay Street. Walk past the Rose Quarter Transit Center, then turn left and walk 60 m south along NE Wheeler Avenue to Interstate Avenue. Continue south along Interstate Avenue 70 m to NE Oregon Street (Figure 1-1). Cross Interstate Avenue and proceed about 50 m south to the bike path/walkway to your right. Walk over the bridge across the railroad tracks and down the ramp toward the Willamette River. Turn north toward the Steel Bridge at the bottom of the ramp and work your way down along the north side of the bridge to the river bank. Up to this point, everything under your feet has been deposits of sand and silt left by numerous successive Bretz/Missoula floods.

The Ice Age Floods National Geologic Trail, also known as the Ice Age Floods Trail, was designated in 2009 as the **first National Geologic Trail** in the United States. A network of marked routes in Montana, Idaho, Washington, and Oregon will connect interpretive facilities. Visitors on the trail will discover the dramatic consequences of the cataclysmic Bretz/Missoula floods.

Figure 1-1. Location map. White line with arrows shows route from convention center to Stop 1 (starred). Bus icon shows location of Rose Quarter Transit Center for travel to Stop 2.

As ice sheets repeatedly dammed off the Clark Fork of the Columbia River in Montana, the resulting lake rose high enough to float the ice and thus breach each ice dam. Huge amounts of water poured across eastern Washington (Figure 1-2), scouring away rock and sediment, then charged through the Columbia River Gorge. The floodwaters spread out into the Portland Basin, Tualatin Basin, and Willamette Valley but were still voluminous enough to inundate the area to an elevation of 115 m, putting most of Portland under 75 to 100 m of water. Thick accumulations of flood gravel were deposited in huge bars emanating from the gorge, and each flood left a distinctive layer of fine sand and silt in slackwater areas. Flood sediments are commonly 20 m thick and up to 60 m in filled scour pits around hills and buttes. Ice-rafted erratic blocks of exotic lithologies are found throughout the area. The most famous erratic is the 15.5-ton iron-nickel Willamette Meteorite, which landed near West Linn and is now in the American Museum of Natural History. The foundation excavation for the Oregon Convention Center provided excellent exposures of these deposits (Figure 1-3) which consist of weakly consolidated tan micaceous quartzo-

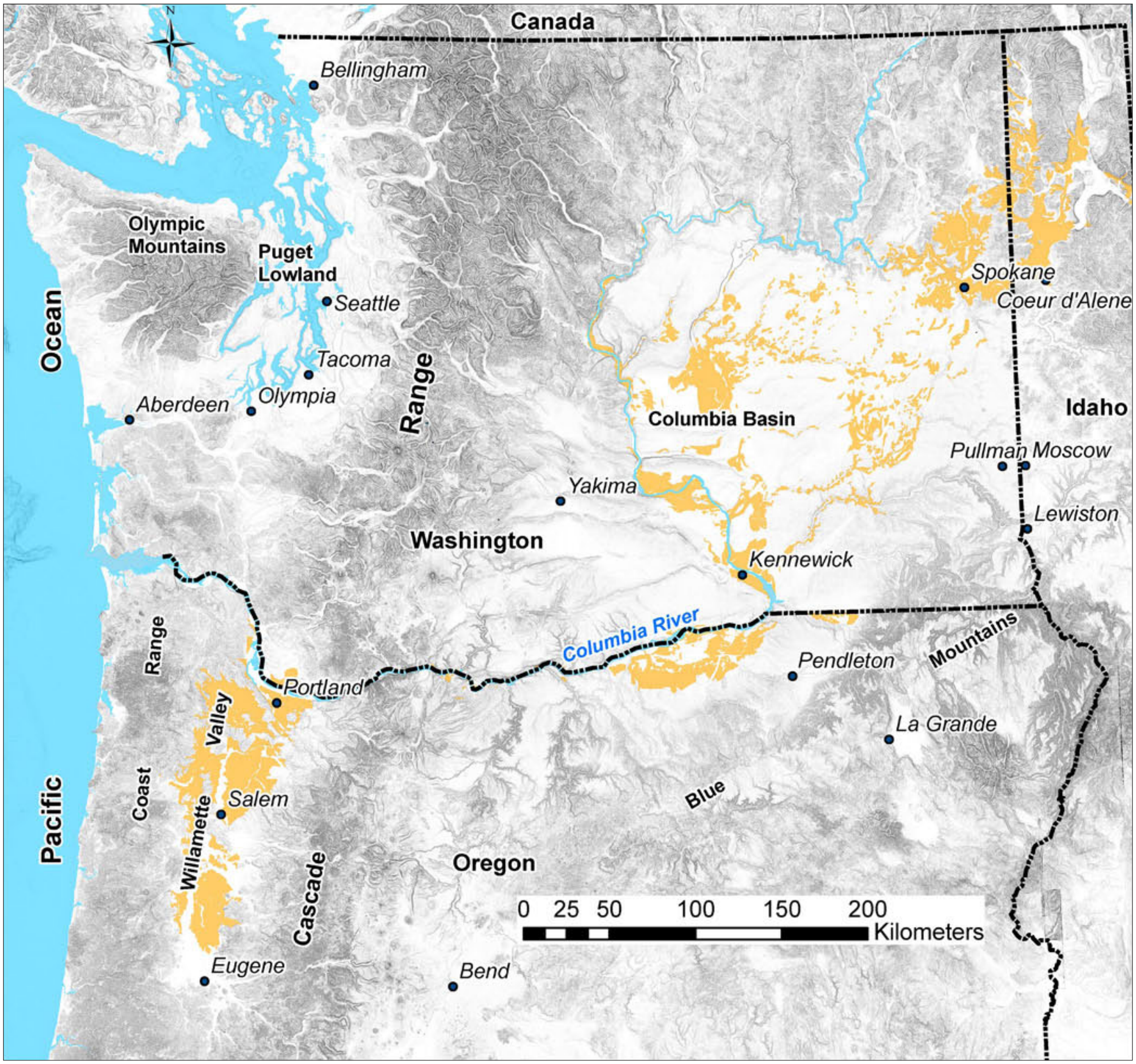

Figure 1-2. Mapped Bretz/Missoula flood deposits in the Pacific Northwest. Data from Oregon, Washington, and Idaho state digital geologic maps.

feldspathic silt and fine sand deposited in beds 10–100 cm thick. The beds are called rhythmites, and each was deposited by a single flood. Dozens of floods are responsible for the total 15–20 m thickness of the deposits. Accumulations of clay and iron oxides mark the tops of many rhythmites and are probably paleosols that developed during the longer intervals between floods. The shallow valley just south of the convention center is called Sullivan's Gulch. This valley can be traced east (Figure 2) to Rocky Butte, where it is apparent that it is a flood-related drainage channel connected to the flow around the butte. Between this site and Rocky Butte, numerous large-scale bar features are visible in the topography (Figure 2). These are sheets of coarse-grained flood gravel, left by successive floods. Note also the pronounced northwest-trending bar deposited in the lee of Rocky Butte. The flood waters reached an elevation of about 115 m above sea level, which means that water depth at this site would have been as much as 110 m. Similar deposits from the Tualatin Basin were recently dated by Ray Wells and Shannon Mahan of the U.S. Geological Survey (USGS) using optically stimulated luminescence (OSL) techniques. The ages are summarized in Table 1-1.

Table 1-1. Optically stimulated luminescence (OSL) ages for Bretz/Missoula deposits, Highway 26 at Bethany, courtesy of Shannon Mahan, USGS.

Sample	Location	Layer Sampled	Age, ka
RW05-0913-16:45	Hwy 26 (bottom)	rhythmite 7	21.6 ± 2.14
RW05-0913-17:05	Hwy 26 (middle)	rhythmite 12	19.7 ± 2.51
RW05-0913-17:20	Hwy 26 (top)	rhythmite 19	16.1 ± 1.28

Troutdale Formation conglomerate makes up the river bank at this location, forming a nearly vertical cliff above the water (Figure 1-4). Be careful! This is virtually the only shoreline of the Willamette River in the entire Portland area that is not armored with rip rap or seawall. Everywhere else, the river's original banks were cut into easily erodible Bretz/Missoula deposits or Holocene alluvium that required reinforcement.

The Troutdale Formation broadly includes all of the fluvial sedimentary rocks deposited in the Portland Basin after the last CRBG flows were emplaced. It includes conglomerate, sandstone, siltstone, and mudstone sourced from the Columbia River (exotic) and from rivers draining the west slope of the Cascades (Cascadian) and includes distinctive hyaloclastite

Figure 1-3. Fine-grained Bretz/Missoula flood deposits exposed in the foundation excavation of the Oregon Convention Center. Dark bands are damp paleosols mark the tops of some rhythmites.

Figure 1-4. Troutdale Formation conglomerate on the east bank of the Willamette River, just upstream of the Steel Bridge. The Marquam Bridge is visible in the background.

sandstone layers that formed when lava flows of the Cascade Range entered the Columbia River. The bulk of the formation is micaceous siltstone and mudstone (originally named the Sandy River mudstone). The next most common lithology is a distinctive conglomerate that is predominantly black CRBG clasts with a scattering of white and tan metamorphic quartzite, probably sourced out of Montana. The age of the unit ranges from middle Miocene where it rests on top of the CRBG, to Pliocene in the southeast margin of the Portland Basin, where it is incised by Pleistocene fans shed from the rivers draining the Cascade Range. The Troutdale Formation makes an excellent aquifer, serving as the backup water supply for the Portland Water Bureau. The CRBG and quartzite conglomerate is a fine source of aggregate where it is at mineable depths. The Troutdale conglomerate is the bearing layer that supports most big buildings in downtown Portland.

As luck would have it, the outcrop here is rather unusual. It is composed of cobble conglomerate with a micaceous sand matrix and clasts that are almost entirely exotic, including metamorphic quartzite, granitoids, and distinctive felsic porphyritic volcanic rocks from the Challis Volcanics of central Idaho. There is very little CRBG in the mix. This raises the question of how all of these exotic clasts managed to traverse the more than 200 km of CRBG that lies upstream of this site without entraining any CRBG material?

The Willamette River stretches almost 300 km from this point to its headwaters near Odell Lake in the Cascade Range. The river drains an area of 28,700 km^2. Typical October flows are 15,000 cubic feet per second (cfs), while peak winter flows in January are about 70,000 cfs. The elevation at this site is approximately 5.5 m, which is flood stage for the Willamette. The most recent significant flood here was in 1996; the river peaked at 8.5 m.

The walkway south from here is the Eastbank Esplanade, which extends a few kilometers south along the river. You can make a nice round trip walk by crossing the river at the Hawthorne Bridge and returning via the Portland waterfront to the Steel Bridge to complete the circuit.

Stop 2. Columbia River Basalt, Portland Hills Silt, and landslides

From Stop 1, retrace your steps to arrive at the Rose Quarter Transit Center (Figure 1-1). Take the #8 bus toward Downtown/Jackson Park, and continue through downtown to the SW Terwilliger and Sam Jackson stop (#5804; see Figure 2-1), a journey of about 25–35 minutes. From the bus stop cross Sam Jackson Parkway to the North, and walk about 150 m west to the two large water tanks, Stop 2 is the cliff exposure behind the tanks.

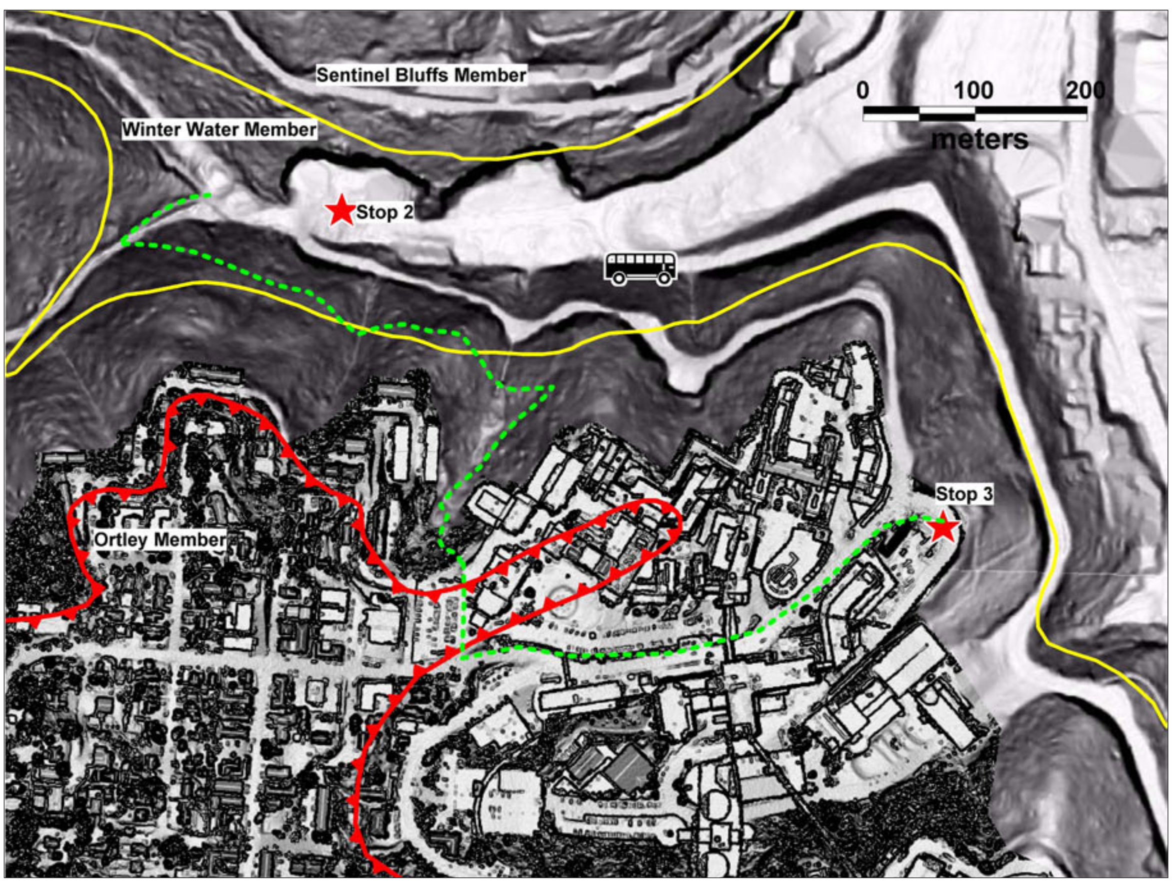

Figure 2-1, Locations for Stops 2 and 3 (starred). Short dashed line (green) is route from Stop 2 to Stop 3; solid lines (yellow) are geologic contacts; toothed line (red) is thrust fault. Composite bare-earth and highest-hit lidar slope map as base. Bus icon denotes Sam Jackson Parkway bus stop (#5804).

The CRBG consists of hundreds of stacked lava flows erupted over the span of almost 10 million years (see Table 1, after References). By far the largest flows (composing the great majority of the volume of the group) were those of the Grande Ronde and Wanapum basalts, both of which are represented in Portland with a collective thickness of about 210 m. Many individual flows are known to be huge, covering thousands to tens of thousands of square kilometers in area, with volumes up to thousands of cubic kilometers (Figure 2-2). From their vents near the Oregon-Idaho-Washington border, the flows entered western Oregon via a wide gap in the Miocene Cascade Range. Some flows reached the Pacific Ocean where they burrowed into soft sediments on the continental shelf and formed huge complexes of sills and dikes.

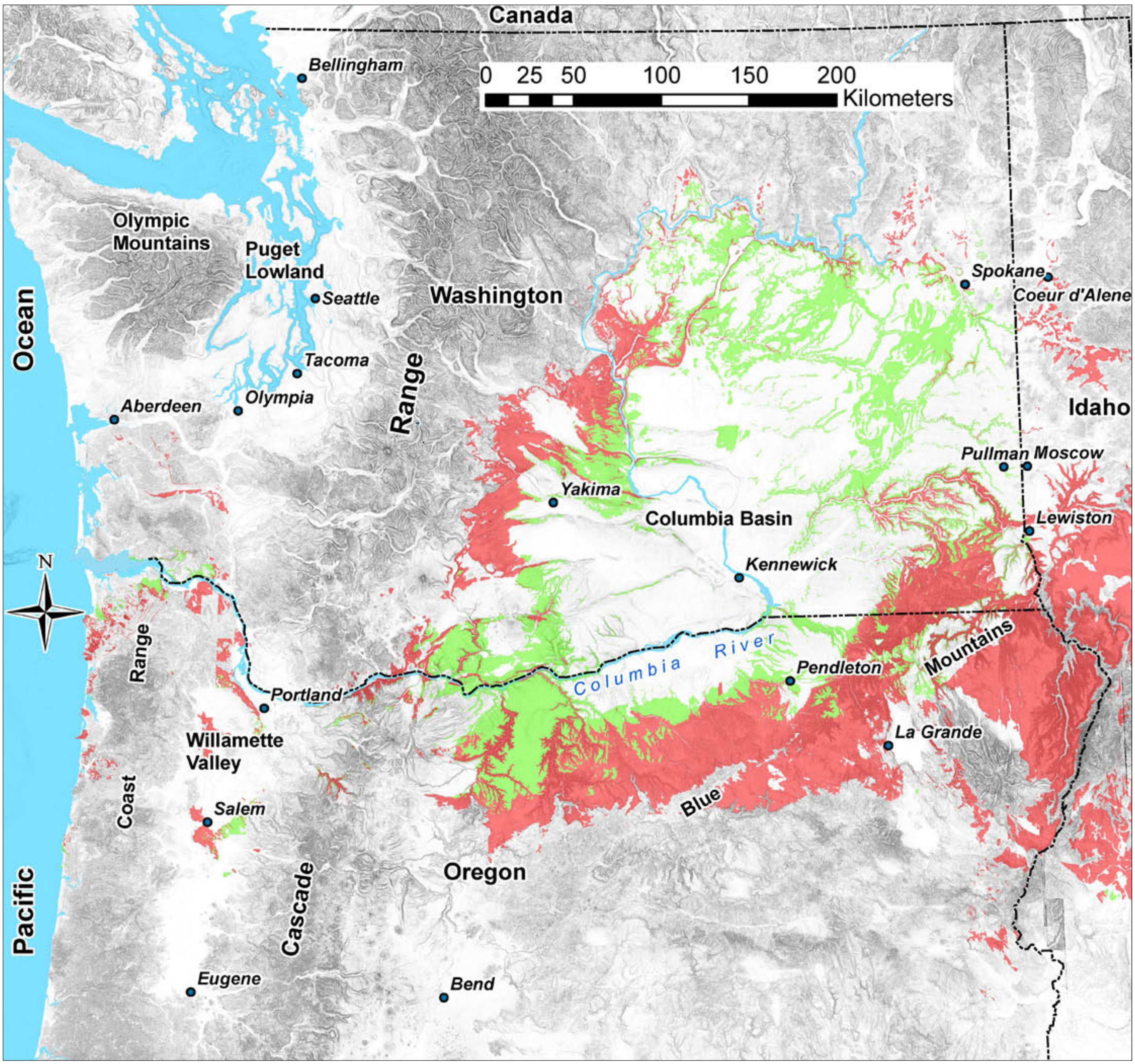

Figure 2-2. Mapped distribution of the Wanapum (green) and Grande Ronde (pink) formations of the Columbia River Basalt Group. Many individual flows span much of the mapped range. Data from Oregon, Washington, and Idaho state digital geologic maps.

This excavated cliff exposes the upper portion of a lava flow belonging to the Winter Water Member of the Grande Ronde Basalt (Figure 2-3). This is a fairly typical outcrop appearance for Grande Ronde flows, which generally have coarse columnar jointed bases overlain by a more complexly jointed entablature zone capped by a rubbly flow top a few meters thick. The contact with the overlying Sentinel Bluffs Member of the Grande Ronde Basalt may be visible depending on the level of vegetative cover.

In hand specimen the Winter Water basalt is atypical in that it has visible phenocrysts of plagioclase up to a few mm long, in contrast to most Grande Ronde flows, which are aphyric. This makes the Winter Water fairly easy to distinguish in the field if enough rock is exposed. With most other Grande Ronde flows, a combination of geochemistry and paleomagnetic direction are needed to differentiate the stratigraphic unit. Even this can be a challenge due to the chemical similarity of many of the flows, as shown in Table 2-1. For example, the only consistent difference between the Winter Water Member (Tgww) and the underlying Ortley Member (Tgo) is in the TiO_2 content. The difficulty in distinguishing the various flows, coupled with poor exposure and severe weathering (which throws the subtle chemical distinctions out the window) makes mapping the CRBG in the Portland area a real challenge.

The chemistry in Table 2-1 also reveals a little secret about the Grande Ronde Basalt, which is that most of it is compositionally basaltic andesite (SiO_2 > 52%) rather than basalt. As the Grande Ronde Formation makes up 85% of the total CRBG volume, the name "Columbia River Basalt Group" is a bit of a misnomer.

From Stop 2, it is a 20-minute hike on a good trail to the Oregon Health and Science University (OHSU) tram terminal (if you prefer not to hike on this maintained trail, get back on the bus and proceed to the OHSU Hospital stop #5028). Walk 100 m west into the parking lot at the hairpin turn in Sam Jackson Parkway and take the trail that leaves the parking lot toward the south, following the signs to OHSU. After a few tens of me-

Figure 2-3. Grande Ronde Basalt (Winter Water Member) at Stop 2. The image spans about 10 m.

Table 2-1. Example Columbia River Basalt x-ray fluorescence whole-rock and trace element geochemistry.

Unit	SiO_2N	TiO_2N	Al_2O_3N	FeOT	MnON	MgON	CaON	Na_2ON	K_2ON	P_2O_5N
Tgww	56.26	2.14	13.72	11.58	0.19	3.26	6.88	3.22	1.83	0.38
Tgo	56.14	1.96	13.99	11.53	0.19	3.56	7.13	3.09	1.74	0.33
Unit	**LOI**	**Rb**	**Sr**	**Y**	**Zr**	**V**	**Ni**	**Cr**	**Nb**	**Ga**
Tgww	0.44	55.5	329	40.8	209	323	9	19.0	14.8	25.2
Tgo	0.40	53.8	335	38.6	184	293	12	17.0	14.4	24.1
Unit	**Cu**	**Zn**	**Co**	**Ba**	**La**	**Ce**	**U**	**Th**	**Sc**	**Pb**
Tgww	13	152	42	656	19	56	0.9	5.1	31	9
Tgo	29	144	44	646	22	52	1.2	7.1	31	8

N, normalized values. Tgww is the Winter Water Member of the Grande Ronde Basalt. Tgo is the Ortley Member of the Grande Ronde Basalt. TiO_2 values are highlighted because this oxide is one of the few distinguishing geochemical markers between the two units.

ters following a fire road along the small valley bottom, the trail turns left up the slope. Weathered Columbia River Basalt peeks out along the uphill side of the trail at first, but as you climb you will start to see light tan micaceous silt in the slope above the trail. This is Portland Hills Silt, a blanket of loess dating from the last continental glaciation (and previous glaciations) that covers much of the Tualatin Mountains to a depth of 10–30 m. Recent OSL dating of the loess by Ray Wells and Shannon Mahan of the USGS (Table 2-2) has provided some constraints on the age of the silt.

Table 2-2. Optically stimulated luminescence (OSL) ages for Portland Hills Silt, courtesy of Shannon Mahan, USGS.

Sample	Location	Depth	Age, ka
RW05-0913-12:15	Beaverton/ Portland Hills	1 m below surface	47.0 ± 6.29
RW05-0913-14:00	Cornelius Pass	2 m below surface	38.7 ± 3.01
RW05-0913-14:30	Cornelius Pass	5.3 m below surface	>79

You will cross a small bridge, then the trail doubles back and continues to climb before reaching a second bridge at the head of a little hollow between apartment buildings to the west and a hospital building to the east. Note the small landslide (Figure 2-4) directly above the bridge. The Tualatin Mountains are plagued with landslides of all sizes and types, as steep slopes, heavy rainfall, and susceptible geology collide. The Portland Hills Silt loses most of its strength when saturated and is notorious for failing in shallow slumps and earthflows.

At the head of the trail proceed south along SW 9th Avenue. Where the trail meets the road, you are crossing the trace of a thrust fault (Figure 2-1) that places the Ortley Member over the Sentinel Bluffs Member. This is one of several thrust faults mapped in the Tualatin Mountains in the Portland area. The fault is probably Miocene in age.

Turn left when you reach Sam Jackson Parkway (the sign may say Gibbs, but it will change shortly). Cross the road beneath the sky bridge, then turn left again and follow the signs for the OHSU tram. You will pass through part of the hospital complex (coffee alert!) and emerge onto the upper platform of the tram, which is Stop 3.

Figure 2-4. Small landslide in Portland Hills Silt along the trail below OHSU. The slide spans about 8 m.

Stop 3. Panorama of Portland Basin, Boring and High Cascades volcanoes, and Willamette River alluvium

In addition to being a fun ride, the tram offers a marvelous panorama from the platform. Figure 3-1 (opposite page) provides an annotated panoramic photo. In the foreground you see the Willamette River and Ross Island. Ross Island is a deposit of Holocene alluvial gravel, originally 40 m thick. The deposit has been mined for years as a source of aggregate; all that remains is a narrow perimeter strip. The debate continues about whether and how to fill the hole as mining winds down and reclamation begins.

The foundation excavations for the lower terminal of the tram exposed Holocene Willamette River sand and clay alluvium overlying Bretz/Missoula sand deposits. The alluvium was carbon-14 dated at 3,512 ± 36 years before present (ybp) by Jim O'Connor of the USGS. The cable stays for the tram are anchored by piles augered into the Troutdale Formation conglomerate beneath the Bretz/Missoula deposits.

In the near distance are several buttes and hills that are either faulted and folded highs of Troutdale Formation, Boring volcanic field volcanoes, or a bit of both. Rocky Butte is a dramatic Boring plug that rises over 100 m above the surrounding Bretz/Missoula deposits and may have barely stood above the water at the peak of the great floods. It has been dated at 125 ± 40 ka by Russ Evarts and Bob Fleck of the USGS. Mt. Tabor is a Troutdale Formation structural high, with a small Boring cinder cone at its north end, which the USGS team has dated at 203 ± 5 ka. Kelly Butte is another Troutdale Formation high, with a thin, undated Boring lava flow draped over its western end. Powell Butte is a fault-bounded Troutdale Formation structural high with an undated Boring lava flow draped over its northern flank. Mt. Scott is a 280-m-high Boring volcano dated at ca. 1.6 Ma that still retains its summit crater (Figure 3-2).

On the skyline, young stratovolcanoes of the High Cascade Range are visible, including Mt. St. Helens in Washington, which erupted spectacularly in May 1980 and just recently finished another multiple-year lava extrusion episode. At 3,911 m, Mt. Hood is Oregon's highest peak and had its most recent eruptions in the 1790s, just before the arrival of explorers Lewis and Clark. Bells Mountain and Silver Star Mountain in Washington are Oligocene to Miocene remnants of the early Tertiary Cascade Arc. The active volcanoes of the High Cascades are built on a platform of these older volcanic and intrusive rocks.

In the foreground the Portland Hills Fault, one of the major tectonic elements of the Portland area, crosses the scene from northwest to southeast, crossing the Willamette River just under Ross Island. Although the fault is buried in this view, it forms the markedly sharp and straight northeast front of the Tualatin Mountains farther north (Figures 2 and 3).

From Stop 3, board the tram for the ride down to the Willamette River floodplain. Upon exiting the tram, board the Portland streetcar heading toward downtown.

The streetcar stop is at the bottom of the tramway. Take the streetcar to the Central Library stop and walk one block north on 10th Street to reach the Galleria/SW 10th Street MAX stop (coffee alert). Board any westbound MAX train; get off at the Sunset Transit Center station for Stop 4.

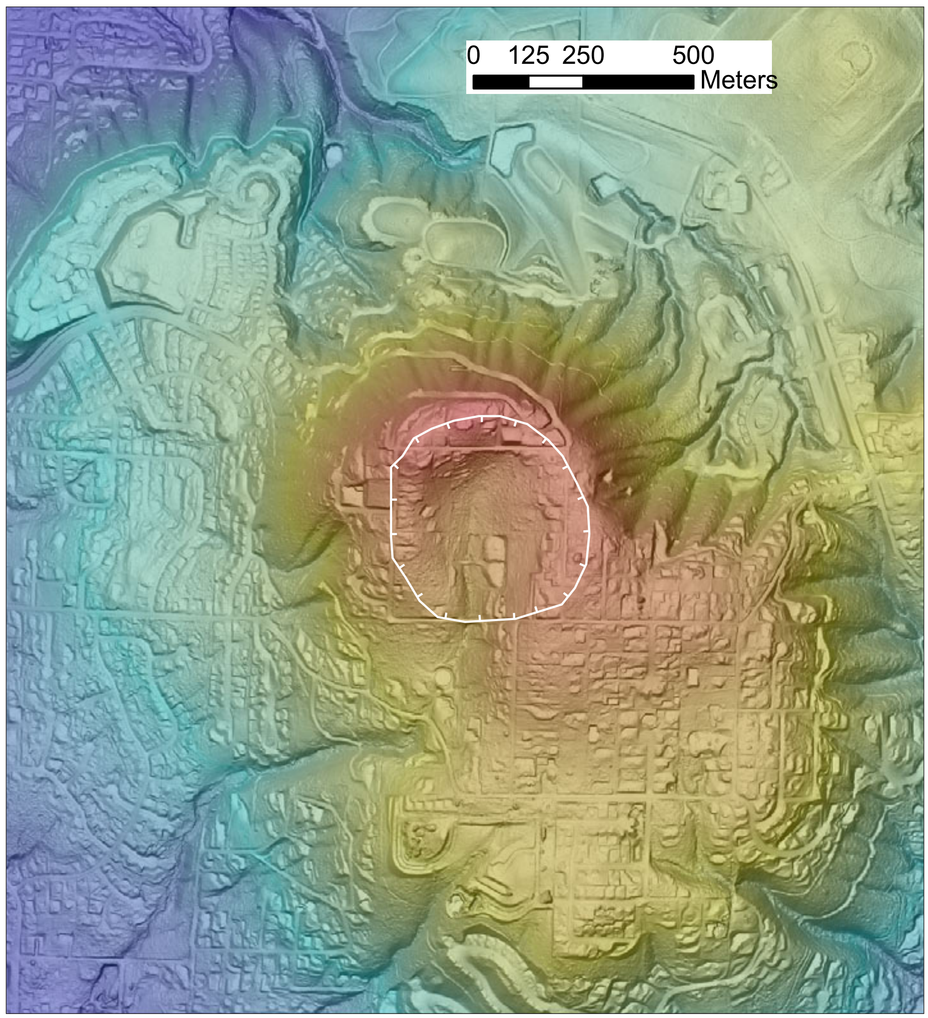

Figure 3-2. Lidar slopeshade image of Mt. Scott, showing the 500-m-wide central crater of this 1.6-Ma Boring volcanic field vent, now covered with subdivisions.

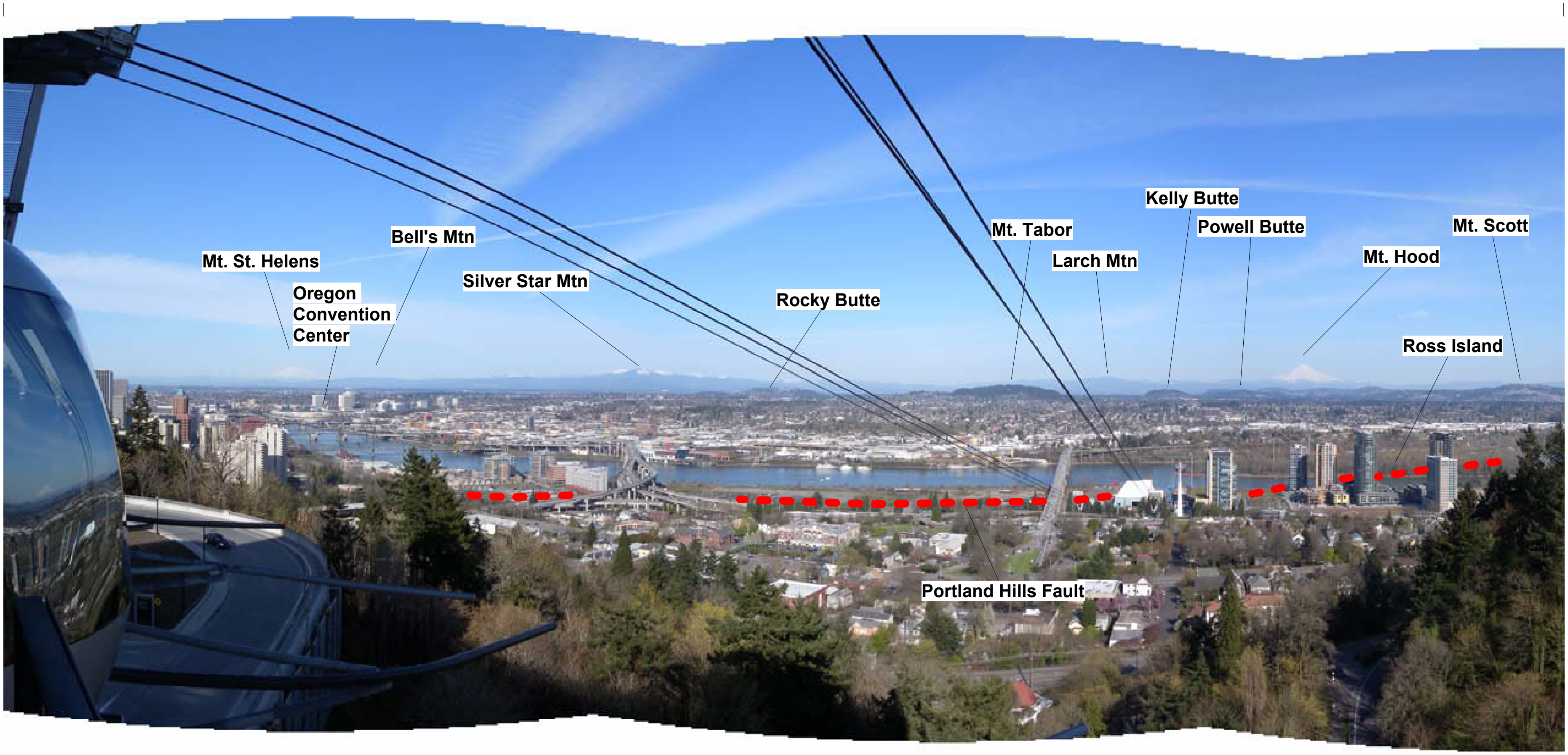

Figure 3-1. Panorama from Oregon Health and Sciences University tram terminal, Stop 3. Features include:

- **Mt. St. Helens (Washington), a Cascade stratovolcano, major eruptions began 1980**
- **Bell's Mountain (Washington), an Oligocene basalt and basaltic andesite**
- **Silver Star Mountain, (Washington), a Miocene grandodiorite**
- **Rocky Butte, a, Boring volcanic field plug 125 ± 40 ka**
- **Mt. Tabor, Troutdale Formation with small Boring volcanic field cinder cone at north end, 203 ± 5 ka**
- **Larch Mountain, a Boring volcanic field volcano, 1,430 ± 30 ka**
- **Kelly Butte, Troutdale Formation with Boring volcanic field flow**
- **Powell Butte, folded and faulted Troutdale Formation**
- **Mt. Hood, a Cascade stratovolcano and the highest point in Oregon (3,429 m; 11,249 ft) last eruption circa 1790**
- **Ross Island, Holocene gravel alluvium in the Willamette River**
- **Mt. Scott, Boring volcanic field volcano, 1.6 Ma**

On an exceptionally clear day, Mt. Adams another Cascade stratovolcano (Washington) may be visible between Mt. St. Helens and Silver Star Mountain. The Portland Hills Fault in the foreground is buried, but 10 km southeast from here trenching and geophysics show that it deforms Bretz/Missoula deposits.

Stop 4. Boring volcanic field flow and vents

Exit the MAX platform and follow the sidewalk around the north side of the parking structure (coffee alert) (Figure 4-1) down the entrance road for the Transit Center to Barnes Road.

Cross the entrance road at Barnes and proceed a few hundred meters west down the sidewalk on the south side of Barnes Road. The road cut here is a fairly good exposure of a Boring volcanic field lava flow (Figure 4-2). This particular flow is part of the informal basaltic andesite of Barnes Road (unit Qbab in Figure 4-1). The lava flow is massive, with crude polygonal joints and some rubbly zones. In hand specimen it is a diktytaxitic, fine- to medium-grained rock with abundant iddingsitized olivine phenocrysts 1 to 2 mm long. This exposure is quite typical of Boring volcanic field lava flows, except that it is fairly fresh. Boring lavas weather rapidly in the wet climate of the Portland area — rocks that are more than a million years old are commonly profoundly weathered to depths of several meters. The lava at this site is the youngest in the area, with a radiometric age of 105 ± 6 ka obtained by Russ Evarts and Bob Fleck of the USGS. This flow may have originated from a vent marked by a broad circular depression several thousand meters east of the stop, or from one of the loess-mantled cones visible farther east (Figure 4-1). Engineering borings for the hospital complex to the east encountered numerous voids in the lava, which are interpreted as lava tubes. The front of the flow is clearly visible in the topography southwest of the stop (Figure 4-1).

The slopes across the creek to the north of the stop are underlain by unit Qbae, the informal basaltic andesite of Elk Point. These lava flows are believed to have erupted from vents that include the two distinct cones located in the northeast of Figure 4-1, although thick loess mantles the cones and no Boring lava or tephra has been observed there. The basaltic andesite of Elk Point has reported radiometric ages of 120 ± 15 ka, 260 ± 110 ka, 860 ± 40 ka, and 1,221 ± 110 ka.

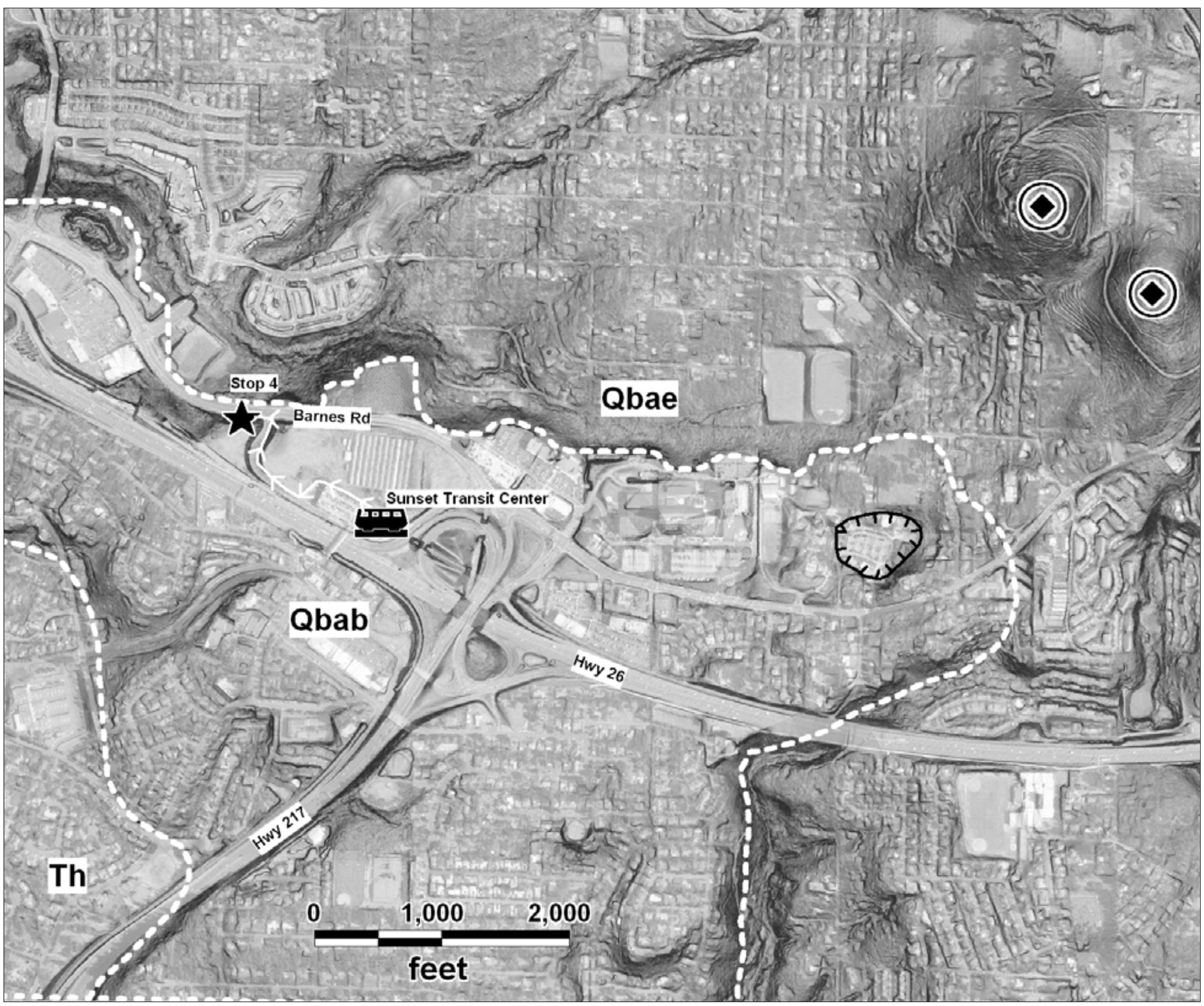

Figure 4-1. Stop 4 location (starred) and geologic map (from Madin and others, 2008). White dashed lines are bedrock geology contacts. Hachured polygon is inferred basaltic andesite of Barnes Road (Qbab) vent. Circled diamond symbols mark inferred basaltic andesite of Elk Point (Qbae) vents. Train icon marks the Sunset Transit Center.

The two units can be readily distinguished by their geochemistry, with marked differences in TiO_2, MgO, and P_2O_5, as shown in Table 4-1.

This site is very near the high water mark of the Bretz/Missoula floods. Slopes uphill from here are mantled with loess, and downhill with flood silt. The Boring lava flow at this site overlies fluvial mudstone and siltstone of the Hillsboro Formation. The Hillsboro Formation fills the Tualatin Basin to the west and is Pliocene to Pleistocene in age and derived from rivers draining the Coast Range.

Return to the Sunset MAX station and board any eastbound train. Get off at the Washington Park/Zoo station for Stop 5.

Figure 4-2. Boring lava flow near Sunset Transit Center. The outcrop is about 8 m high.

Table 4-1. Boring lava x-ray fluorescence whole-rock and trace element geochemistry.

Unit	SiO_2N	TiO_2N	Al_2O_3N	FeOT	MnON	MgON	CaON	Na_2ON	K_2ON	P_2O_5N
Qbae	53.97	1.34	17.73	8.09	0.13	5.95	7.92	3.73	0.80	0.34
Qbab	54.15	1.43	17.25	8.40	0.14	5.20	7.74	3.68	1.11	0.40
Unit	**Rb**	**Sr**	**Y**	**Zr**	**V**	**Ni**	**Cr**	**Nb**	**Ga**	**Cu**
Qbae	7	770	19	149	142	115	166	11.3	23	49
Qbab	10.2	1000	20	180	165	91	114	10.8	22	57
Unit	**Zn**	**Co**	**Ba**	**La**	**Ce**	**U**	**Th**	**Sc**	**Pb**	
Qbae	92	0	324	24	28	—	1	23	3	
Qbab	95	32	495	18	52	<0.5	1.5	20	6	

N, normalized values. Qbae is basaltic andesite of Elk Point. Qbab is basaltic andesite of Barnes Road.

Stop 5. Portland Hills structure, Zoo station core hole

The 3-mile-long Robertson MAX tunnel through the Tualatin Mountains was constructed between 1993 and 1998. The western third was excavated by drilling and blasting, the eastern portion with a tunnel boring machine. The difference in construction techniques was due to the variable geology encountered along the way. The tunnel boring machine had particular trouble and was plagued with geology-related delays in its first years of operation. Thus it is fitting that the public art in the Washington Park/Zoo station includes a beautifully displayed core (Figure 5-1) from one of the many geotechnical borings made along the tunnel route. This is in fact the most accessible and complete “exposure” of Portland geology in existence, so take a moment to walk along the core as it traverses Columbia River Basalt, Boring Lava, and loess. The station is located 80 m below ground surface, and is the deepest train station in North America. Unfortunately, the entire tunnel is lined with concrete, so there is nothing to see out the light rail car windows! If you have a moment to ride the elevators to the surface, you will note that instead of floors, the display reads in geologic time. Beautiful landscaping with columns of Columbia River Basalt surrounds the surface entrance to the station.

One of the construction workers on the tunnel project was a Portland State University geology student named Ken Walsh, who made a detailed map of the tunnel. Tragically, Ken and his thesis adviser, Marvin Beeson, both died before publishing the tunnel map. Ray Wells of the USGS received the data from Ken’s family and has assembled it into a summary poster, which he has kindly allowed to be excerpted here (Figure 5-2).

Proceeding from the west portal (Figure 5-2) the first 1,200 m of the tunnel traverse Boring volcanic field lava flows interlayered with cinders, breccia, and loess, which required that this part of tunnel be blasted. The lavas range in age from 120 to 1,470 ka and are offset by several strands of the Sylvan fault. The second strand in from the west is quite dramatic, as it thrusts Columbia River Basalt flows over Boring lavas about 1 million years old.

The Sylvan fault together with the Oatfield fault (Figure 3) are part of a northwest-trending northeast-side-up, right-lateral fault zone that extends 15 km northwest of the tunnel and 25 km southeast. The fault is clearly Quaternary in age, since there is substantial deformation of the young Boring lava flows. There is, however, no visible surface expression of the fault, even in high-resolution lidar imagery. Perhaps this is because the fault is buried by loess over much of its extent.

Leaving the Boring lava behind, the tunnel proceeds downsection to the east, entering the Columbia River Basalt right at a minor fault. The tunnel proceeds rapidly down through a tilted section of the Wanapum Basalt (basalt of Gingko, Frenchman Springs Member) and the Sentinel Bluffs and

Figure 5-1. Core display in Washington Park/Zoo MAX station, the most complete "exposure " of Portland area geology.

Winter Water Members of the Grande Ronde Basalt before encountering a thrust fault. The tunnel then follows along near the bottom of the Sentinel Bluffs Member as far as the Washington Park/Zoo station. East of the station the tunnel again descends in to the Winter Water Member, encountering the Sentinel Bluffs Member just before the east portal.

The tunnel map captures nearly the entire structure of the Tualatin Mountains (commonly referred to as the Portland Hills), which are a prominent geomorphic feature clearly visible in Figure 2 (and even at the regional scale in Figure 1). The tunnel map shows that the mountains are a broad gentle anticline, which has accommodated compression both by folding and thrusting. The anticline is bounded by high-angle fault zones, including the Sylvan-Oatfield fault zone to the west and the Portland Hills fault zone just east of the tunnel. The Portland Hills fault zone is a significant potential threat to Portland, as zone is directly beneath downtown. However, there is no clear surface trace of the fault, and no evidence has been found for Holocene deformation near Portland. Some 15 km southeast of Portland, the Portland Hills Fault appears to fold Bretz/Missoula deposits, indicating at least one event in the late Pleistocene or Holocene. There is still great uncertainty in the amount of seismic risk posed to Portland by the Portland Hills Fault and other local faults. Far more is known about the greater risks posed by subduction megathrust earthquakes on the Cascadia Subduction Zone, the most recent of which was an event of estimated magnitude 9 in January 1700. The potential rupture zone for future Cascadia megathrust earthquakes may only be 100 km west of downtown Portland.

Board any eastbound train to complete your journey back to the Oregon Convention Center. You will cross the Portland Hills Fault near the Goose Hollow Station. From there to back to the Convention Center, you will traverse highly urbanized Bretz/Missoula flood deposits and alluvium of the Willamette River. You may spot the Troutdale Formation at Stop 1 from the window of the train as you cross the Steel Bridge if you are sitting on the right-hand side.

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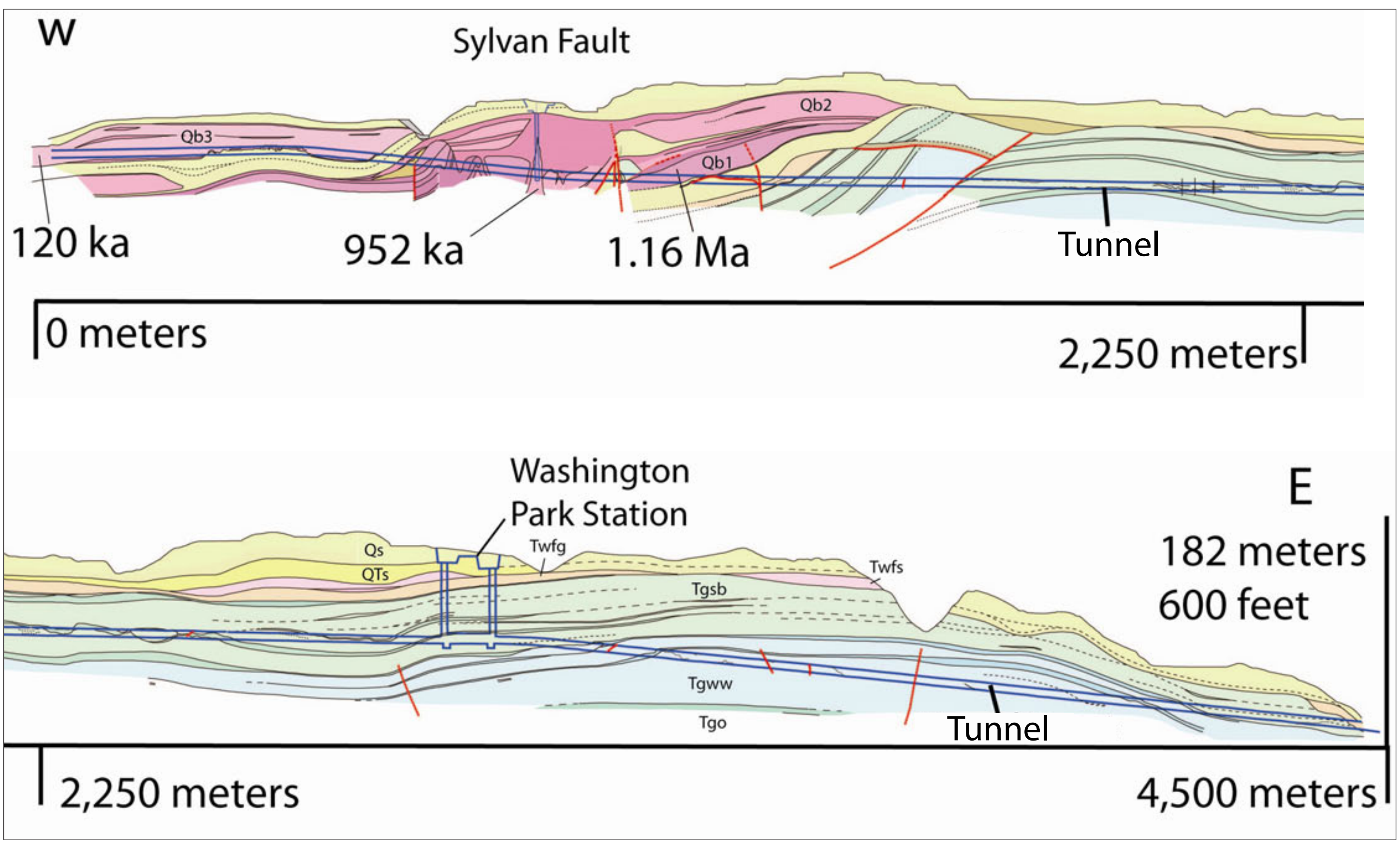

Figure 5-2. Simplified version of the geologic section through the Tualatin Mountains along the MAX light rail tunnel. Qb1, Qb2, and Qb3 are Pleistocene Boring Volcanic Field lavas and tephra. Qs is Pleistocene loess. QTs is Pliocene or early Pleistocene loess. Twfg is basalt of Ginkgo, Frenchman Springs Member, Wanapum Basalt. Twfs is basalt of Sand Hollow, Frenchman Springs Member, Wanapum Basalt. Tgsb is Sentinel Bluffs Member, Grande Ronde Basalt. Tgww is Winter Water Member; Grande Ronde Basalt. Tgo is Ortley Member, Grande Ronde Basalt. Figure courtesy of Russ Evarts, USGS. (Also see Table 1, after References.)

REFERENCES

Allen, J. E., Burns, M., and Sargent, S. C., 1986, Cataclysms on the Columbia: Portland, Oregon, Timber Press, 211 p.

Beeson, M. H., and Moran, M. R., 1979, Columbia River Basalt Group stratigraphy in western Oregon: Oregon Geology, vol. 41, no. 1, p. 11–14.

Beeson, M. H., and Tolan, T. L., 1990, The Columbia River Basalt Group in the Cascade Range: a middle Miocene reference datum for structural analysis: Journal of Geophysical Research, vol. 95, no. B12, p. 19,547–19,559.

Beeson, M. H., Perttu, R., and Perttu, J., 1979, The origin of the Miocene basalts of coastal Oregon and Washington: An alternative hypothesis: Oregon Geology, vol. 41, no. 10, p. 159–166.

Beeson, M. H., Perttu, R., and Perttu, J., 1979, The origin of the Miocene basalts of coastal Oregon and Washington: An alternative hypothesis: Oregon Geology, vol. 41, no. 10, p. 159–166.

Beeson, M. H., Fecht, K. R., Reidel, S. P., and Tolan, T. L., 1985, Regional correlations within the Frenchman Springs Member of the Columbia River Basalt Group: new insights into the middle Miocene tectonics of northwestern Oregon: Oregon Geology, vol. 47, no. 88, p. 87–96.

Beeson, M. H., Tolan, T. L., and Anderson, J. L., 1989, The Columbia River Basalt Group in western Oregon — geologic structures and other factors that controlled flow emplacement patterns, in Reidel, S. P., and Hooper, P. R., eds., Volcanism and tectonism in the Columbia River flood-basalt province: Geological Society of America Special Paper 239, p. 223–246.

Beeson, M. H., Tolan, T. L., and Madin, I. P., 1989, Geologic map of the Lake Oswego quadrangle, Clackamas, Multnomah and Washington counties, Oregon: Oregon Department of Geology and Mineral Industries Geologic Map Series, GMS-59, scale 1:24,000.

Beeson, M. H., Tolan, T. L., and Madin, I. P., 1991, Geologic map of the Portland Quadrangle, Multnomah and Washington Counties, Oregon: Oregon Department of Geology and Mineral Industries Geologic Map Series, GMS-75, scale 1:24,000.

Benito, G., and O'Connor, J. E., 2003, Number and size of last-glacial Missoula floods in the Columbia River valley between the Pasco Basin, Washington, and Portland, Oregon: GSA Bulletin, vol. 115, no. 5, p. 624–638.

Blakely, R. J., Wells, R. E., Yelin, T. S., Madin, I. P., and Beeson, M. H., 1995, Tectonic Setting of the Portland-Vancouver area, Oregon and Washington: Constraints from low altitude aeromagnetic data: GSA Bulletin, vol. 107, no. 9, p. 1051–1062.

Blakely, R. J., Beeson, M. H., Cruikshank, K., Wells, R. E., Johnson, A., and Walsh, K., 2004, Gravity study through the Tualatin Mountains, Oregon: Understanding crustal structure and earthquake hazards in the Portland urban area: Bulletin of the Seismological Society of America, vol. 94, no. 4, p. 1402–1409.

Bretz, J. H., Smith, H. T. U., and Neff, G. E., 1956, Channeled scabland of Washington: New data and interpretations: Geological Society of America Bulletin, vol. 67, no. 8, p. 957–1049.

Burns, W. J., 2007, Comparison of remote sensing datasets for the establishment of a landslide mapping protocol in Oregon, AEG Special Publication 23: Vail, Colo., AEG Conference Presentations, 1st North American Landslide Conference.

Conrey, R. M., Uto, K., Uchiumi, S., Beeson, M. H., Madin, I. P., Tolan, T. L., and Swanson, D. A., 1996, Potassium-argon ages of Boring Lava, northwest Oregon and southwest Washington: Isochron West, no. 63. p. 3–9.

Evarts, R. C., O'Connor J. E., Wells, R. E., and Madin, I. P., 2009, The Portland basin: A (big) river runs through it: GSA Today, vol. 19, no. 9, p. 4–10.

Fleck, R. J., Evarts, R. C., Hagstrum, J. T., and Valentine, M. J., 2002, The Boring Volcanic Field of the Portland, Oregon area — geochronology and neotectonic significance: Geological Society of America Abstracts with Program, vol. 33, no. 5, p. 33–34.

Hooper, P.R., 1982, The Columbia River basalts: Science, vol. 215, no. 4539, p. 1463–1468.

Lentz, R. T., 1981, The petrology and stratigraphy of the Portland Hills Silt — a Pacific Northwest loess: Oregon Geology, vol. 43, no. 1, p. 3–10.

Liberty, L. M., Hemphill-Haley, M. A., and Madin, I. P., 2003, The Portland Hills Fault: uncovering buried faults in Portland, Oregon using near-surface geophysical methods: Tectonophysics, vol. 368, p. 89–103.

Madin, I. P., 1994, Geologic map of the Damascus quadrangle, Clackamas and Multnomah counties, Oregon: Oregon Department of Geology and Mineral Industries Geologic Map Series GMS-60, 9 p., scale 1:24,000.

Madin, I. P., 2004, Geologic mapping and database for Portland area fault studies: final technical report: Oregon Department of Geology and Mineral Industries Open-File Report O-04-02, 18 p.

Madin, I. P., Ma, L., and Niewendorp, C. A., 2008, Preliminary geologic map of the Linton 7.5′ quadrangle, Multnomah and Washington counties, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report, O-08-06, 35 p., scale 1:24,000.

Ma, L., Madin, I. P., Olson, K. V., Watzig, R. J., Wells, R. E., Niem, A. R., and Priest, G. R. (compilers), Oregon Geologic Data Compilation, release 5 ((OGDC-5; statewide); Oregon Department of Geology and Mineral Industries Digital Data Series.

Mundorff, M. J., 1964, Geology and ground-water conditions of Clark County, Washington, with a description of a major alluvial aquifer along the Columbia River: U.S. Geological Survey Water-Supply Paper 1600, 269 p., 3 pl.

Schlicker, H. G., and Deacon, R. J., 1967, Engineering geology of the Tualatin Valley region, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 60, 103 p., 4 pls.

Swanson, D. A., Wright, T. L., Hooper, P. R., and Bentley, R. D., 1979, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geological Survey Bulletin 1457-G, 59 p.

Tolan, T. L., Reidel, S. P., Beeson, M. H., Anderson, J. L., Fecht, K. R., and Swanson, D. A., 1989, Revisions to the areal extent and volume of the Columbia River Basalt Group, in Reidel, S. P., and Hooper, P. R., eds., Volcanism and tectonism in the Columbia River flood-basalt Province: Geological Society of America Special Paper 239, p. 1–20.

Treasher, R. C., 1942, Geologic history of the Portland area: Oregon Department of Geology and Mineral Industries Short Paper 7, 17 p., 1 pl.

Trimble, D. E., 1963, Geology of Portland, Oregon, and adjacent areas: U.S. Geological Survey Bulletin 1119, 119 p.

Waitt, R. B., Jr., 1985, Case for periodic colossal jokulhaups from Pleistocene glacial Lake Missoula: Geological Society of America Bulletin, vol. 96, p. 1271–1286.

Wells, R., Walsh, K., Beeson, M., Blakely, R., Fleck, R., and Duvall, A., in press, A tunnel runs through it — an inside look at Oregon's Portland Hills and its faults: U.S. Geological Survey Open-File Report.

Wilson, D. C. 1998, Post Middle Miocene geologic evolution of the Tualatin Basin, Oregon: Oregon Geology, vol. 60, no. 5, p. 99–116.

Series		Group	Formation	Member	Isotopic Age (m. y.)	Magnetic Polarity
Miocene	Upper	Columbia River Basalt Group	Saddle Mountains Basalt	**Lower Monumental Member**	6	N
				Ice Harbor Member	8.5	
				Basalt of Goose Island		N
				Basalt of Martindale		R
				Basalt of Basin City		N
				Buford Member		R
	Middle			**Elephant Mountain Member**	10.5	R,T
				Pomona Member	12	R
				Esquatzel Member		N
				Weissnefels Ridge Member		
				Basalt of Slippery Rock		N
				Basalt of Tenmile Creek		N
				Basalt of Lewiston Orchards		N
				Basalt of Cloverland		N
				Asotin Member	13	
				Basalt of Huntzinger		N
				Wilber Creek Member		
				Basalt of Lapwai		N
				Basalt of Wahluke		N
				Umatilla Member	13.5	N
				Basalt of Sillusi		N
				Basalt of Umatilla Member		N
			Wanapum Basalt	**Priest Rapids Member**	14.5	
				Basalt of Lolo		R
				Basalt of Rosalia		R
				Roza Member		T,R
				Shumaker Creek Member		N
				Frenchman Springs Member		
				Basalt of Lyons Ferry		N
				Basalt of Sentinel Gap		N
				Basalt of Sand Hollow	15.3	N
				Basalt of Silver Falls		N,E
				Basalt of Ginkgo		E
				Basalt of Palouse Falls		E
				Eckler Mountain Member		
				Basalt of Dodge		N
				Basalt of Robinette Mountain		N
				Vantage Horizon		
			Grande Ronde Basalt	Member of Sentinel Bluffs	15.6	N_2
				Member of Slack Canyon		
				Member of Field Springs		
				Member of Winter Water		
	Lower		Grande Ronde Basalt (Prineville Basalt)	Member of Umtanum		
				Member of Ortley		
				Member of Armstrong Canyon		
				Member of Meyer Ridge		R_2
				Member of Grouse Creek		
				Member of Wapshilla Ridge		
				Member of Mt. Horrible		
			Grande Ronde Basalt (Picture Gorge Basalt)	Member of China Creek		N_1
				Member of Downey Gulch		
				Member of Center Creek		R_1
				Member of Rogersburg		
				Member of Teepee Butte		
				Member of Buckhorn Springs	16.5	
			Imnaha Basalt			R_1
						T
						N_0
					17.5	R_0

Table 1. Columbia River Basalt Group stratigraphic nomenclature chart from "Columbia River Basalt Stratigraphy in the Pacific Northwest." (http://or.water.usgs.gov/proj/crbg/stratigraphy.html)