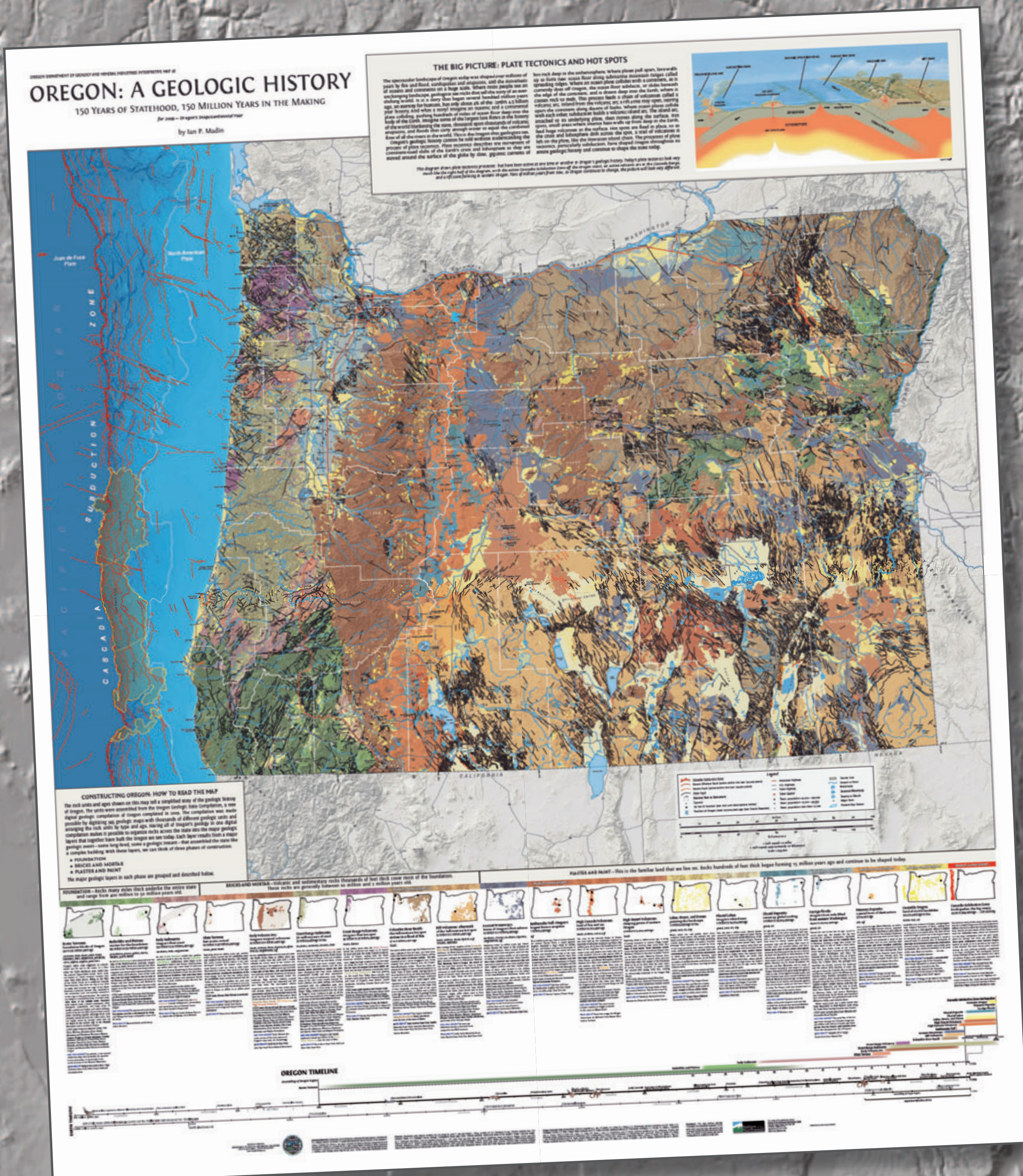
OREGON GEOLOGY

OREGON DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES VOLUME 69, NUMBER 1, FALL 2009



A new geologic map for Oregon's sesquicentennial year. See page 62.

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From the State Geologist

—Vicki S. McConnell

Welcome to the first *Oregon Geology* published since 2007. At that time we felt we could keep to an annual schedule for producing *Oregon Geology* but that has proven to not be so. Part of the reason we did not publish in 2008 was the lack of submitted articles by the geologic community. So I am sending out the plea to all of you here in Oregon — send us your geology, paleontology, geography, geophysics, and geochemistry articles!! *Oregon Geology* has always been considered a valuable teaching tool and source of reliable information about the geology of the Northwest so let's keep up the tradition. We are counting on you. (See page 94 for contributor info.)

We have made many changes at DOGAMI in the last two years. I want to take a moment to tell you about our changes and our new directions and assure you that we remain committed to producing the best relevant geologic information possible. The downturn in the economy has hit Oregon hard and has affected state agencies. Our funding structure and business model continues to evolve to be more and more "payment for services contracts" rather than long-term state-funded programs. This means that we offer services that our local and federal partners need and expect while satisfying our statutory mandates and strategic plans. You can view our 2009–2015 Strategic Plan on the website.

Unfortunately, we have had to downsize our field offices to save money and to keep our staff. The Grants Pass field office is closed, and the Baker City field office is relocating to the Baker County Court House. We have also moved the Nature of the Northwest Information Center from the first floor to the ninth floor of the Portland State Office Building.

I am pleased and proud to announce we have completed the initial Oregon Geologic Data Compilation (OGDC-5). This was a six-year, multi-staff project to compile in digital format the geologic data for the state. Now we begin the work of developing derivative maps and information such as a new Oregon State Geologic Map (IMS-28). An interactive geologic map based on OGDC is available from our website. The digital data GIS product and the wall map are available for purchase through the Nature of the Northwest. Visit our website to view a variety of other interactive maps.

Two other programs keeping the geologic survey staff busy are the Oregon Lidar Consortium and the FEMA Coos County Multi-hazards Mapping Program. Both programs underscore the many uses of digital elevation data that can now be collected via lidar (light detection and ranging) technology. In the Mineral Regulation and Reclamation Program renewable energy in the form of geothermal resource development has taken off in the state. We are hopeful that the first geothermal energy production will occur within the next two years.

All things change; we are working to change for the better.

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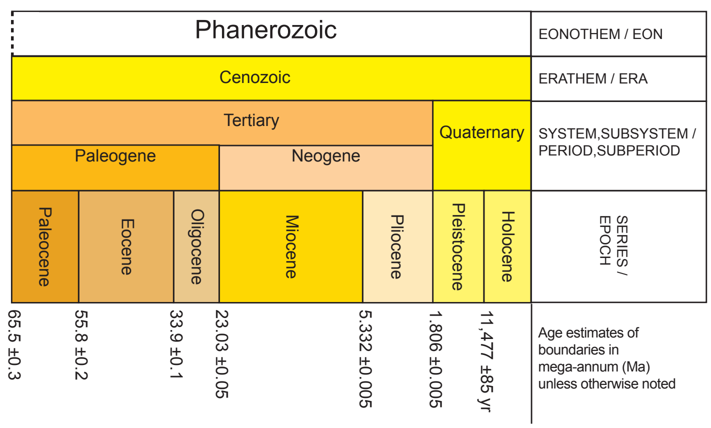
Cover: "Oregon: A Geologic History," DOGAMI Interpretive Map 28 by Ian P. Madin. 50- by 58-inch full-color wall poster. See page 93 to order.

Field trip guides to the geology of the northern half of Lower Crooked Basin, Crook, Deschutes, and Jefferson Counties, Oregon — Overview

The north half of the of the Lower Crooked Basin resides at the intersection of the High Lava Plains and Blue Mountains physiographic provinces and encompasses approximately 2,338 km^2 (903 mi^2) of the Crooked River drainage in central Oregon (Overview Figure 2). This part of the basin extends from Ochoco Divide on the east to Redmond on the west and from Prineville Reservoir on the south to Lake Billy Chinook on the north (see Overview Figure 2). The area is drained by the northwest-flowing Crooked River and its major tributaries: McKay Creek, Mill Creek, Marks Creek, and Ochoco Creek. Topographic relief in the north half of the basin ranges from 1,779 m (5841 ft) along Ochoco Divide on the northeast to 610 m (2,000 ft) at Lake Billy Chinook in the northwest corner of the basin. The city of Prineville, which encompasses a population of greater than 10,000 people within its urban growth boundary lies near the geographic center of the basin.

The Lower Crooked Basin has been the locus of episodic volcanic eruptions for much of the past 45 million years (see Overview Figure 1), including the formation of two large-scale rhyolite calderas during the Paleogene and eruption of numerous lavas from local small vents during the Neogene. Four distinct geologic domains composed of volcanic and sedimentary rocks spanning most of the Cenozoic Era are preserved within the north half of the of the Lower Crooked Basin. The Ochoco Mountains, which form the upland topography of the eastern half of the basin, are composed of Eocene andesite and dacite domes and flows and silicic volcanic and intrusive rocks that are part of the Clarno Formation. These rocks make part of the Ochoco volcanic field, which culminated with the eruption of the Tuff of Steins Pillar and formation of the Wildcat Mountain caldera around 40 Ma. The topographically low western part of the basin is underlain by Oligocene basalt lavas, rhyolite domes, and rhyolite ash-flow tuff that make up the Lower Crooked volcanic field and that are correlative with the John Day Formation. The main vent feature of the Lower Crooked volcanic field is the large Crooked River caldera, which erupted the voluminous Tuff of Smith Rock at 29.56 Ma. Paleogene rocks in the west part of the basin are overlain by a cover of middle Miocene, Pliocene, and Quaternary basalt lavas and interbedded sedimentary rocks. These units include the Simtustus Formation, Prineville Basalt, Deschutes Formation, and basalts erupted from Newberry Volcano.

The following three field trip guides summarize geologic mapping in the Lower Crooked Basin that was partially funded by the U.S. Geological Survey National Cooperative Geologic Mapping program during 2005 and 2006. The field trips are organized chronologically, beginning with guides to two previously unrecognized Paleogene calderas and ending with a guide to overlying Neogene basalt stratigraphy exposed along the meandering course of the Wild and Scenic Crooked River south of Prineville.

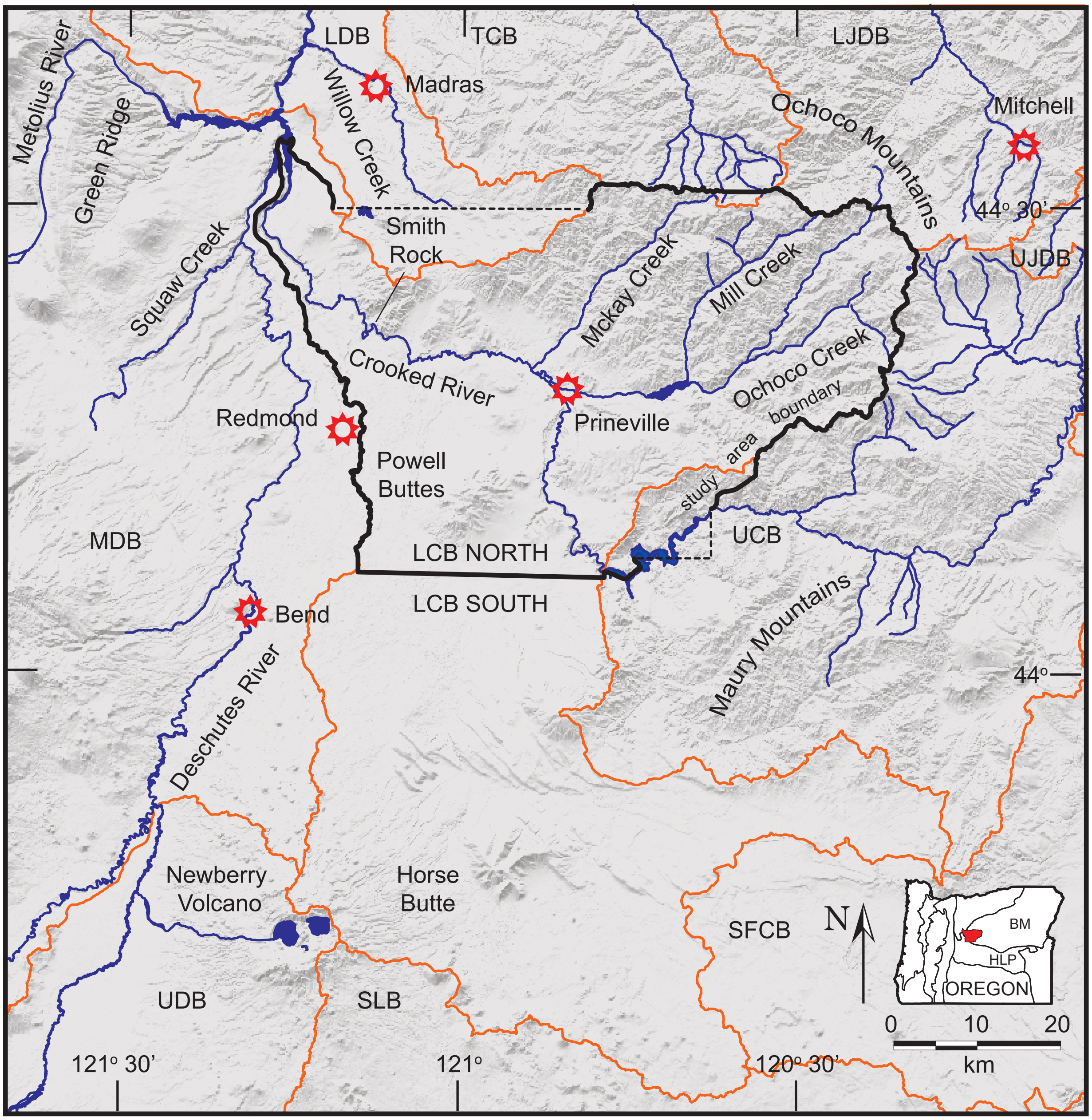


Overview Figure 1. Portion of geologic time chart (from U.S. Geological Survey, 2007) pertaining to Lower Crooked River trip guides in this issue.

CENTRAL OREGON FIELD TRIP GUIDES DEDICATION

This series of Lower Crooked Basin field trip guides is dedicated to Larry A. Chitwood (1942–2008), Deschutes National Forest Geologist, whose tremendous spirit and joy of learning, intellectual breadth, and love of geology inspired us all.

—Jason D. McClaughry, Caroline L. Gordon, and Mark L. Ferns



Overview Figure 2. Location of the north half of the Lower Crooked Basin in the state of Oregon (LCB north). Solid black line is the boundary of the geologic map compiled by Oregon Department of Geology and Mineral Industries in the Prineville area. The mapped region corresponds to the watershed hydrologic boundary of the LCB north; dashed black line indicates where the watershed boundary has been modified to incorporate relevant 1:24,000 scale geologic mapping. Orange lines demarcate the boundaries of hydrologic basins adjacent to the LCB north. South half of the Lower Crooked Basin (LCB south); Upper Crooked Basin (UCB); South Fork of the Crooked Basin (SFCB); Summer Lake Basin (SLB); Upper Deschutes Basin (UDB); Middle Deschutes Basin (MDB); Lower Deschutes Basin (LDB); Trout Basin (TB); Lower John Day Basin (LJDB); Upper John Day Basin (UJDB). Base is shaded relief 30-m DEM. Inset figure of Oregon shows physiographic provinces: BM, Blue Mountains; HLP, High Lava Plains.

Field trip guide to the middle Eocene Wildcat Mountain Caldera, Ochoco National Forest, Crook County, Oregon

by Jason D. McClaughry[1], Caroline L. Gordon[2], and Mark L. Ferns[1]

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Overview: This field trip examines the stratigraphy of the middle Eocene Wildcat Mountain caldera exposed east of Prineville, in the Ochoco Mountains of north-central Oregon. Geologic factors that control landslide deposits and mineralization in the east part of the Lower Crooked Basin are discussed. This field trip is 152.7 km (94.9 mi).

INTRODUCTION

The Wildcat Mountain caldera, in the eastern part of the Lower Crooked Basin, is a volcanic vent complex that collapsed and filled with more than 90 km^3 (21.5 mi^3) of rhyolitic ash-flow tuff during the middle Eocene. It is one of only a few caldera sources for Paleogene ash-flow tuff sheets identified in Oregon and is the first recognized to be Eocene (Figure 1) (Hladky and Wiley, 1993; Hladky, 1996; Ferns and others, 2001; McClaughry and Ferns, 2007). Until recently, the lack of Paleogene calderas in Oregon was a noteworthy anomaly considering that numerous Paleogene calderas have been mapped elsewhere in the western United States. Several Paleogene calderas have been identified in adjacent Idaho (McIntyre and others, 1982; Leonard and Marvin, 1982; Moye and others, 1988), and many more have been identified farther south in volcanic fields of the Great Basin (Steven and Lipman, 1976; Ludington and others, 1996). The Wildcat Mountain caldera is part of a broad sweep of voluminous ash-flow tuff magmatism, between ca. 41 and 25 Ma, preserved in volcanic and intrusive rocks distributed across the axis of the Blue Mountains in central and eastern Oregon (Walker and Robinson, 1990; Robinson and others, 1990), the West Cascades in southwest Oregon (Retallack and others, 2004), at Hart Mountain in south-central Oregon (Mathis, 1993) (Figure 1), and near Potlatch in northern Idaho (Kauffman and others, 2003). Regionally, these igneous rocks may represent a northward extension of the contemporaneous (ca. 43 and 23 Ma) "ignimbrite flare-up" in the Great Basin (Stewart and Carlson, 1976; Best and others, 1989; Christiansen and Yeats, 1992; Ludington and others, 1996; Honn and Smith, 2007). In central and eastern Oregon this magmatic episode is recorded in the Eocene Clarno and middle Eocene to early Miocene John Day Formations, which cover more than 30,000 km^2 (11,600 mi^2) (Figure 1; Swanson, 1969; Robinson, 1975; Robinson and others, 1984, 1990; Smith and others, 1998).

Rocks of the middle Eocene Wildcat Mountain caldera record the onset of widespread Paleogene ash-flow tuff eruptions in north-central Oregon and overlap the regional transition from dominantly calc-alkaline magmatism that characterizes the Clarno Formation to the bimodal basalt and rhyolite volcanic assemblage associated with the John Day Formation. Investigators in central and eastern Oregon have long speculated on the sources of widespread tuffs that characterize the John Day Formation (Robinson and others, 1984, 1990), but only recent geologic mapping has revealed the locations of corresponding

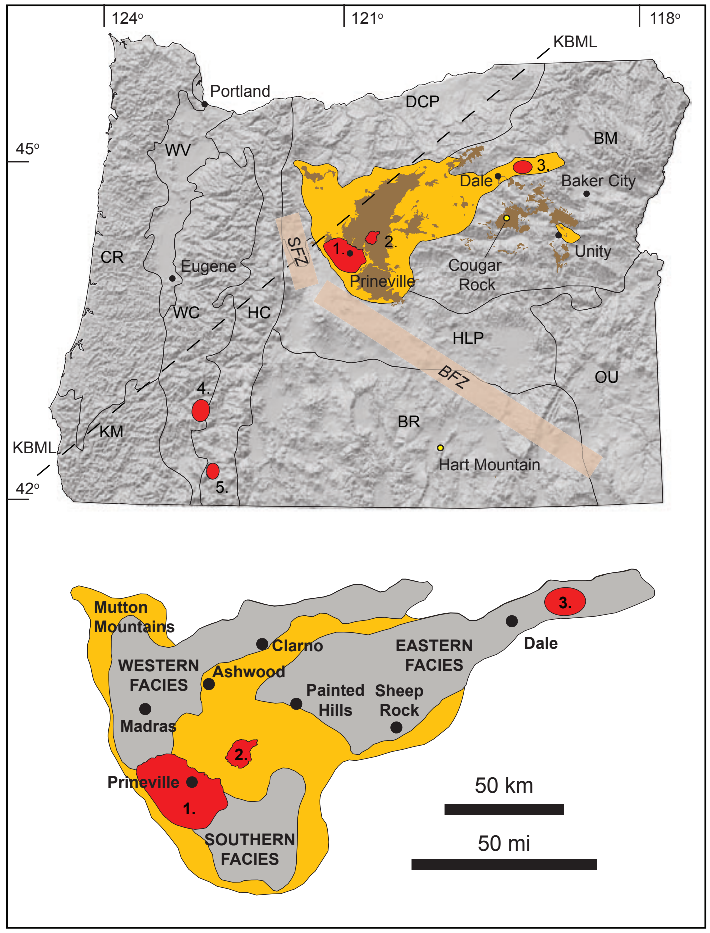

Figure 1. (top) Location of known Paleogene calderas in Oregon. Red-filled polygons are calderas: 1, Crooked River caldera; 2, Wildcat Mountain caldera; 3, Tower Mountain caldera; 4 and 5, unnamed, suggested calderas. Locations of known Paleogene volcanic centers at Cougar Rock and Hart Mountain are shown for reference. Orange shade represents approximate distribution of ash-flow tuffs in the late Eocene to Oligocene John Day Formation. Brown polygons show the distribution of the Eocene Clarno Formation. Dashed black line labeled KBML is the inferred trace of the Klamath-Blue Mountain gravity-anomaly lineament. SFZ, Sisters Fault Zone; BFZ, Brothers Fault Zone. Solid black lines demarcate physiographic provinces (after Walker, 1977): WV, Willamette Valley; CR, Coast Range; KM, Klamath Mountains; WC, West Cascades; HC, High Cascades; DCP, Deschutes Columbia Plateau; BM, Blue Mountains; HLP, High Lava Plains; BR, Basin and Range; OU, Owyhee Uplands. (bottom) Enlarged central part of area shown in top figure with the distribution of the "western," "southern," and "eastern" facies after Robinson and others (1990) within the John Day Formation. Some geographic points are shown for reference.

vents. Regional workers have suggested that pyroclastic rocks within the John Day Formation were vented from now-buried eruptive centers in or marginal to a nascent Cascade Range. These presumed buried sources were used to build a tectonic model in which John Day volcanism documented a westward jump of a subduction zone at the end of "Clarno arc" volcanism (Coleman, 1949; Robinson and others, 1984, 1990; White and Robinson, 1992; Bestland and others, 1999). The location of the Wildcat Mountain caldera well east of the previously postulated source area documents a much more regionally extensive magmatic episode not related to a largely inferred ancestral Cascade Range.

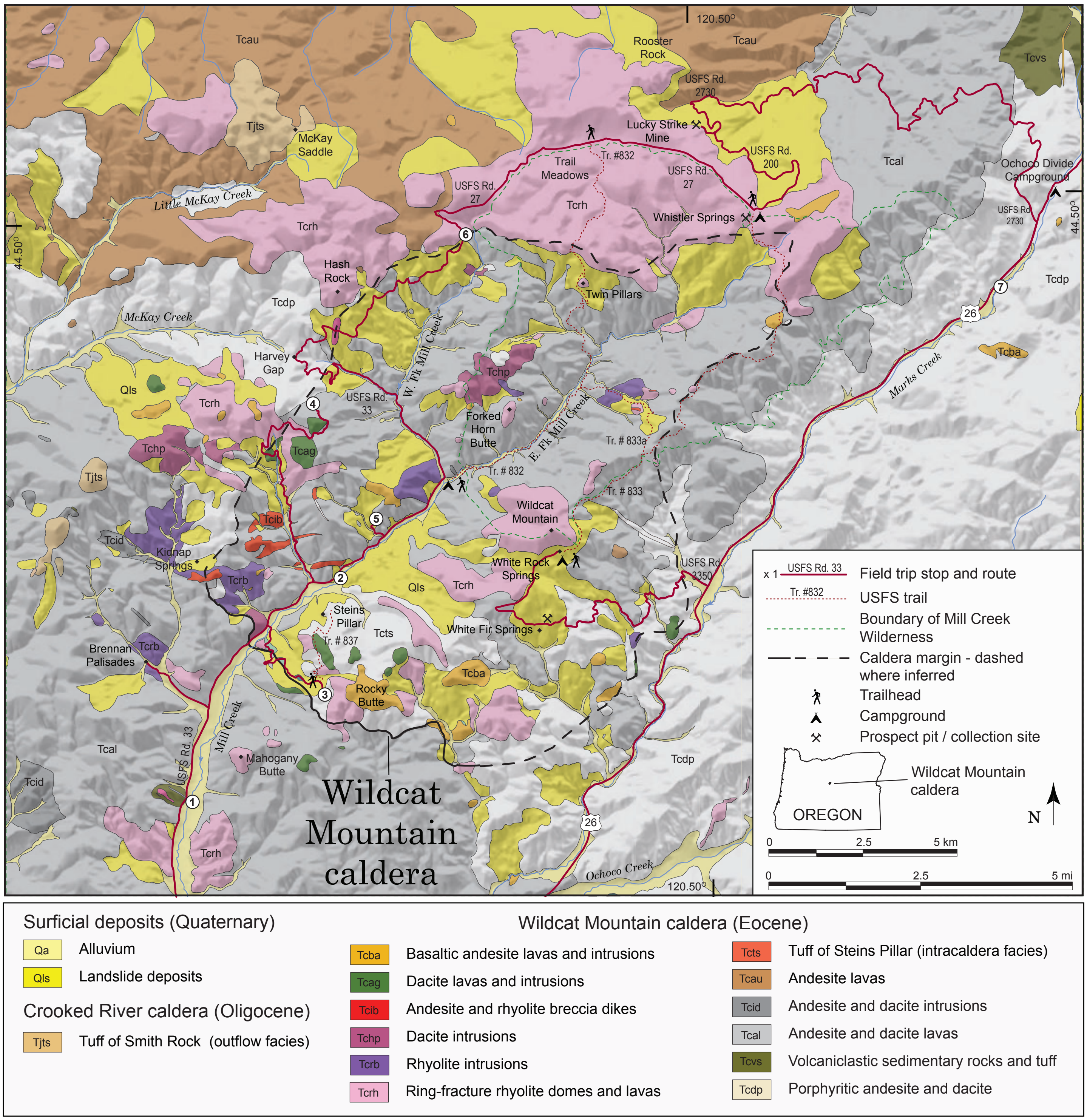

Figure 2. Geologic map of the Wildcat Mountain caldera and vicinity labeled with field trip route and associated stops 1 through 7.

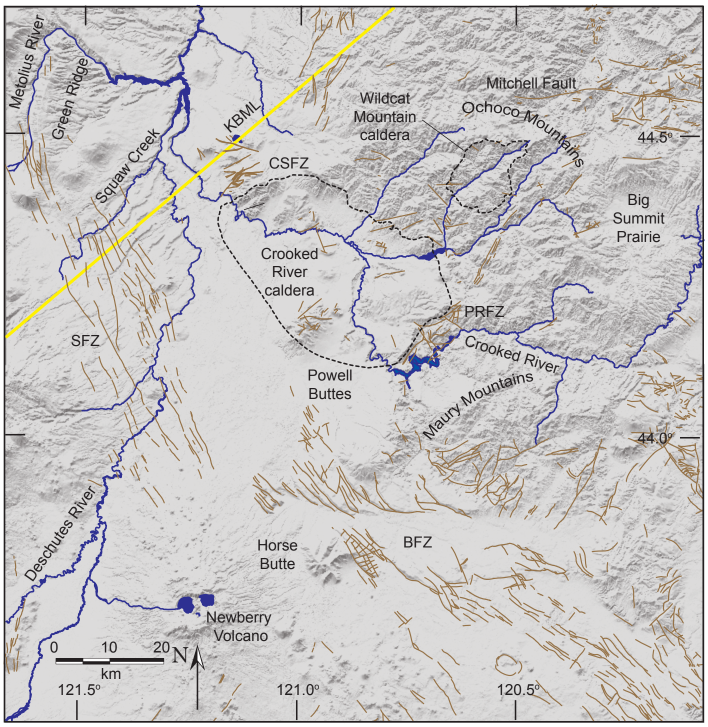

Figure 3. Fault lineament map of central Oregon with caldera structures delineated in the Lower Crooked Basin. The Wildcat Mountain caldera is coincident with a relatively stable tectonic area near the junction of the northwest trending Brothers fault zone (BFZ) and the north-northwest trending Sisters fault zone (SFZ). The northern edge of this area is coincident with the Klamath-Blue Mountain gravity-anomaly lineament (KBML) (Riddihough and others, 1986).

Location and geologic setting

The Wildcat Mountain caldera is a ~16 km × ~11 km (10 mi × 7 mi), northeast trending, volcano-tectonic depression located 19 km (12 mi) northeast of the city of Prineville in the Ochoco Mountains, a topographically high region that encompasses part of the Ochoco National Forest and the Mill Creek Wilderness (Figure 2). Terrain in the Ochoco Mountains is characterized by rugged relief with associated broad plateaus and upland basins; streams west of Ochoco Divide drain into the Lower Crooked Basin following a distinct northeast trend parallel to the dominant structural fabric of the highland (Figure 3). Post-volcanic erosion has stripped away most of the intracaldera fill and outflow deposits, and part of the original topographic rim of the caldera, leaving a distinct depression with more than 800 m of vertical relief. The caldera is drained by Mill Creek and is accessible on the south by U.S. Forest Service road 33 (Mill Creek road) and U.S. Forest Service road 27 on the north. These roads lead to trailhead access points at Wildcat Campground, Steins Pillar, Bingham Prairie, and Whistler Springs (Figure 2).

The deeply eroded Wildcat Mountain caldera is a discrete eruptive center within the Ochoco volcanic field, a complex of variably exhumed Eocene volcanic and intrusive rocks that lie along the crest of the Ochoco Mountains (Figure 3). Although previous workers (Waters, 1966; Waters and Vaughan, 1968; Swanson, 1969) have correlated these rocks with various parts of both the Clarno and John Day Formations, lithologic distribution, geochemistry, geochronology, and structure now indicate these rocks form a single volcanic field. The original extent of the Ochoco volcanic field is currently unknown, but it may be preserved from the Maury Mountains on the south to the Horse Heaven mining district on the north, forming a belt of coincident Eocene vents and quicksilver deposits (Figure 3; Waters and others, 1951; Brooks, 1963; Swanson, 1969). The Ochoco volcanic field is underlain by variably deformed Cretaceous and older (?) sedimentary rocks exposed between Ochoco Divide and Mitchell. It is flanked on the west, north, and east by Eocene to Oligocene depocenters that are exposed in an arcuate belt between Gray Butte, Clarno, and the Painted Hills. The depocenters preserve a regionally segmented and stratigraphically discontinuous volcanic and sedimentary succession of the Clarno and John Day Formations (Walker, 1990; Robinson and others, 1990; Smith and others, 1998; Retallack and others, 2000; Bestland and others, 1999). The Horse Heaven mining district, characterized by a thick section of andesite, tuff, and a 42.1 ± 0.8 Ma mineralized (cinnabar) rhyolite flow and dome complex lies between Clarno and Wildcat Mountain (Waters and others, 1951; Swanson and Robinson, 1968; Fiebelkorn and others, 1982). The Oligocene Crooked River caldera forms an embayment along the southwest part of the Ochoco Mountains, partially overlapping the Ochoco volcanic field (Figure 3).

Regional Paleogene stratigraphy

Deformed Paleozoic to Mesozoic accreted terranes and Cretaceous marine rocks form the core of the Blue Mountains of central and eastern Oregon which is blanketed by a discontinuous succession of Paleogene volcanic and volcanogenic sedimentary rocks regionally referred to as the Clarno and John Day Formations (Figure 4). The older Clarno Formation consists of Eocene non-marine alkaline to calk-alkaline volcanic rocks and intrusions and volcanogenic sedimentary rocks that reputedly range in age from ca. 54 to 39 Ma (Merriam, 1901a,b; Evernden and others, 1964; Evernden and James, 1964; Swanson and Robinson, 1968; Swanson, 1969; McKee, 1970; Enlows and Parker, 1972; Rogers and Novitsky-Evans, 1977, Manchester, 1981; Fiebelkorn and others, 1982; Vance, 1988; Walker and Robinson, 1990; Retallack and others, 2000; Appel, 2001; Bestland and others, 1999). A regional stratigraphy has not been erected for the Clarno Formation, but available $^{40}Ar/^{39}Ar$ dates obtained from north-central Oregon form a tightly constrained cluster of ages for intermediate calc-alkaline rocks that range between 43.86 ± 0.89 and 41.50 ± 0.48 Ma (Bestland and others, 1999; Appel, 2001). Urbanzyk (1994) identified a similar aged (43.5 ± 0.5 to 36.7 ± 0.2 Ma) magmatic pulse in rocks correlative with the Clarno Formation at Cougar Rock in the Elkhorn Mountains of eastern Oregon and a secondary pulse that occurred between 37.6 ± 0.4 and 33.6 ± 0.3 Ma (Figure 1). Older rocks, that range in age from 53.6 ± 0.3 to 45.26 ± 0.31, similar to the Challis volcanic field of Idaho (ca. 51–44 Ma; McIntyre and others, 1982) are exposed near the hamlets of Clarno and Mitchell (Bestland and others, 1999; Appel, 2001). These rocks are inferred to mark the lower boundary of the Clarno Formation in north-central

Oregon, although the precise stratigraphic relationships of the older units is not clear.

The John Day Formation is a dissected belt of late Eocene to early Miocene volcanogenic sedimentary rocks, mafic lavas, rhyolite domes, and widespread rhyolite tuffs originally thought to be entirely younger and chemically distinct from the Clarno Formation (Marsh, 1875; Peck, 1964; Swanson, 1969; Fisher and Rensberger, 1972; Robinson, 1975; Robinson and Brem, 1981; Robinson and others, 1984; Obermiller, 1987; Robinson and others, 1990). The regional stratigraphy of the John Day Formation was established by Peck (1964), Fisher and Rensberger (1972); Robinson and Brem (1981), and Robinson and others (1990). Robinson and Brem (1981) divided the formation into a "western", "southern", and "eastern" facies (Figure 1). The "western" facies is divided into members designated alphabetically from A to I (Figure 4; Peck, 1964; Robinson and Brem, 1981; Robinson and others, 1990). The "eastern" facies is divided into four members that include from oldest to youngest the Big Basin, Turtle Cove, Kimberly, and Haystack Valley members (Fisher and Rensberger, 1972). The "southern" facies has not been formally divided into members. The base of the John Day Formation is generally defined by the regionally widespread Member A ash-flow tuff that has $^{40}Ar/^{39}Ar$ ages of 39.72 ± 0.03 Ma near the Painted Hills, 39.22 ± 0.03 Ma near Clarno, and 39.17 ± 0.15 Ma near Ashwood (Bestland and Retallack, 1994a,b; Smith and others, 1998; Retallack and others, 2000). An ash flow defined as Member I near the top of the formation has been dated at 27.7 ± 0.3 Ma (K/Ar) but may be as young as 22 Ma (?) (Robinson and others, 1990).

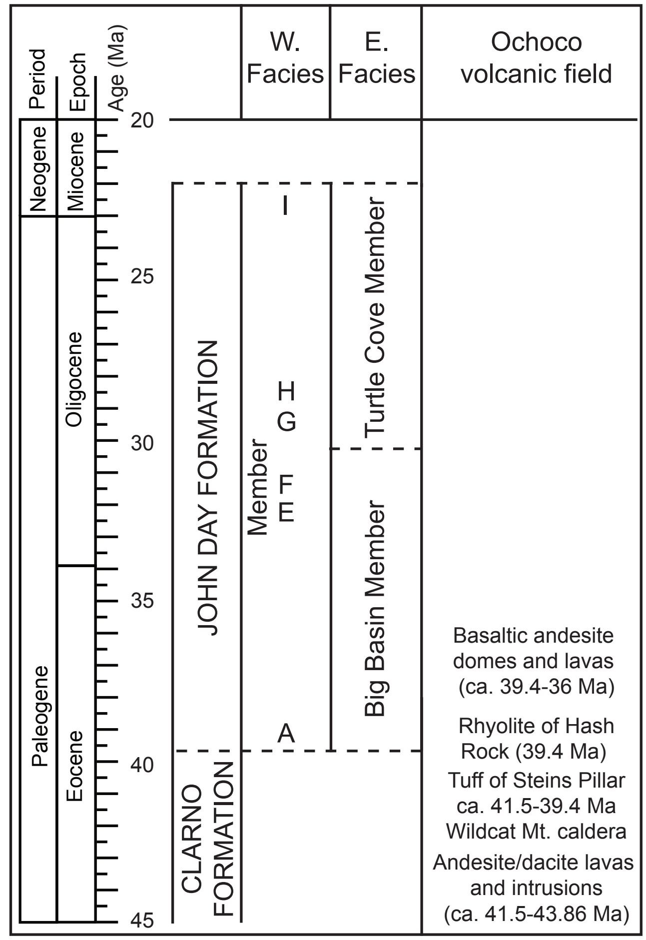

Figure 4. Generalized stratigraphic section for the John Day and Clarno Formations in central Oregon and correlative major units of the Eocene Ochoco volcanic field.

Wildcat Mountain caldera overview

The Wildcat Mountain caldera is characterized thickly ponded silicic ash-flow tuff, nearly vertical caldera-bounding faults, and ring fracture rhyolite domes and intrusions that coincide with a regional gravity low (Figure 2). All these features are consistent with caldera formation (Williams, 1941; Smith, 1960; Smith and Bailey, 1968; Lipman, 1976, 1984, 1997; Christiansen, 2001). The earliest recognized magmatism associated with the Wildcat Mountain caldera produced a series of variably eroded, overlapping andesite and dacite lavas, domes, and shallow intrusions between 43.86 ± 0.89 and 41.50 ± 0.48 Ma (Ferns and McClaughry, 2007). Massive andesite lavas erupted around the northern margin of the volcanic center at 41.50 ± 0.48 Ma, although no evidence of any volcanic edifice preceding caldera formation has been found. Initial intermediate volcanism in the field was followed closely by eruption of the Tuff of Steins Pillar between 41.50 and 39.35 Ma and synvolcanic subsidence of the Wildcat Mountain caldera. Rhyolite and dacite lavas, domes, and intrusions were emplaced along the ring-fracture and in central vent areas around 39.35 ± 0.30 Ma following the main subsidence phase. Repeated injection of silicic magma within central areas of the caldera during this phase formed a prominent central resurgent dome that was accompanied by emplacement of linear breccia pipes and hydrothermal alteration along the ring-fracture. This phase of magmatic and hydrothermal activity around the periphery of the Wildcat Mountain caldera produced mercury mineralization between Kidnap Springs and Strickland Butte that was explored by prospectors and mined to a limited extent between 1940 and 1942 (Brooks, 1963). Post mineralization emplacement of basaltic andesite to andesite flows and plugs occurred along caldera margins up until ca. 38–36 Ma, when major volcanic activity in the field ceased.

Rocks of the Wildcat Mountain caldera and Ochoco volcanic field are calc-alkaline and display remarkably consistent chemical compositions throughout their magmatic evolution (Table 1, Figure 5a). Intermediate to silicic basement rocks and rocks associated with the Wildcat Mountain caldera are characterized by relatively enriched amounts of Al (aluminum) and correspondingly relatively depleted contents of K (potassium), Na (sodium), and Fe (iron). These rocks also display characteristically low contents of incompatible high-field-strength elements (HFSE) such as Nb (niobium) and Zr (zirconium), low contents of Y (yttrium), and, generally, lower abundances of the light rare-earth elements (LREE) La (lanthanum) and Ce (cerium) (Table 1, Figure 5b). Rocks of the Wildcat Mountain caldera and Ochoco volcanic field are distinct from adjacent, ca. 10–13 My younger Lower Crooked volcanic field rocks. Mafic rocks preserved within the Lower Crooked volcanic field are Fe- and Ti-rich tholeiites while silicic rocks are characterized by relatively enriched amounts of Y, Zr, Nb, La, and Ce (McClaughry and others, 2009; Figure 5a,b).

FIELD TRIP GUIDE

Note: Road logs are reported in miles [black-boxed numbers] to match most car odometers. GPS coordinates, recorded in longitude and latitude (NAD 27, deg.dddd), are given for each field stop. Compass directions to points of interest are given in azimuthal format. Metric system units are used for all scientific measurements; corresponding standard U.S. units are given in parentheses. Field trip mileage begins and ends at the United States Forest Service Office in Prineville. The reader is encouraged to check with the Ochoco National Forest Office in Prineville for the most current road conditions and/or possible road closures in effect for the forest before embarking on the field trip.

Objectives of this field trip

The purpose of this field trip is to view the geology of the middle Eocene Wildcat Mountain caldera, including intracaldera ash-flow tuff deposits, such as those preserved at Steins Pillar. The route traverses a particularly scenic part of the Ochoco National Forest and circumnavigates the Mill Creek Wilderness in the northeastern part of the Lower Crooked Basin. We place emphasis on the general stratigraphy of the Wildcat Mountain caldera and the geologic factors that control the geomorphology of the upper Mill Creek drainage, the distribution of landslide deposits, and the location of mineralized zones and historic mercury mines located on this part of the Ochoco National Forest. As a note of general interest, the Ochoco National Forest is well known for its geode (thunderegg) localities, and three sites occur along the field trip route as noted in the road log by mileage and GPS locations, and in Figure 2. The Wildcat Mountain caldera is also traversed by a well-maintained trail system that leads to important geologic features of the caldera located within the Mill Creek Wilderness. Trailheads are noted in the road log by mileage and GPS coordinates and are displayed in Figure 2.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 1

0.0 *Start field trip at the Ochoco National Forest Office on the east end of Prineville and proceed to Stop 1. Turn right onto US 26.* Directly north of the USFS office is Barnes Butte, an upper Oligocene rhyolite dome complex related to the Crooked River caldera. The butte is capped by a chemically equivalent, densely welded ash-flow tuff erupted from the dome complex between 29.56 and 27.97 Ma. An Oligocene age for the rhyolite dome at Barnes Butte is based on a $^{40}Ar/^{39}Ar$ radiometric age determination of 27.97 ± 0.32 Ma (whole-rock; McClaughry and Ferns, 2006a).

3.2 A gravel quarry and prospect half way up the cliff-face on your right exposes a brick orange outcrop of strongly welded, hydrothermally altered Tuff of Barnes Butte. Cavities in the tuff contain blood-red, opaque to translucent opal and white to black chalcedonic quartz. The alteration zone is near the southeast margin of the Crooked River caldera.

5.3 The Oligocene Rhyolite of Ochoco Reservoir, exposed north of the highway is a south-dipping sanidine-phyric rhyolite that erupted along the southeast margin of the Crooked River caldera. The rhyolite has a $^{40}Ar/^{39}Ar$ age of 27.54 ± 0.36 Ma (whole-rock; McClaughry and Ferns, 2006b). The base of the rhyolite lava at this mileage point is a popular public collection site for colorful agate and jasper that can be found on the ground surface below the cliffs overlooking the site. Many specimens have cavities filled with drusy quartz. *Park away from the highway and hike 0.4 km (0.25 mi) toward the prominent cliff-face, north of Ochoco Reservoir.*

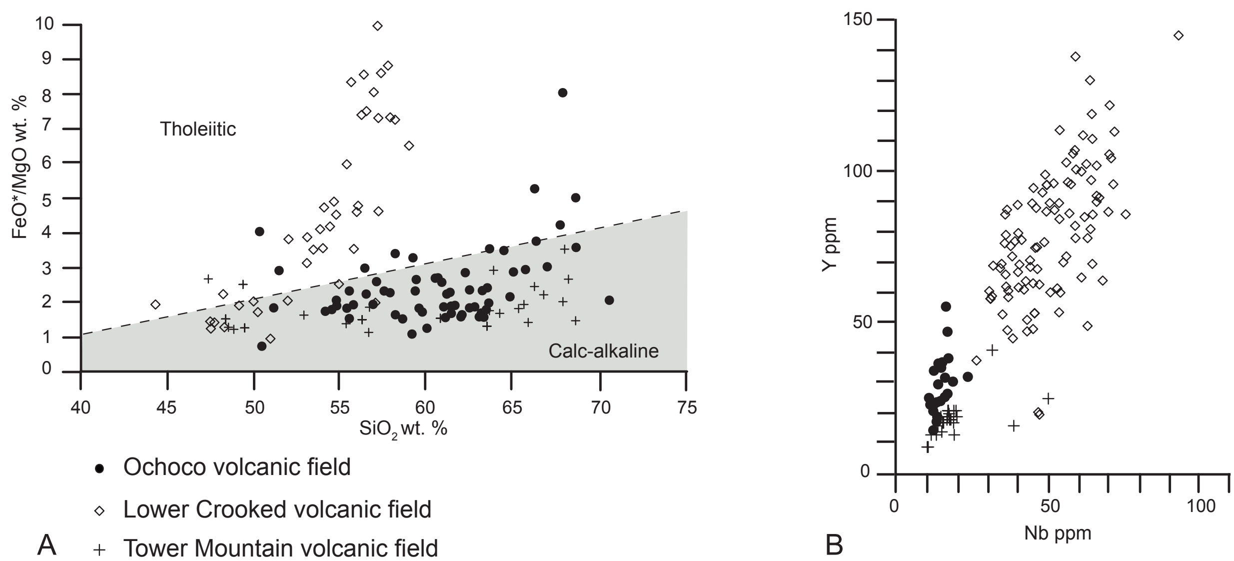

Figure 5. Variation diagrams for whole-rock geochemical analyses from the Ochoco, Lower Crooked, and Tower Mountain volcanic fields. (a) FeO*/MgO versus SiO_2 diagram showing differences between mafic to intermediate rocks within the three volcanic systems. Tholeiitic and calc-alkaline fields are from Miyashiro (1974). (b) Plot of Y versus Nb for silicic rocks within the three volcanic systems.

Table 1. Representative geochemical analyses for Wildcat Mountain caldera stratigraphic units.

	Precaldera Andesite-Dacite Domes, Flows, and Intrusions					Tuff of Steins Pillar	Post-Caldera Rhyolite Domes, Flows, and Intrusions				Post-Caldera Dacite Intrusions		Post-Caldera Basaltic Andesite and Andesite Flows and Intrusions	
Sample	279 LCJ 06	45 P 05	59 LC 06	89 LCJ 06	119 LCJ 06	151 LCJ 07	149 LC 06	280 LCJ 06	269 LCJ 06	308 LCJ 07	125 LCJ 06	101 LCJ 06	360 LCJ 07	423 LCJ 07
Geographic Area	Harvey Gap	Mill Creek	Old Dry Creek	Schoolhouse Creek	Jesse Spring	Steins Pillar	Wildcat Mountain	Hash Rock	Twin Pil-lars	Brennan Palisades	N. of Forked Horn Butte	E. of Green Mountain	Basaltic andesite	Andesite
Unit	Tcdp	Tcid	Tcal	Tcal	Tcau	Tcts	Tcrh	Tcrh	Tcrh	Tcrb	Tchp	Tchp	Tcba	Tcag
UTM N	4926670	4915308	4918300	4919486	4929665	4919034	4922150	4929440	4928305	4918879	4925964	4923605	4918279	4919601
UTM E	688690	685994	682290	687237	692047	688149	695180	694450	695980	685330	694194	685502	692456	698232
Age (Ma)	43.86	42.79	—	—	41.50	41.5–39.35	—	39.35	39.35	—	—	—	ca. 38–36	ca. 38–36
Oxides, weight percent														
SiO_2	58.60	66.09	59.93	62.87	57.64	75.25	76.26	74.85	74.12	72.83	68.22	68.91	56.29	61.84
Al_2O_3	17.95	15.68	16.02	17.26	16.55	13.56	13.28	13.78	13.83	14.29	16.19	16.19	16.64	16.46
TiO_2	0.83	0.68	1.14	0.82	1.48	0.23	0.13	0.20	0.30	0.41	0.61	0.54	1.18	0.91
FeO*	5.96	4.47	7.64	5.11	8.13	1.98	1.77	1.99	1.90	2.72	4.09	3.27	8.19	5.59
MnO	0.11	0.07	0.17	0.11	0.21	0.02	0.02	0.02	0.04	0.05	0.17	0.06	0.14	0.11
CaO	7.69	4.90	6.52	5.97	7.48	2.87	0.40	0.94	1.30	1.51	3.85	3.54	8.15	6.22
MgO	4.05	2.19	3.19	2.40	3.48	1.01	0.00	0.00	0.11	0.12	0.56	0.73	4.71	3.71
K_2O	1.33	2.20	1.53	1.42	1.38	4.32	5.17	3.91	3.92	3.70	2.13	2.13	1.11	1.72
Na_2O	3.30	3.54	3.44	3.82	3.38	0.72	2.93	4.28	4.40	4.26	3.99	4.49	3.26	3.20
P_2O_5	0.18	0.18	0.42	0.21	0.27	0.04	0.04	0.03	0.07	0.10	0.20	0.14	0.33	0.24
LOI	1.59	2.57	1.84	1.71	1.24	8.68	1.65	1.16	1.13	1.21	3.41	2.02	2.12	3.02
Trace Elements, parts per million														
Ni	73	20	43	15	26	3	1	2	1	1	20	10	48	21
Cr	91	39	49	27	46	13	1	0	2	3	33	14	70	64
Sc	20	13	20	16	25	7	3	6	5	6	11	11	22	15
V	136	89	145	122	207	26	12	9	16	25	71	52	201	134
Ba	341	528	450	521	346	657	1010	950	935	772	512	715	261	445
Rb	43.8	86.7	37.9	39.6	53.0	125.9	184.5	128.7	139.2	131.1	62.2	60.6	30.4	67.8
Sr	383	357	347	406	346	289	31	88	93	127	302	370	434	393
Zr	148	153	269	187	164	111	158	299	266	281	233	202	215	182
Y	20.8	14.4	31.1	21.6	29.1	19.0	34.2	26.6	24.2	25.5	24.0	23.3	27.3	23.1
Nb	9.2	9.6	20.3	10.8	12.5	13.3	12.2	16.7	14.4	15.8	14.1	11.3	15.7	12.2
Ga	17.4	18.1	18.8	17.6	18.7	12.6	16.1	16.1	17.2	16.8	17.4	16.7	20.4	17.7
Cu	54	28	63	36	54	5	2	1	5	10	27	27	112	33
Zn	66	55	94	67	88	35	52	51	44	58	69	53	94	76
Pb	4	4	6	7	5	6	9	10	10	10	9	9	3	4
La	16	21	25	21	16	23	42	37	35	31	31	26	19	21
Ce	31	47	52	38	34	40	79	75	71	60	55	54	40	43
Th	4.9	5.8	3.8	4.0	3.9	13.6	4.4	14.8	16.1	12.0	4.7	6.0	4.3	3.9
U	0.7	1.9	0.8	1.9	1.8	3.0	0.0	3.7	4.5	4.3	3.1	1.6	0.0	1.2
Co	23	12	24	17	29	0	0	0	0	1	10	5	28	13

Note: Major element determinations have been normalized to a 100% total on a volatile-free basis and recalculated with total iron expressed as FeO*. Oxides as weight percent; trace elements as parts per million. Coordinates in Universal Transverse Mercator (UTM NAD 27). LOI is loss on ignition.

5.5 Ochoco Lake County Park is on the right. The park is developed on a large hummocky landslide deposit composed of intermixed rhyolite and tuffaceous siltstone. The landslide originates from tension-cracked, southerly dipping, outcrops of the Rhyolite of Ochoco Reservoir upslope to the north.

6.1 Crossing the southeast ring-fracture zone of the Oligocene Crooked River caldera. The rocks exposed on the north-side of the highway are composed of middle Eocene andesite and dacite lavas and subvolcanic intrusive rocks that are part of the Clarno Formation. These rocks crop out discontinuously along US 26 east to Ochoco Divide and along Mill Creek Road (USFS 33).

7.5 *Turn left onto Mill Creek Road (USFS Road 33), drive north to Stop 1.*

9.1 Outcrop of middle Eocene andesite on the left. Lithologically and chemically similar andesite and dacite lavas and domes form thick homogeneous masses across this part of the Ochoco Mountains.

9.9 Distinct tan to orange, hoodoo forming outcrops of the Rhyolite of Mill Creek are exposed on the west side of the road. This rhyolite also caps Mahogany Butte, visible ~3.2 km (2 mi) north-northeast of this point. The rock is typically a stony, planar to tightly flow-folded rhyolite with flow, dome and intrusive margins marked by zones of relatively fresh vitrophyre, perlite, spherulites, and agate-filled lithophysae (gas cavities). The rhyolite forms a northeast trending outcrop belt across the southeast part of the Wildcat Mountain caldera where it intrudes intracaldera facies of the Tuff of Steins Pillar. Where the rhyolite is coincident with the inferred margin of the Wildcat Mountain caldera, it is bleached white, silicified, and displays propylitic alteration (epidote and chlorite).

11.1 *Stop 1.* Dike exposed in roadside quarry. *Pull off and park in the county right-of-way on the right side of the road.*

STOP 1. PRE-CALDERA DACITE INTRUSION

GPS coordinates -120.6653, 44.3694

An ~ 8 m (26 ft) thick and ~ 600 m (1969 ft) long, N50°W trending, vertical dike of hornblende and plagioclase-phyric dacite is exposed in the rock quarry at stop 1 (Figure 6; Table 1). The dike has an $^{40}Ar/^{39}Ar$ age (hornblende) of 42.79 ± 0.44 Ma and is part of a northwest trending belt of middle Eocene calc-alkaline andesite and dacite intrusions exposed between Mill Creek and McKay Creek to the west (Figure 2; McClaughry and Ferns, 2006b). These intrusions form part of the basement to the Wildcat Mountain caldera and mark the locations of feeder conduits for some of the andesite and dacite lavas of similar composition exposed across this part of the Ochoco Mountains (Table 1). The Mill Creek dike intrudes a section of tan to orange, crudely stratified, clast-supported volcaniclastic tuff-breccia composed of angular, mafic volcanic clasts and angular to sub-round, vesicular, mafic volcanic blocks and bombs up to 20 cm (8 in) across.

The northwest orientation (N50°W) of the pre-caldera andesite and dacite intrusions is identical to that observed both in pyroclastic dikes that were the feeders to the Tuff of Steins Pillar and in many silicic intrusions in and around Wildcat Mountain caldera (Figure 2). Similarly oriented dike alignments have been observed in post-subsidence intrusive rocks in the Oligocene Tower Mountain caldera (Ferns and others, 2001) and in Oligocene mafic-dike swarms near Mitchell (Taylor, 1981). Additionally, local Eocene and Oligocene depocenters along the axis of the Blue Mountains (e.g., Clarno, Painted Hills, Figure 1) preserve broadly folded Eocene and Oligocene stratified rocks with northeast trending fold axes and west-northwest trending faults and dikes (Taylor, 1977,1981; Walker and Robinson, 1990; Bestland and others, 1999). These combined structural elements indicate a regional tectonic stress regime of northwest-southeast directed compression and complementary northeast-southwest directed extension in north-central Oregon during the middle Eocene to early Miocene (Taylor, 1977, 1981; Robyn and Hoover, 1982).

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 2

12.6. *Optional stop. Brennan Palisades (4.0 km, 2.5 mi roundtrip). Turn left onto USFS Road 3370, and proceed west. [Please note that USFS road 3370 has a seasonal closure in effect from December 1 to May 1 to protect winter range areas]. In 0.9 miles, turn left onto USFS Road 3370-100. Travel 0.4 miles to the signed parking area at Brennan Palisades.* The crenulated vertical rock face at Brennan Palisades (GPS coordinates −121.6769, 44.4007) was named for Claude C. Brennan, a member of a pioneer Crook County ranch family, who operated an adjoining ranch on Mill Creek for many years until his death in 1983 (McArthur, 1992). Brennan Palisades presents a good outcrop of a distinctly layered, feldspar-phyric rhyolite dome complex that weathers to hoodoos and balanced rocks (Table 1). The distinct layering, characteristic of the Rhyolite of Brennan Palisades, is defined by alternating vesicle-rich and massive, vesicle-poor bands. The bands are typically 2–5 cm (0.8–2.0 in) thick, distinctly segregated, and laterally

Figure 6. N50°W trending, hornblende- and plagioclase-phyric dacite dike cutting tuff breccia along Mill Creek Road at stop 1.

continuous over tens of meters. Locally bands show well-developed kink folds, and are separated by coarse breccia layers and lense-shaped, boudinlike features up to 30 cm (11.8 in) thick and 60 cm (23.6 in) long. At Brennan Palisades, the layering dips gently to the west, with the dip angle steepening to the east-southeast. The rhyolite intrudes early to middle Eocene andesite and dacite at Brennan Palisades; near the junction of Mill and Schoolhouse Creeks the rhyolite intrudes intracaldera facies of the Tuff of Steins Pillar.

14.0 Flow-foliated outcrop of rhyolite on the left. Crossing southern ring-fracture zone of the Wildcat Mountain caldera.

15.7 Stop 2. Steins Pillar viewpoint. *Turn right into the developed parking area.*

STOP 2. STEINS PILLAR VIEWPOINT

GPS coordinates -120.6176, 44.4173

Steins Pillar and Wildcat Mountain are two of the most prominent features in the Wildcat Mountain caldera (Figure 7). Steins Pillar is one of a series of north-northwest trending spires of strongly welded intracaldera ash-flow tuff. It is ~106 m (350 ft) tall and consists of a compound cooling unit of pink to buff colored, massive to flow banded, variably spherulitic, lithophysal, rheomorphic tuff (Figure 7b). The spire-forming tuff is propylitically altered with secondary quartz and small calcite veins; thin breccia veins are locally pervasive. Wildcat Mountain, visible on the east-northeast (80°), is part of a post-caldera rhyolite flow and dome complex that intrudes the Tuff of Steins Pillar (Table 1). White-colored outcrops exposed below the summit are part of the intracaldera facies (Figure 7a).

Waters (1966, p. 142) first vividly described Steins Pillar as an "accumulation of hot pumice fragments, glass shards, and violently vesiculating lava that frothed from numerous volcanic orifices – many of whose sites are now filled with plugs, domes, and dikes of rhyolite. Among these former centers of eruption are the ridges on either side of Benefield Creek, Forked Horn Butte, Mahogany Butte, and many unnamed sharp buttes both to the north and south of Steins Pillar (Figure 2). The flows of hot pumice fragments and glass shards pouring from these volcanic centers spread into and filled an ancient broad valley. Part of the valley, in the area between Wildcat Mountain and Steins Pillar, now lies buried beneath as much as 1000 feet of sintered and welded tuff." The Tuff of Steins Pillar is now interpreted as the eruptive product of a single cataclysmic eruption in the middle Eocene that formed the Wildcat Mountain caldera.

Leave the viewpoint parking area and turn left onto Mill Creek Road (USFS Road 33). Travel 1.3 miles south to the intersection with USFS 3300-500.

17.0 *Turn left onto USFS Road 3300-500. Cross Mill Creek and continue 3.2 mile to stop 3.* The route to stop 3 crudely traces the southern ring-fracture of Wildcat Mountain caldera where discontinuously exposed outcrops of the intracaldera tuff are juxtaposed against middle Eocene andesite wall rocks. Outcrops are mantled here by a large landslide deposit. Factors contributing to the landslide are locally steep slopes combined with near vertical contacts between intracaldera tuff, the caldera wall, and post-caldera rhyolite intrusions.

17.5 Well exposed outcrop of white-colored, friable, pumice-lithic tuff that is part of the intracaldera facies of the Tuff of Steins Pillar.

17.6 USFS Road 3300-500 makes a sharp right turn south and crosses a small drainage. The drainage traces the southern ring fracture of the Wildcat Mountain caldera where a vertical contact juxtaposes intracaldera tuff facies exposed on the north with aphyric andesite basement rocks exposed on the south.

19.0 ***Optional hike*** *(see OPTIONAL HIKE 1 – STEINS PILLAR TRAIL #837, page 13). Trailhead parking for Steins Pillar trail #837 is on the left side of the road.*

19.2 *Stop 3. Park behind the berm that blocks the road.*

STOP 3. THE TUFF OF STEINS PILLAR AND POST-SUBSIDENCE RHYOLITE DIKES

GPS coordinates -120.6216, 44.3932

The rheomorphic intracaldera tuff exposed at Steins Pillar is succeeded upward by at least 305 m of massive, poorly sorted, nonwelded to weakly welded, locally propylitically altered and zeolitized, lithic- and pumice-rich tuff (Figure 8). Diffuse layering in the tuff is defined by alternating layers of lithics and pumices. Lithics consist of aphyric to vesicular andesite rock fragments and flow-banded, aphyric rhyolite. Andesite lithics are composed of an equi-granular plagioclase and pyroxene groundmass, are angular, and have a maximum size of 10 cm (4 in) across; these clasts average 2–5 cm (0.8–2.0 in) across. Rhyolite lithics are spherulitic, flow banded, angular, and reach a maximum size of 37 cm (14.6 in) across; rhyolite clasts average 10–15 cm (4–6 in) across. Pumices are white to pale-green, banded, average 2–4 cm (0.8–1.6 in) in length, are moderately flattened, and are generally aligned in outcrop. Lithics and pumices are encased in a matrix of sparsely scattered, anhedral, clear to white sanidine crystals, sparse hornblende needles, and devitrified glass and ash. The tuff contains characteristically low contents of Nb (12.4–13.8 ppm), Zr (110–145 ppm), Y (19–27.9 ppm), La (23–29 ppm), and Ce (40–58 ppm) (Table 1).

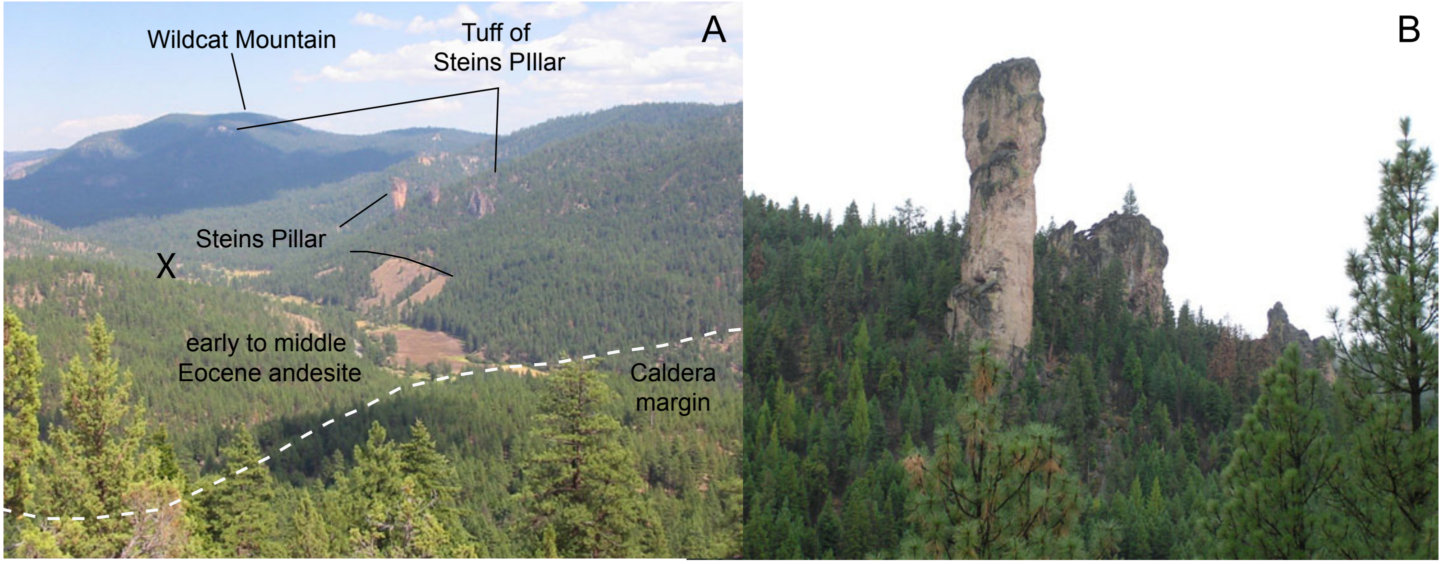

Figure 7. (a) View of the southwest margin of the Wildcat Mountain caldera, showing the location of Wildcat Mountain and Steins Pillar. Dashed white line shows the approximate location of the caldera margin. The X in the center-left of the photograph shows the location of Stop 2 (b) Steins Pillar as viewed from the parking area at Stop 2.

OPTIONAL HIKE 1 – STEINS PILLAR TRAIL #837

GPS coordinates -120.6228, 44.3948

The trailhead is the starting point for a 5.8 km (3.6 mi) round trip hike that reaches several nice viewpoints above Steins Pillar (Figure 2). The well-maintained trail (#837) climbs from 1305 m (4280 ft) at the parking area to a viewpoint at an elevation 1396 m (4580 ft) that offers views of the Cascade Range on the west and the Mill Creek Wilderness on the north. From the viewpoint on to trails end, the route follows a fairly constant elevation along a wooded slope. At 0.5 km (0.3 mi) the trail passes through a small window of columnar-jointed porphyritic dacite that forms part of the basement to the Wildcat Mountain caldera. Between 0.7 km (0.45 mi) and 1.1 km (0.7 mi), the trail passes by outcrops of pumice-lithic tuff that make up the upper part of the intracaldera facies of the Tuff of Steins Pillar. Between 1.1 km (0.7 mi) and 1.5 km (0.9 mi) the intracaldera tuff is capped by a relatively fresh, black glassy dacite lava that erupted from vents along the caldera margin following caldera formation. This flow weathers to a surface of scattered boulders and cobbles. The trail winds through discontinuous, poorly exposed outcrops of the intracaldera tuff from 1.5 km (0.9 mi) to trails end at the base of Steins Pillar. Along the way, good vantage points of Steins Pillar are available from the top of a north trending ridge at 1.8 km (1.1 mi) and at the official trail end at 2.9 km (1.8 mi). The pillar itself is formed from variably brecciated and flow-foliated rheomorphic tuff that forms the base of the intracaldera facies. Return to the parking area along the same trail.

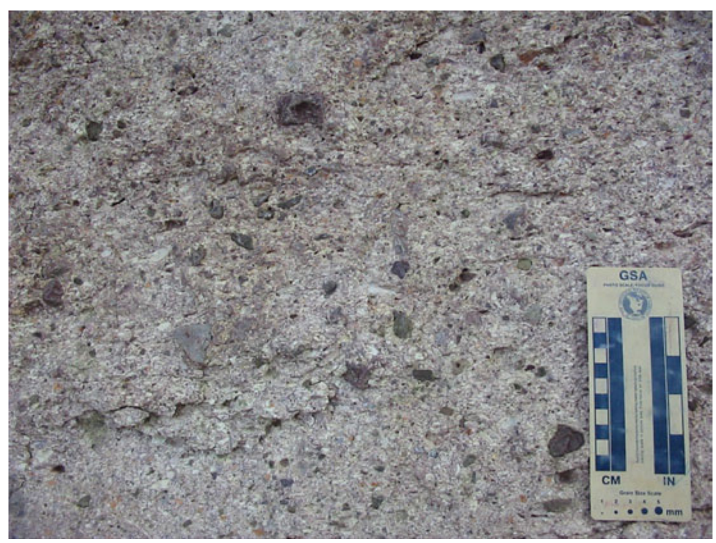

Figure 8. Pumice- and lithic-rich intracaldera tuff exposed at stop 3.

Outflow facies of the Tuff of Steins Pillar are completely absent in the vicinity of Wildcat Mountain caldera and have not been yet been identified elsewhere in the region. The stratigraphic position of the Tuff of Steins Pillar above 41.50 ± 0.48 Ma andesite lavas and beneath the 39.35 ± 0.30 Ma Rhyolite of Hash Rock on the north rim of the caldera indicates this unit is approximately temporally correlative but slightly older than the widespread 39.2–39.7 Ma Member A tuff, which regionally defines the base of the John Day Formation (Figure 4; Peck, 1964; Swanson and Robinson, 1968; Robinson, 1975; Robinson and others, 1990; Smith and others, 1998; Retallack and others, 2000). Member A has chemical affinities similar to the Tuff of Steins Pillar but is distinguished on the basis of its relatively elevated amounts of incompatible high field strength elements such as Nb (27.3–34.8 ppm) and Zr (219–339 ppm), higher contents of Y (69–90 ppm), and higher contents of the light rare earth elements, La (43–81 ppm) and Ce (121–124 ppm) (P. E. Hammond, personal communication, 2008).

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 4 AND 5

21.4 *Return along the same route back to the junction of USFS Road 3300-500 and Mill Creek Road (USFS Road 33). Turn right on Mill Creek Road (USFS Road 33).*

21.5 View of Steins Pillar to the east. Roadcuts here are composed of andesite lavas that form the basement to the Wildcat Mountain caldera.

22 Wildcat Mountain is visible on the northeast. The mountain is capped by a rhyolite dome complex that intrudes intracaldera facies of the Tuff of Steins Pillar. White outcrops exposed below the summit are exposures of the tuff.

22.4 *Turn left on Lemon Creek Road (USFS Road 3360). [Please note that USFS road 3360 has a seasonal closure in effect from December 1 to May 1 to protect winter range areas.]*

22.7 An east-west trending, middle to late Eocene breccia dike is exposed west of Lemon Creek at the intersection of USFS Road 3360 and USFS Road 3360-200. The dike is up to 200 m (656 ft) wide and is discontinuously exposed over a length of 4 km (2.5 mi) between Mill Creek and Dry Creek. Dike rock is typically a purple to green-colored, clast-supported, monolithologic breccia composed of angular andesite and dacite clasts up to 5 cm (2 in) in diameter that are encased in a dark purple gray silicified matrix. Locally, anastomosing breccia zones enclose coherent andesite and dacite blocks that exceed 1 m across (3.3 ft). The breccia matrix is distinctly green-colored and is composed of rock fragments, free crystal fragments (alkali-feldspar, plagioclase, and pyroxene), and very fine devitrified vitric ash and crystal ash. The westernmost terminus of this dike and a second dike system exposed at milepoint 22.9 are both spatially associated with the Kidnap Springs area mercury occurrences. See Brooks (1963) for information regarding the history and development of the Kidnap Springs mercury prospects.

23.1 *Continue north on USFS Road 3360.* The route crosses another east-west trending middle to late Eocene breccia dike that intrudes andesite basement rocks of the Wildcat Mountain caldera. This intrusive body consists of several discrete breccia masses up to 400 m (1312 ft) wide and up to 2 km (1.25 mi) long. The breccia is typically bleached to white and orange colors, clast-supported, and monolithologic composed of angular vesicular, aphyric to sanidine-phyric rhyolite clasts up to 30 cm (11.8 in) across. Clasts are supported in a red to pink, fine-grained, altered matrix that is lithologically equivalent to the clasts. The dikes display pervasive sulfide alteration and minor quartz veining.

24.6 For the next 0.7 miles, the route passes through good exposures of middle Eocene to Oligocene dacite lavas that post-date caldera formation. These lavas typically are black, glassy, appear very fresh and unaltered, and are chemically characterized by low amounts of Zr, Y, Nb, La, and Ce (Table 1). The lavas form blocky to massive, platy to columnar-jointed outcrops that weather to platy and boulder armored surfaces. These lavas are unconformable across and intrude older Eocene deposits, including the Tuff of Steins Pillar. A gravel, composed of clasts of the Tuff of Steins Pillar, is locally exposed at the base of some of the dacite lavas.

25.4 *Stay right on USFS Road 3360-300.*

25.5 Rock pit on the left side of the road is a rhyolite pitrun material source for the USFS.

25.9 Propylitically altered outcrop of silicified rhyolite.

26.1 *The road branches at this milepoint, please stay left. Please note, this road is a native surface and as such should only be traveled during favorable weather conditions.*

26.6 Middle Eocene to Oligocene glassy dacite lava is exposed on the left side of the road.

26.9 *The road branches at this mile point, please stay left.*

27.3 Stop 4. Viewpoint from the landing at the end of the road spur.

STOP 4. PANORAMIC OVERVIEW OF THE WILDCAT MOUNTAIN CALDERA

GPS coordinates -120.6207, 44.4562

A panoramic overview of the northern half of the Wildcat Mountain caldera and the geomorphology of the upper Mill Creek drainage is visible at stop 4 (Figure 9). Key elements of the caldera geology include the topographic expression of the caldera, the rhyolite of Hash Rock, central resurgent dome, and landslide deposits that line the interior of the caldera.

The resurgent core to the caldera has been deeply eroded, leaving all but a small portion of the intracaldera tuff and the partly dismantled topographic caldera rim that now forms the basin in the upper part of the Mill Creek drainage. Here the locally well-preserved caldera wall is defined by mature dissected, oversteepened topography composed of sharp-crested ridges and steep valley walls. The exposed margin of the Wildcat Mountain caldera is the fault-bounded structural zone along which the caldera subsided and is identified by the distribution of intracaldera tuff, hydrothermal alteration zones, rhyolite intrusions, and oversteepened topographic slopes. North of the overlook, the caldera margin is defined by an oversteepened, encircling topographic rim and an arcuate band of rhyolite dikes that extend from south of Hash Rock on the north-northeast (15°) to Twin Pillars on the northeast (65°). These dikes were conduits for the Rhyolite of Hash Rock, which forms a nearly continuous plateau around the north rim of the caldera from Hash Rock to the viewpoint east of Whistler Spring (Figures 2 and 9). The caldera margin to the east *(see OPTIONAL HIKE 3 – WILDCAT MOUNTAIN TRAIL #833, page 19)* is defined by intracaldera tuff outcrops and cinnabar-bearing hydrothermal alteration zones exposed below Whistler Springs.

The interior of the caldera, visible in the middle-ground on the east-northeast (80°), is marked by a prominent northeast elongated, ~11 km^2 (7 mi^2) rectilinear ridge that forms the drainage divide between the east and west forks of Mill Creek. This ridge parallels the major long axis of the caldera and is composed of andesite basement rock intruded by numerous dacite and rhyolite dikes and plugs. Forked Horn Butte, visible on the east (90°) is one of the high-standing rhyolite plugs. The ridge is a resurgent dome formed by the repeated injection of silicic magma into central parts of the caldera following the main subsidence phase.

Landslide deposits cover ~15% of the land surface within the interior depression of the Wildcat Mountain caldera and generally consist of coalescing slide-masses of variable age that are as large as 7 km^2 (2.5 mi^2). Small hummocky debris flow lobes, that cover less than 0.1 km^2 (0.04 mi^2), are commonly confined within narrow, steep, modern drainages. Much of the landslide terrain exposed within the caldera has been recurrently active since at least the early Holocene. Landslide deposits form subdued slopes within the caldera downslope from the caldera wall and central resurgent dome.

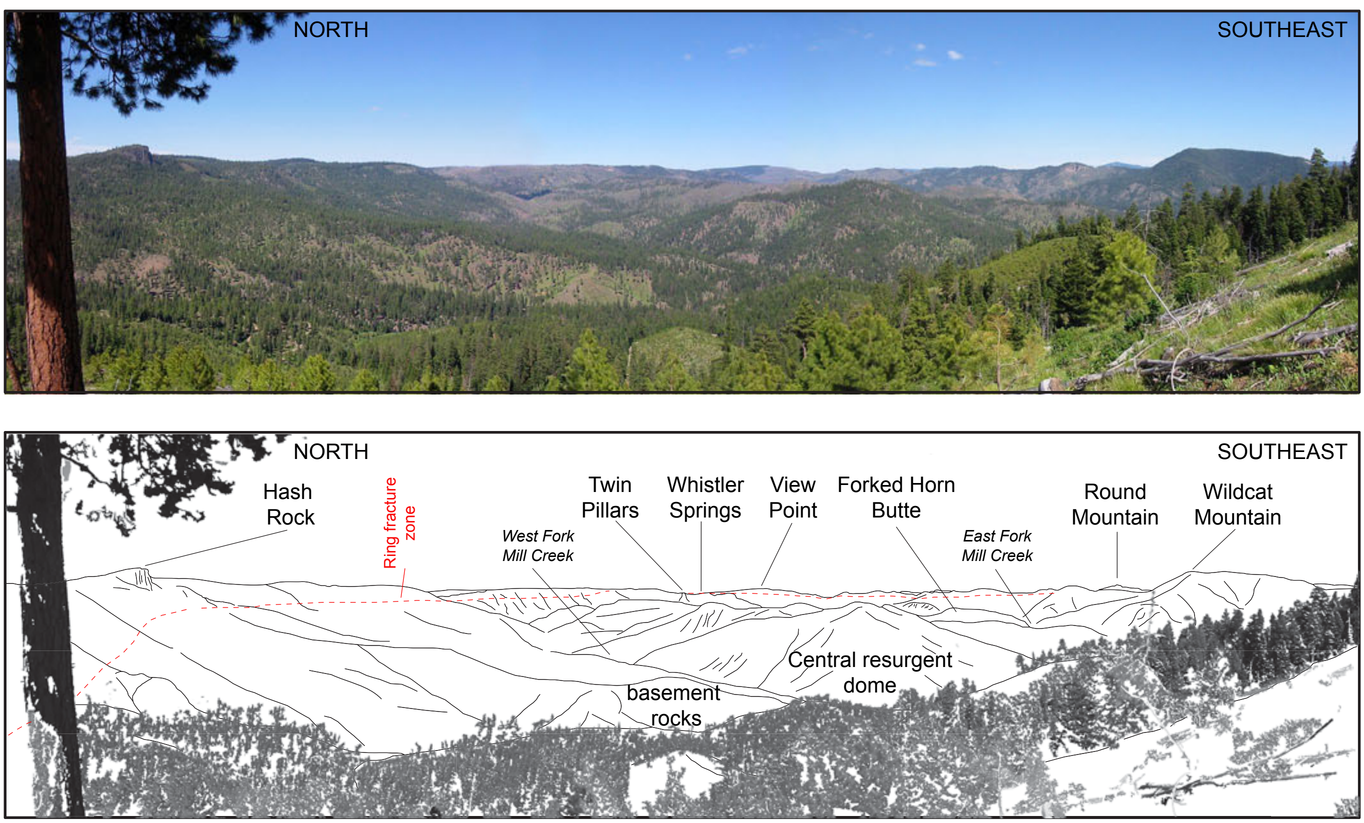

Figure 9. Panoramic view across the Wildcat Mountain caldera from stop 4. Line drawing highlights geologic features and locations discussed in the text.

The upper Mill Creek drainage is a dense mixed conifer forest with mountain meadows that receives less than 49.0 cm (19.3 in) of precipitation annually, much of which occurs as snow during winter months (Hall, 1972). The dense forests are subject to recurrent forest fires such as the 2000 Hash Rock Fire, which burned ~ 75 km^2 (29 mi^2; 18,500 acres). Many shallow-seated slope failures in the Mill Creek drainage have formed in response to post-fire surface conditions and rain on snow precipitation events. Large, more deeply-seated landslides in the upper Mill Creek drainage, are controlled by the geomorphology of the caldera. Geologic factors controlling slope-failure in the upper Mill Creek drainage include 1) depositional contacts where post-caldera lavas disconformably overlie older, deeply eroded pre-caldera basement rocks, 2) depositional contacts where post-caldera lavas disconformably overlie the less competent Tuff of Steins Pillar; 3) steeply dipping contacts between intrusive bodies; and 4) oversteepened, variably faulted and hydrothermally altered sections of the ring fracture zone of the Wildcat Mountain caldera.

32.2 *Return 4.9 miles to Mill Creek Road via the same route. Turn left on Mill Creek Road (USFS Road 33).*

33.6 *Turn left on USFS Road 3300-450. Proceed 0.3 miles to the location where an active earthflow has blocked the road.*

33.9 Stop 5. Doe Creek landslide.

STOP 5. DOE CREEK LANDSLIDE

GPS coordinates -120.6042, 44.4299

Landslide deposits are a major geologic feature within the upper reaches of the Mill Creek drainage basin. In the fall of 2000, an earthflow with an estimated volume of ~76,455 m^3 (100,000 yd^3) occurred along Doe Creek, a small drainage tributary to the main stem of Mill Creek in the Ochoco National Forest (Figure 2). The slope-failure occurred following a long dry summer, as landslide terrain, previously considered to be dormant, reactivated. Downslope movement of the slide-mass created a distinct headscarp cut into middle Eocene andesite lavas that form part of the basement rock of the Wildcat Mountain caldera; distal portions of the slide-mass engulfed standing trees and overran USFS Road 3300-450 (Figure 10). Unlike most active landslides, the movement has been constant (15 m, 50 ft) through the first 5 years with no apparent hiatus. A small flowing spring developed at the terminus of the slide deposit during the summer of 2005. Advent of spring development in 2005 corresponded with the cessation of large-scale movement in the slide-mass, with the exception of periodic minor adjustments.

A slope stability investigation was initiated by the USFS on the Doe Creek earthflow in August of 2001 in order to understand the mechanics and potential reactivation of similar terrain within the Ochoco National Forest. The study on Doe Creek included three auger holes of nearly continuous standard penetration testing and the installation of piezometers to monitor groundwater levels and to serve as simple slope movement indicators. Radiometric age-date testing of charcoal collected from auger holes indicated that the most recent historic movement in the landslide complex was ~ 9,240 BP. The presence of undisturbed in-situ Mazama tephra recovered from one of the drill holes suggests that no landslide movement has occurred

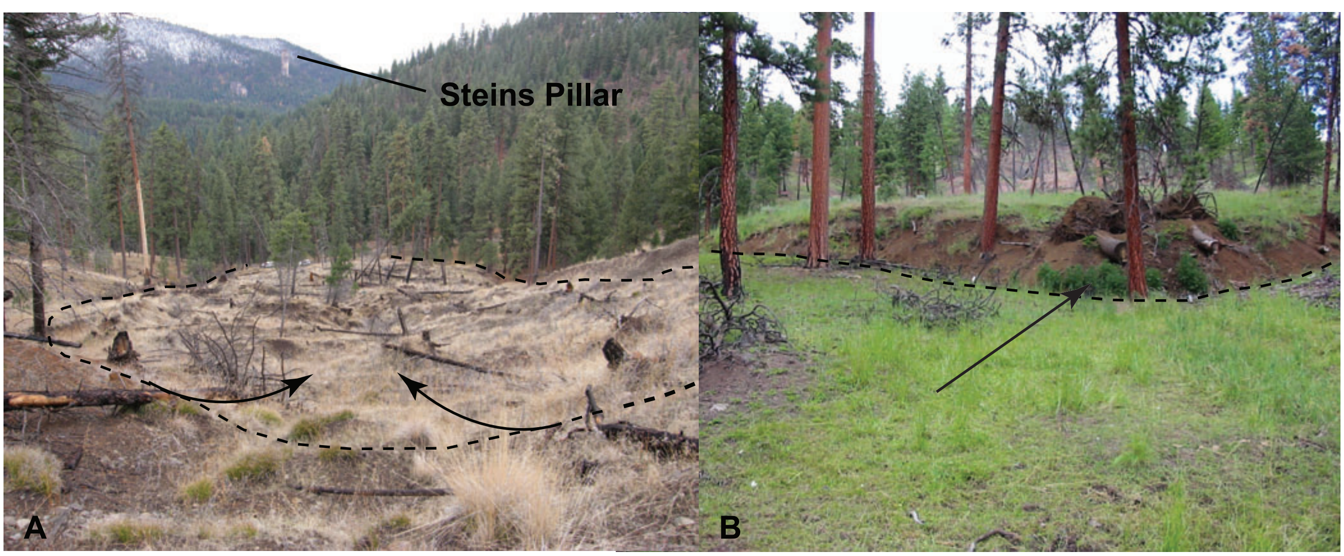

Figure 10. The Doe Creek earthflow exposed on the north side of Doe Creek at stop 5. (a) Photo looking southeast from the landslide headscarp. Arrows show the direction of slide movement. Dashed black line denotes the boundary of the slide mass. Note the irregular, hummocky topography and subvertical orientation of trees on the landslide surface. Steins Pillar is visible in the background. (b) View of the landslide toe looking northwest toward the headscarp area. The landslide toe has engulfed standing trees and blocked USFS Road 3300-450 at this location. The arrow points to the area where a small spring developed in 2005.

at this location since at least ~6,850 BP (L. Chitwood, personal communication, 2001).

Geologic mapping by DOGAMI during 2005 and 2006 characterized the geology of the upper Mill Creek area and identified the previously unknown Wildcat Mountain caldera. The Doe Creek earthflow was found to be part of a larger landslide complex covering ~ 0.44 km^2 (0.17 mi^2, 109 acres) near the southern margin of the caldera. The landslide complex occurs within pre-caldera basement rocks composed of early to middle Eocene platy andesite flows crosscut by post-caldera rhyolite intrusions. Middle Eocene basaltic andesite lavas disconformably overlie platy andesite lavas along Squirrel Ridge (Figure 2).

The reactivation of dormant landslide terrain on the east side of the Cascade Range is directly related to rain-on-snow events beneath the transient snow zone (1,372 m; 4,500 ft) elevation band. The Doe Creek landslide originates on a south-facing slope in an area that receives minor average annual precipitation (~49.0 cm, 19.3 in). The landslide occurred independently of extraordinary precipitation events. Following its discovery the slide moved 25 m (80 ft), even with very little precipitation for a year (Mathisen and Gordon, 2006). An area on Harvey Creek, to the northwest of the Doe Creek headscarp, was clear cut in the mid to late 1970s to 1980s. In the case of the Doe Creek earthflow, a number of geologic factors played a role in slide reactivation including (1) failure of incompetent interflow zones within early to middle Eocene platy andesite lavas that form the basement of the Wildcat Mountain caldera; (2) alteration zones associated with the post-caldera rhyolite intrusions; and (3) disconformable contacts between early Eocene platy andesite lavas that predate the caldera and overlying middle Eocene basaltic andesite lavas that postdate the caldera.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 6

34.3 *Return back to Mill Creek Road (USFS Road 33) on USFS Road 3300-450. Turn left on Mill Creek Road (USFS Road 33).*

35.0 View north to Forked Horn Butte, a post-caldera rhyolite plug.

35.5 *Continue left on Mill Creek Road (USFS Road 33).* The road on the right leads to Wildcat Campground and the south trailhead for the Twin Pillars trail #832 (GPS coordinates 120.5793, 44.4399) *(see OPTIONAL HIKE 2 – TWIN PILLARS TRAIL #832, page 18).* Twin Pillars is approximately 8.9 km (5.5 mi) north from the Wildcat Campground trailhead.

37.1 The road crosses the west fork of Mill Creek.

39.9 Harvey Gap is the drainage divide between the southeast-flowing west fork of Mill Creek and the west-flowing McKay Creek. ***At the saddle, turn right on USFS Road 3320.*** Here, porphyritic andesite forms part of the basement to the Wildcat Mountain caldera and is exposed in the quarry north of the intersection. A sample from this quarry has an $^{40}Ar/^{39}Ar$ age of 43.86 ± 0.89 Ma (plagioclase; Ferns and McClaughry, 2007), which marks the onset of magmatism in this part of the Ochoco volcanic field.

40.5 Wildcat Mountain, residing near the central part of the caldera is visible on the southeast (125°). Straight ahead is Hash Rock, a high-standing erosional remnant of the Rhyolite of Hash Rock.

41.0 A north trending rhyolite dike is well exposed in the road cut, due south of Hash Rock. The dike consists of a brown to white weathering aphyric to sparsely plagioclase-phyric rhyolite cored by fresh-appearing, flow-banded vitrophyre and numerous lithophysae up to 3 cm (1.2 in) across. Lithophysae are commonly filled by a white radial fibrous zeolite, identified by XRD (x-ray diffraction) as mordenite. Mordenite is a common zeolite widely found in silica-rich rocks; the occurrence of fine euhedral crystals, such as those that fill the cavities in the rhyolite dike, typically indicates a hydrothermal genesis (Ostroumov and Corona-Chávez, 2003).

44.2 Stop 6. The Rhyolite of Hash Rock.

STOP 6. THE RHYOLITE OF HASH ROCK

GPS coordinates -120.5723, 44.4955

The rhyolite of Hash Rock, part of a post-caldera flow field, forms a nearly continuous rim and plateau around the northern margin of the caldera (Figures 2 and 9). The northern margin of the lava extends outward from the caldera to Rooster Rock, where the lava terminates in a large landslide deposit. The relatively planiform rhyolite lava presently covers an area of ~50 km^2 (20 mi^2) and ranges in thickness from 180 m (600 ft) near Hash Rock and Rooster Rock to over 305 m (1,000 ft) at the viewpoint west of Whistler Springs. This lava was fed by fissure-conduits now preserved south of Hash Rock and at Twin Pillars (northeast, 65°).

The rhyolite is purple-gray, aphyric to sparsely plagioclase-phyric, with euhedral plagioclase laths up to 3 mm long. Outcrops typically are distinctly flow banded with tight flow-folds

Figure 11. Tightly folded flow banding typical of the Rhyolite of Hash rock. Pencil for scale at the left of photograph is 15 cm (6 in) long.

(Figure 11). A fresh glassy vitrophyre and dense lithophysal zones are locally common along intraflow margins and at the base of the lava. An $^{40}Ar/^{39}Ar$ age of 39.35 ± 0.30 Ma (plagioclase) was obtained from a sample on the plateau above the east fork of Mill Creek where the rhyolite overlies bedded airfall deposits related to the eruption of the Tuff of Steins Pillar. Similar to the Tuff of Steins Pillar, the Rhyolite of Hash Rock contains characteristically low contents of Nb (13.7–16.7 ppm), Zr (257–299 ppm), Y (26.6–36.6 ppm), La (37 ppm) and Ce (65–75 ppm) (Table 1). A geochemical analysis from the preserved remnant of the feeder conduit at Twin Pillars shows geochemical traits similar to that of the plateau-capping rhyolite lava (Table 1).

Following collapse of the Wildcat Mountain caldera, rhyolite lavas, domes, plugs, and dikes, geochemically similar to the Tuff of Steins Pillar, were emplaced along the structural margin of the caldera and intruded central portions of the intracaldera ash-flow tuff. These include rhyolites that form Hash Rock and Twin Pillars, as well as Strickland Butte, Forked Horn Butte, Wildcat Mountain, Brennan Palisades, Mahogany Butte, and numerous other less prominent ridges and buttes in and around Wildcat Mountain caldera (Figure 2). Most rhyolites intrude or overlie the intracaldera facies of the Tuff of Steins Pillar; no rhyolites have yet been identified that were definitively emplaced prior to caldera formation. Elongation of some rhyolite dikes and domes parallel to the caldera margin suggests that these complexes were likely erupted from ring-fracture fissures. Other rhyolite intrusions and dikes are elongated in a northwest-southeast direction parallel to the dominate structural fabric observed in local faults and pre-caldera intermediate dikes.

The arcuate ring-fractures of the caldera and local northwest-southeast oriented fault structures that allowed emplacement of rhyolite intrusions also served as conduits for upward movement of hot fluids after the main caldera subsidence phase. The

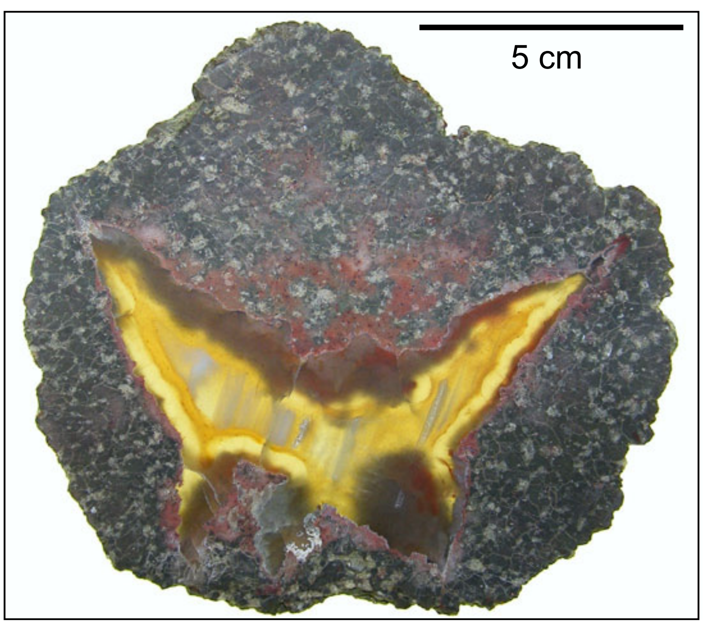

Figure 12. Butterfly wing, agate-filled geode (thunderegg) from the Lucky Strike Mine.

OPTIONAL HIKE 2 – TWIN PILLARS TRAIL #832 [north trailhead at Trail Meadows]

GPS coordinates -120.5323, 44.5149

The trail starts on the south side of the road, opposite the parking area. The trailhead, at an elevation of 1671 m (5483 ft), is the starting point for a 9.4 km (5.8 mi) round trip hike that enters the Mill Creek Wilderness and reaches the base of Twin Pillars, where there is a panoramic viewpoint of the Wildcat Mountain caldera (Figure 2). The well-maintained trail (#832) follows a relatively flat plateau across Bingham Prairie for 1.1 km (0.7 mi) and then ascends to the caldera rim at an elevation of ~1,792 m (5,880 ft). The trail descends the rim to the base of Twin Pillars at a distance of 4.7 km (2.9 mi) and an elevation of 1,645 m (5,400 ft). A short off-trail scramble up a moderately inclined talus slope reaches a nice viewpoint on the north-side of the 61 m (200 ft) tall monolith. Both the plateau of Bingham Prairie and the distinct rim north of the headwaters of Mill Creek are part of the Rhyolite of Hash Rock. Twin Pillars is a composite dike, composed of several east-west (90°) oriented planar sheets of blue-gray, plagioclase-phyric rhyolite marked by vertical flow banding (Figure 13). Landslide deposits, sourced in the oversteepened caldera wall, are exposed on the north and surround the base of Twin Pillars. From the base of Twin Pillars, return 4.7 km (2.9 mi) to the Bingham Prairie trailhead by the same route. Trail #832 also continues south along the east fork of Mill Creek where it ends at Wildcat Campground, 8.9 km (5.5 mi) from Twin Pillars. This part of the route travels along the east flank of the central resurgent dome where middle Eocene andesite and dacite lavas and domes are crosscut by numerous dacite and rhyolite intrusions.

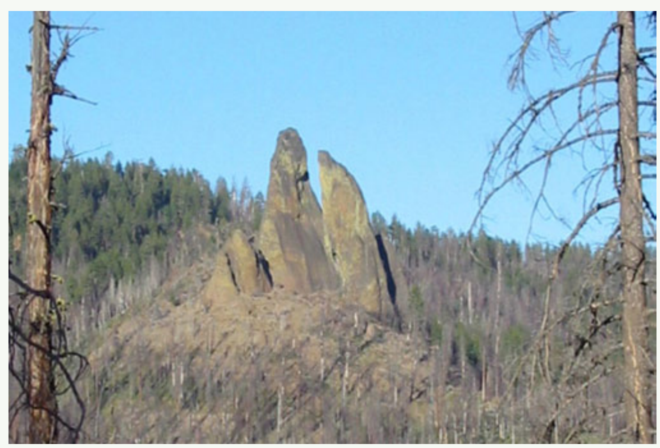

Figure 13. View north toward Twin Pillars from the interior of the Wildcat Mountain caldera. Twin Pillars is a composite dike, composed of several east-west (90°) oriented planar sheets of blue-gray, plagioclase-phyric rhyolite.

OPTIONAL HIKE 3 – WILDCAT MOUNTAIN TRAIL #833

GPS coordinates -120.4816, 44.4974

Trail #833 begins at Whistler Campground at an elevation of 1,744 m (5,720 ft) and enters the northeast part of the Mill Creek Wilderness (Figure 2). It is 14.2 km (8.8 mi) from Whistler Springs Campground on the north to White Rock Campground on the south. The first 3.2 km (2.0 mi) of the trail drops to an elevation of 1,645 m (5,400 ft) skirting the headwaters area of the east fork of Mill Creek. This stretch of the trail is underlain by thick exposures of the Rhyolite of Hash Rock and treks through woodlands that were severely burned during the 2000 Hash Rock fire. At the 3.9 km (2.4 mi) waypoint the trail again gains elevation to 1,707 m (5,600 ft) and traverses the east side of a high-standing intrusion of basaltic andesite. This intrusion is one of a number of basaltic andesite plugs and lavas emplaced along the arcuate caldera ring-fracture following the main subsidence phase. The basaltic andesites are calc-alkaline in chemical composition characterized by 54.79 to 56.92 wt. % SiO_2, 16.4 to 17.64 wt. % Al_2O_3, 1.17 to 1.43 wt. % TiO_2, 8.08 to 9.48 wt. % FeO, and 3.63 to 5.53 wt. % MgO (Figure 5 and Table 1). On the south, the plug intrudes lithic-dominated tuff breccia interpreted as part of the intracaldera facies of the Tuff of Steins Pillar. The breccia exposed here is directly juxtaposed against older early to middle Eocene andesite; this vertical, unfaulted depositional contact marks the trace of the caldera ring-fracture at this locality (Figure 14). From the 3.9 km (2.4 mi) waypoint to the 11.1 km (6.9 mi) waypoint, at the intersection with Belknap Trail 833a, the trail follows a fairly constant elevation along an open, narrow ridge-crest composed of andesite that is a remnant of the eastern topographic wall of the caldera. This ridge crest is topographically oversteepened towards the interior of the caldera and is locally intruded by rhyolite plugs. Open areas along the ridge crest offer panoramic views of the Wildcat Mountain caldera and the Pleistocene High Cascade volcanoes in the distance on the west. Belknap Trail #833a is a 3.7 km (2.3 mi) long spur that connects to Twin Pillars Trail #832. A 1.8 km (1.1 mi) side-trip down the Belknap Trail #833a reaches a prominent exposure at an elevation of 1,524 m (5,000 ft) of an east-west trending breccia dike that intrudes one of the post-subsidence rhyolite plugs (Figure 2). From the intersection with Belknap Trail #833a to the end of Trail #833, the route follows along a ridge of andesite basement rock. Near the 13 km (8.1 mi) waypoint to trails end at White Rock Campground, Trail #833 passes across a large landslide deposit composed of chaotic blocks of rhyolite derived from Wildcat Mountain on the west.

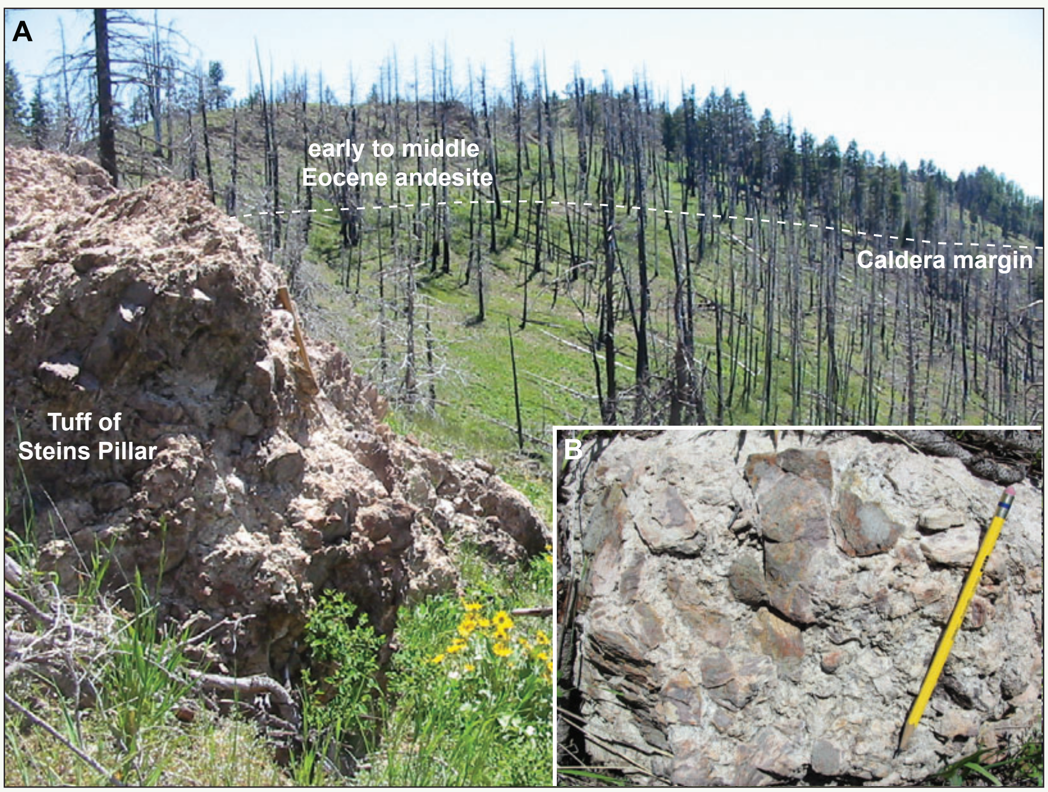

Figure 14. Lithic-rich intracaldera tuff exposed along Wildcat Mountain Trail #833. (a) Tuff is directly juxtaposed against early to middle Eocene andesite that forms the wall of the Wildcat Mountain caldera. (b) Close-up view of the lithic-rich tuff. Pencil for scale at the right of photograph is 15 cm (5.9 in) long.

rhyolite dome complex at Strickland Butte along the western margin of the caldera is associated with hydrothermal alteration and fracture-coating mercury mineralization; this area was a site of past mineral exploration and limited resource production. Most notably, the area between Kidnap Springs and Strickland Butte was the site of ca. 1940s mercury mine developed in variably silicified rhyolite (Brooks, 1963). Numerous other locations along the ring fracture of the caldera also show evidence of mercury mineralization; agate-filled geodes are locally abundant, associated with lithophysal zones within or at the base of rhyolite lavas and margins of intrusions (Figure 12).

44.8 *Turn right on USFS Road 27 and travel 2.2 miles east to Trail Meadows. [Cautionary note. The route across USFS 27 may at times be impassable due to fallen trees blown down during frequent high-energy wind storms across this part of the Ochoco Mountains.]*

47.0 *Trail Meadows, keep right on USFS 27.*

47.8 ***Optional hike*** *(see OPTIONAL HIKE 2 – TWIN PILLARS TRAIL #832, page 18)*. Trailhead parking for Twin Pillars trail #832. The parking area is on the left side of the road. Leaving the trailhead, continue on the field trip route 3.0 miles east on USFS Road 27 from the Twin Pillars trailhead to the intersection with USFS Road 200/Whistler Road.

50.7 *Left turn onto USFS Road 200/Whistler Road*. ***Optional hike*** *(see OPTIONAL HIKE 3 – WILDCAT MOUNTAIN TRAIL #833, page 19)*. Trailhead parking for Wildcat Mountain trail #833. A right turn enters Whistler Spring campground, a popular site for public geode prospecting and trailhead for the Wildcat Mountain Trail #833. The access road is maintained but has a seasonal closure due to snow.

53.9 ***Optional Stop.*** *Follow access road to the parking area (GPS coordinates -120.4966, 44.5178) for the Lucky Strike Mine, a mining claim that produces precious agate-filled geodes derived from a lithophysal zone at the base of the Rhyolite of Hash Rock (Figure 12). A fee for collection, based on the weight of mined products, is charged by the mine operators. Please inquire at the mine office for information. The mines are generally open from 8 am to 5 pm, mid May through mid November as weather permits. Leaving the mine access road, proceed past the access road 1.3 miles on USFS 200 to the intersection with USFS Road 2730.*

55.2 *Right turn on USFS Road 2730. Proceed 11 miles on USFS Road 2730 to the intersection with US 26.*

66.2 *Right turn on US 26. Continue west 1.1 mile west along Marks Creek to Stop 7.*

67.3 *Stop 7. Turn left on USFS Road 2630 (Crystal Springs Road) and park near the restroom facilities.* The knob-forming outcrops east of the road, in the center of the valley are the subject of stop 7.

Figure 15. Outcrop of porphyritic andesite at stop 7, along Marks Creek.

STOP 7. MIDDLE EOCENE PORPHYRITIC ANDESITE

GPS coordinates -120.4029, 44.4809

The Wildcat Mountain caldera is part of a larger igneous complex, known as the Ochoco volcanic field, that consists largely of andesite and dacite lavas, domes, and intrusions (Figure 15). The outcrops along Marks Creek consists of porphyritic andesite characterized by blocky, equant phenocrysts of plagioclase up to 3 to 4 mm across, with lesser amounts of hornblende and hypersthene set in a fresh appearing glassy groundmass. Subvertical to vertical flow foliations are common. The porphyritic andesite contains characteristically low amounts of Zr, Y, Nb, La, and Ce (Table 1). Coarse-grained porphyritic rocks are associated with more aphyric varieties. The contact relations between the two lithologies are typically diffuse and complex. The gradational nature of the porphyritic to aphyric rocks over tens of meters limits the mappable demarcation of distinct lithologies in the field, and suggests these rocks may have been part of overlapping dome and flow fields or shallow, subvolcanic intrusive masses. Elsewhere in the Ochoco volcanic field, closely spaced vertical bands or "dikes" of coarse-grained, porphyritic andesite and dacite, with locally abundant granitic xenoliths up to 3 m (9.8 ft) across have been observed within outcrops of similar lithology. Abundant granitic xenoliths suggest the Ochoco volcanic field may have been underlain by comagmatic granitic intrusions.

Coarse-grained porphyritic andesite, such as that exposed along Marks Creek, records the earliest phases of magmatism within the Ochoco Volcanic field. Similar rocks exposed at Harvey Gap on the west flank of the Wildcat Mountain caldera have an $^{40}Ar/^{39}Ar$ age of 43.86 ± 0.89 Ma (Ferns and McClaughry, 2007), the oldest high-precision radiometric age reported for rocks in the Ochoco volcanic field. Walker and Robinson (1990) report a K/Ar age of 53.7 ± 1.0 Ma for andesite from a locality somewhere near Cadle Butte (?), 27 km (17 mi) southwest of stop 7, but the date is of uncertain quality, location, and stratigraphic position.

74.2 ***Optional stop.*** White Fir Springs thunderegg collecting locality (GPS coordinates -120.5447, 44.4228). *Turn right off US Highway 26 onto USFS Road 3350 and proceed 4.5 miles to the collecting area at White Fir Springs.* This site on the Ochoco National Forest is open to the public (no fee) and offers colorful jasper-filled geodes. White Rock Campground is an additional 2.4 miles up USFS Road 3350. The access road is maintained but has a seasonal closure due to snow. White Rock Campground (GPS coordinates -120.5508, 44.4073) provides trailhead access to the south part of Wildcat Mountain Trail #833 *(see OPTIONAL HIKE 3 – WILDCAT MOUNTAIN TRAIL #833, page 19)*. *Continuing past USFS Road 3350, return to Prineville on US Highway 26.*

94.9 *Ochoco National Forest Office in Prineville.* **End of field trip.**

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$^{40}Ar/^{39}Ar$ age determinations were prepared and analyzed by John Huard at the College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis. X-ray fluorescence (XRF) geochemical analyses were prepared and analyzed by Stanley Mertzman, Franklin and Marshall College, Lancaster, Pennsylvania. Analytical procedures for the Franklin and Marshall X-ray laboratory are described by Boyd and Mertzman (1987) and Mertzman (2000) and are available online at http://www.fandm.edu/x7985. Geochemical analytical results, shown in Table 1, have been normalized on a volatile-free basis and recalculated with total iron expressed as FeO*.

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John Day Fossil Beds National Monument

The Turtle Cove Member, exposed in the Painted Hills and Sheep Rock Units of the John Day Fossil Beds National Monument, is the thickest and most regionally extensive member in the "eastern" facies of the John Day Formation. This part of the John Day Formation, ranging in age from ca. 30.4–22.6 Ma, is famous for its picturesque blue-green tuffs, spectacular pinnacled peaks, and rich fossil record. Prominent tuff marker beds that punctuate the fossil-bearing sedimentary sections in the national monument have provided an important time-datum that has allowed for the detailed characterization of one of the richest fossil records of Tertiary plants and animals in North America.

Carroll Rim (top left) in the Painted Hills consists of a succession of paleosols, punctuated by at least three distinct tuff marker beds. Carroll Rim itself is formed from the Member H tuff. A moderately strenuous 0.5 mi hike ascends Carroll Rim on the northeast and offers a spectacular viewpoint of the Painted Hills and outcrops of fallout and ash-flow tuffs that are part of the Turtle Cove Member ("eastern" facies) of the John Day Formation. A short walk up the hill to the south reaches the Painted Hills overlook which views the red banded badland hills of the older Big Basin Member.

The **Thomas Condon Paleontology Center** in the Sheep Rock Unit of the John Day Fossil Beds National Monument features exhibits that showcase some of the spectacular paleontological specimens that have been recovered from the John Day Formation. A short hike up the trail that begins near the south end of the parking area ascends to an overlook of **Sheep Rock and the John Day River (top right)**. Sheep Rock is formed from a well-exposed section of the Turtle Cove Member, which here consists of an assemblage of blue-green to tan variably zeolitized siltstones and paleosols and interbedded tuffs. The Member H tuff forms a prominent marker bed at the midpoint of the stratigraphic section. The section at Sheep Rock is capped by a remnant of middle Miocene Columbia River Basalt.

(photo credits: Jason McClaughry, DOGAMI)

Field trip guide to the Oligocene Crooked River caldera: Central Oregon's Supervolcano, Crook, Deschutes, and Jefferson Counties, Oregon

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Overview: This field trip examines the stratigraphy of the Oligocene Crooked River caldera near Prineville, Oregon, and visits three of central Oregon's state parks—Prineville Reservoir, Smith Rock, and Peter Skene Ogden—where key features of the caldera geology are prominently exposed. Geologic factors that control regional groundwater flow, mineralization, and landslide deposits in the Lower Crooked Basin are discussed. This field trip is 185 km (116 mi).

INTRODUCTION

The Crooked River caldera, in the western part of the Lower Crooked Basin, is a large vent complex that collapsed and filled with more than 580 km^3 (139 mi^3) of rhyolitic ash-flow tuff during the Oligocene. Although the caldera forms a large volcano-tectonic depression with a remarkable semi-elliptical topographic expression, it was not identified until recently (McClaughry and Ferns, 2006a, 2007). Including the ~41.50–39.34 Ma Wildcat Mountain caldera exposed along the crest of the Ochoco Mountains (McClaughry and others, 2009a) and the ~29.8–28.1 Ma Tower Mountain caldera (Ferns and others, 2001) in northeast Oregon, recognition of the Crooked River caldera brings to only three the number of Paleogene calderas identified and detailed in Oregon (Figure 1). Geologic studies suggests two additional calderas of Oligocene to early Miocene age in the southwest Oregon Cascades, but these have yet to be fully mapped (Hladky and Wiley, 1993; Hladky, 1996).

The rocks that form the Crooked River caldera are correlative with the late Eocene to earliest Miocene (?) John Day Formation, a dissected belt of volcanogenic sedimentary rocks, mafic lavas, rhyolite domes and lavas, and widespread rhyolite ash-flow tuff sheets (Swanson, 1969; Robinson, 1975; Robinson and Stensland, 1979; Robinson and Brem, 1981; Robinson and others, 1984, 1990; Smith and others, 1998) that cover much of central Oregon (Figure 1). Investigators in Oregon have long

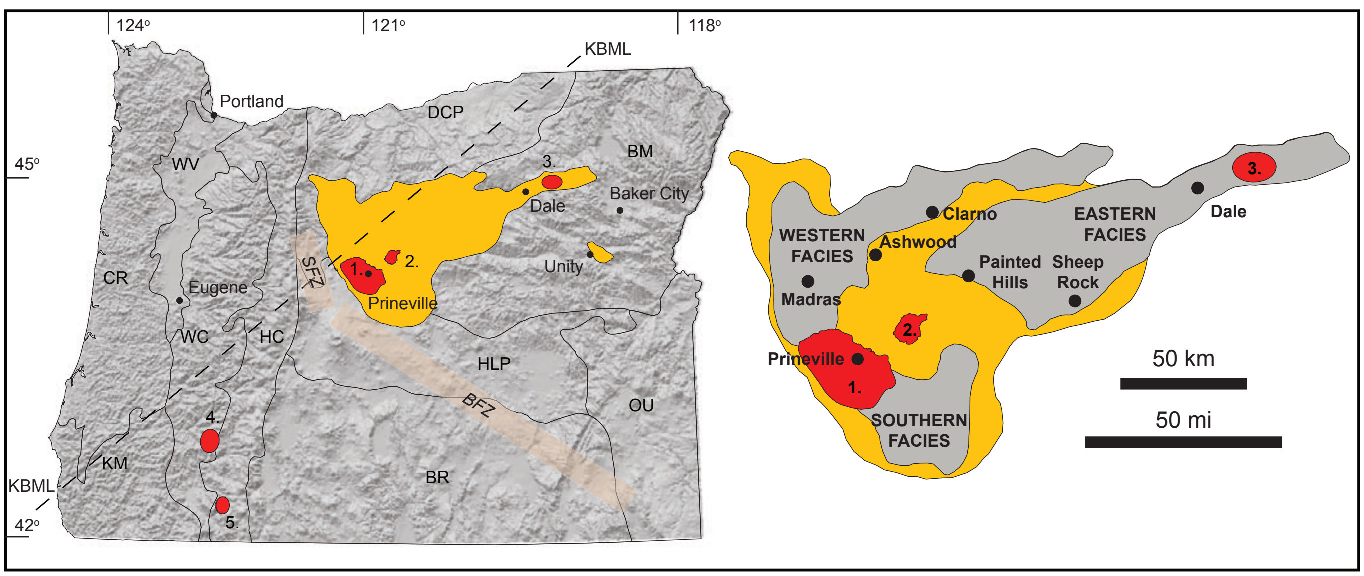

Figure 1. (left) Location of Paleogene age calderas in Oregon. Red-filled polygons are calderas: (1) Crooked River caldera; (2) Wildcat Mountain caldera; (3) Tower Mountain caldera; (4, 5) unnamed, suggested calderas. Orange shade represents the approximate distribution of ash-flow tuffs in the late Eocene to early Miocene John Day Formation. Dashed black line labeled KBML is the inferred trace of the Klamath-Blue Mountain gravity-anomaly lineament. Solid black lines demarcate physiographic provinces (after Walker, 1977). SFZ, Sisters Fault Zone; BFZ, Brothers Fault Zone. Solid black lines demarcate physiographic provinces (after Walker, 1977): WV - Willamette Valley;CR - Coast Range; KM - Klamath Mountains; WC - West Cascades; HC - High Cascades; DCP - Deschutes Columbia Plateau; BM - Blue Mountains; HLP - High Lava Plains; BR - Basin and Range; OU - Owyhee Uplands. (right) Enlarged central part of area shows the distribution of the "western," "southern," and "eastern" facies of Robinson and others (1990) within the John Day Formation.

speculated on the sources of ash-flow tuffs in the John Day Formation (Robinson and others, 1984, 1990), but recognition of corresponding calderas has been hindered by limited detailed regional geologic mapping. Regional workers have suggested that pyroclastic rocks within the John Day Formation were vented from a nascent West Cascade Range or were erupted near the eastern margin of the present-day Cascades (Robinson, 1975; Robinson and Brem, 1981; Robinson and others, 1984, 1990; Bestland and others, 2002). From volume estimations of ash-flow tuffs within the formation, Robinson and others (1990) concluded that such eruptions would not have resulted in collapse calderas. Therefore, small inlier Oligocene rhyolite domes at Powell Buttes, Grizzly Mountain, and Juniper Butte were suggested as eruptive sites (Swanson, 1969; Robinson and others, 1984, 1990) as well as the Smith Rock-Gray Butte area (Obermiller, 1987; Smith and others, 1998). The Crooked River caldera is a volcanic vent much larger than the small, isolated eruptive centers envisaged by preceding workers and is comparable in size to some of the largest calderas known worldwide (Table 1).

Location and geologic setting

The Crooked River caldera forms a ~41 km × 27 km (25 mi × 17 mi), semi-elliptical, northwest-southeast elongated volcano-tectonic depression whose partially eroded remains form the western part of the Lower Crooked Basin between Prineville and Redmond in central Oregon (Figure 2). The main subsidence area of the caldera extends from Gray Butte on the northwest, along the western front of the Ochoco Mountains, and to the southeast nearly to Prineville Reservoir. It is drained by the through-flowing Crooked River, for which the structure is named, and the tributaries of Ochoco Creek and McKay Creek.

The caldera is coincident with a relatively undissected structural area juxtaposed between the Klamath-Blue Mountain gravity-anomaly lineament and the Brothers and Sisters fault zones (Figure 3). Two major fault zones that parallel the northeast trend of the Klamath-Blue Mountain gravity-anomaly lineament bracket the caldera. The Cyrus Springs fault zone (Smith and others, 1998) bounds the northwest margin while the Prineville Reservoir fault zone bounds the southwest margin. These lineaments define a circumferential, peripheral fault zone that mimics the arcuate structural margin of the caldera. This peripheral fault zone extends at least 10 km (6 mi) outside the main area of subsidence and is associated with numerous small rhyolite intrusions (Figure 2).

Two distinct suites of precaldera rocks enclose the intracaldera ash-flow tuff. Along the northeast sector of the caldera, intracaldera ash-flow tuff is juxtaposed directly against Eocene calc-alkaline andesite to dacite domes and lavas. These rocks make up part of the Ochoco volcanic field, a ca. 10–13 My older complex of variably exhumed Eocene silicic volcanic and intrusive rocks, which are part of the Clarno Formation. Development of the Ochoco volcanic field culminated with the eruption of the Tuff of Steins Pillar and collapse of the Wildcat Mountain caldera between 41.5 and 39.35 Ma (McClaughry and others, 2009). Late Eocene to early Oligocene (36 to 30 Ma) interstratified rhyolite ash-flow tuffs, Fe- and Ti-rich mafic to intermediate lavas and volcaniclastic rocks correlated to the John Day Formation unconformably overlie rocks of the Ochoco volcanic field and form the northwest and southeast sectors of the caldera wall. These John Day age rocks were deposited onto middle Eocene calc-alkaline volcanic rocks in a subsiding basin that developed marginally to the Ochoco volcanic field in the middle Eocene to early Oligocene (Smith and others, 1998). The southwest margin of the caldera is poorly defined, as the ring-fracture here is completely buried by relatively undeformed middle Miocene to Pleistocene basalt lavas and sedimentary rocks.

John Day Formation stratigraphy

The regional stratigraphy of the John Day Formation was established by Peck (1964), Fisher and Rensberger (1972), Robinson and Brem (1981), and Robinson and others (1990). Robinson and Brem (1981) divided the formation into "western," "southern," and "eastern" facies. The "western" facies is divided into members designated alphabetically from A to I (Peck, 1964; Robinson and Brem, 1981; and Robinson and others, 1990). The "eastern" facies is divided into four members that include from oldest to youngest the Big Basin, Turtle Cove, Kimberly, and Haystack Valley members (Fisher and Rensberger, 1972). The "southern" facies has not been formally divided into members. The base of the John Day Formation has generally been defined by the regionally widespread Member A ash-flow tuff, which has returned $^{40}Ar/^{39}Ar$ ages of 39.72 ± 0.03 Ma near the Painted Hills (Bestland and Retallack, 1994b; Retallack and others, 2000), 39.22 ± 0.03 Ma near Clarno (Bestland and Retallack, 1994a), and 39.17 ± 0.15 Ma near Ashwood (Smith and others, 1998). Many workers consider the Member A ash-flow tuff to be a distinct time-stratigraphic horizon that demarcates the migration of volcanism away from the Clarno arc toward a volcanic axis centered along a nascent Cascade arc and backarc settings east of the Cascades (Robinson, 1975; Robinson and Brem, 1981; Robinson and others, 1984; Robinson and others, 1990; Bestland, 1997; Bestland and others, 2002). An ash flow, defined as Member I, near the top of the formation has been dated at 27.7 ± 0.3 Ma (K/Ar) but may be as young as 22 Ma (?) (Robinson and others, 1990).

Rocks of the Crooked River caldera straddle a stratigraphic discontinuity between the "western" and "southern" facies of the John Day Formation and are correlative with Members G and H of Peck (1964) and Robinson (1975). The Tuff of Smith Rock, correlative with Member G of the "western" facies, has returned $^{40}Ar/^{39}Ar$ ages of 29.53 ± 0.09 Ma and 29.57 ± 0.17 Ma at Haystack Reservoir (Smith and others, 1998) and 29.56 ± 0.17 Ma at McKay Saddle (Table 2 [located before References section]). These dates are indistinguishable from geochemically similar John Day Formation Member G tuffs exposed north of the Crooked River caldera that have returned similar $^{40}Ar/^{39}Ar$ ages of 29.61 ± 0.10 Ma west of Teller Flat and 29.54 ± 0.10 Ma near Antelope (Smith and others, 1998; Table 2). The Tuff of

Barnes Butte, erupted between 29.56 and 27.97 Ma, is stratigraphically correlative with Member H of the western facies (Peck, 1964; Robinson, 1975). Smith and others (1998) report an $^{40}Ar/^{39}Ar$ age of 27.62 ± 0.63 Ma for the Member H tuff exposed at Haystack Reservoir.

Ash-flow tuffs erupted from the Crooked River caldera are temporally correlative to the Turtle Cove Member in the "eastern" facies. The Turtle Cove Member includes two distinct airfall tuffs beneath Carroll Rim in the Painted Hills that have concordant $^{40}Ar/^{39}Ar$ ages of 29.75 ± 0.02 Ma and 28.70 ± 0.06 Ma (Bestland and Retallack, 1994b; Retallack and others, 2000). The Member H ash-flow tuff ("Picture Gorge ignimbrite"; Fisher, 1966; Robinson and others, 1984) capping Carroll Rim has $^{40}Ar/^{39}Ar$ ages of 28.65 ± 0.05 Ma and 28.65 ± 0.07 Ma (Retallack and others, 2000).

Table 1. Compilation of some of the largest known explosive eruptions on Earth, including the Crooked River caldera. The table includes caldera-forming eruptions at Crater Lake and Newberry Volcano in Oregon for regional reference. Red ellipses show relative areas of the collapse structures. Gray fill indicates the three Paleogene-age calderas identified in Oregon. Data are from references cited in the table and from Mason and others (2004). Ma is millions of years ago.

Caldera Name and Location	Related Ash Flow Unit(s)		Caldera Diameter (km)	Deposit Bulk Volume (km3)	Age (Ma)	Reference
La Garita (Colorado, USA)	Fish Canyon Tuff		100 × 35	5000	27.8	Lipman (1997)
Toba (Indonesia)	Younger Toba Tuff		100 × 30	2800	0.074	Rose and Chesner (1987)
Yellowstone (Wyoming, USA)	Huckleberry Ridge Tuff		100 × 50	2450	2	Christiansen (1984, 2001)
Yellowstone (Wyoming, USA)	Lava Creek Tuff		85 × 45	1000	0.6	Christiansen (1984, 2001)
Blue Creek (Snake River Plain, Idaho, USA)	Blue Creek Tuff		55 × 30	500	5.6	Morgan and others (1984)
McDermitt complex (Nevada, Oregon USA)	Double H Tuff and Long Ridge Tuffs (3 members)		45 × 30	1030	15.7–15.6	Rytuba and McKee (1984); Castor and Henry (2000)
Crooked River (Oregon, USA)	Smith Rock Tuff		41 × 27	> 580	29.5	this report; McClaughry and Ferns (2007)
Long Valley (California, USA)	Bishop Tuff		35 × 20	500	0.7	Bailey (1976)
Tilzapotla (Guererro State, Mexico)	Tilzapotla Tuff		33 × 24	> 600	34	Moran-Zenteno and others (2004)
Virgin Valley (Nevada, USA)	Idaho Canyon Tuff		20 to 25	?	16.3	Castor and Henry (2000)
Twin Peaks (Idaho, USA)	Challis Creek Tuff		20	500	45	Hardyman (1981)
Wildcat Mountain (Oregon, USA)	Steins Pillar Tuff		16 × 11	~90	40	McClaughry and others (2009)
Tower Mountain (Oregon, USA)	Dale Tuff		14	~90	28.5	Ferns and others (2001)
Mahogany Mountain (Oregon, USA)	Leslie Gulch Tuff		20 × 15	360	15.5	Vander Meulen (1989)
Unknown (Harney Basin, Oregon, USA)	Rattlesnake Tuff	?	unknown	332	7.05	Streck and Grunder (1995)
Henry's Fork (Island Park, Idaho, USA)	Mesa Falls Tuff		19	280	1.3	Christiansen (1984, 2001)
Three Fingers (Oregon, USA)	Spring Creek Tuff		~16 × 13	?	15.4	Vander Meulen (1989)
Big Cottonwood Canyon (Nevada, USA)	Big Cottonwood Canyon		≥ 15	?	39.7	Castor and others (2003)
Crater Lake (Oregon, USA)	Deposits of climactic eruption		10 × 8	50	0.007	Bacon and Lanphere (2006)
Newberry (Oregon, USA)	Tepee Draw Tuff, basaltic andesite lapilli tuff		7 × 5	> 10	0.5–0.3	Linneman (1990); MacLeod and others (1995)

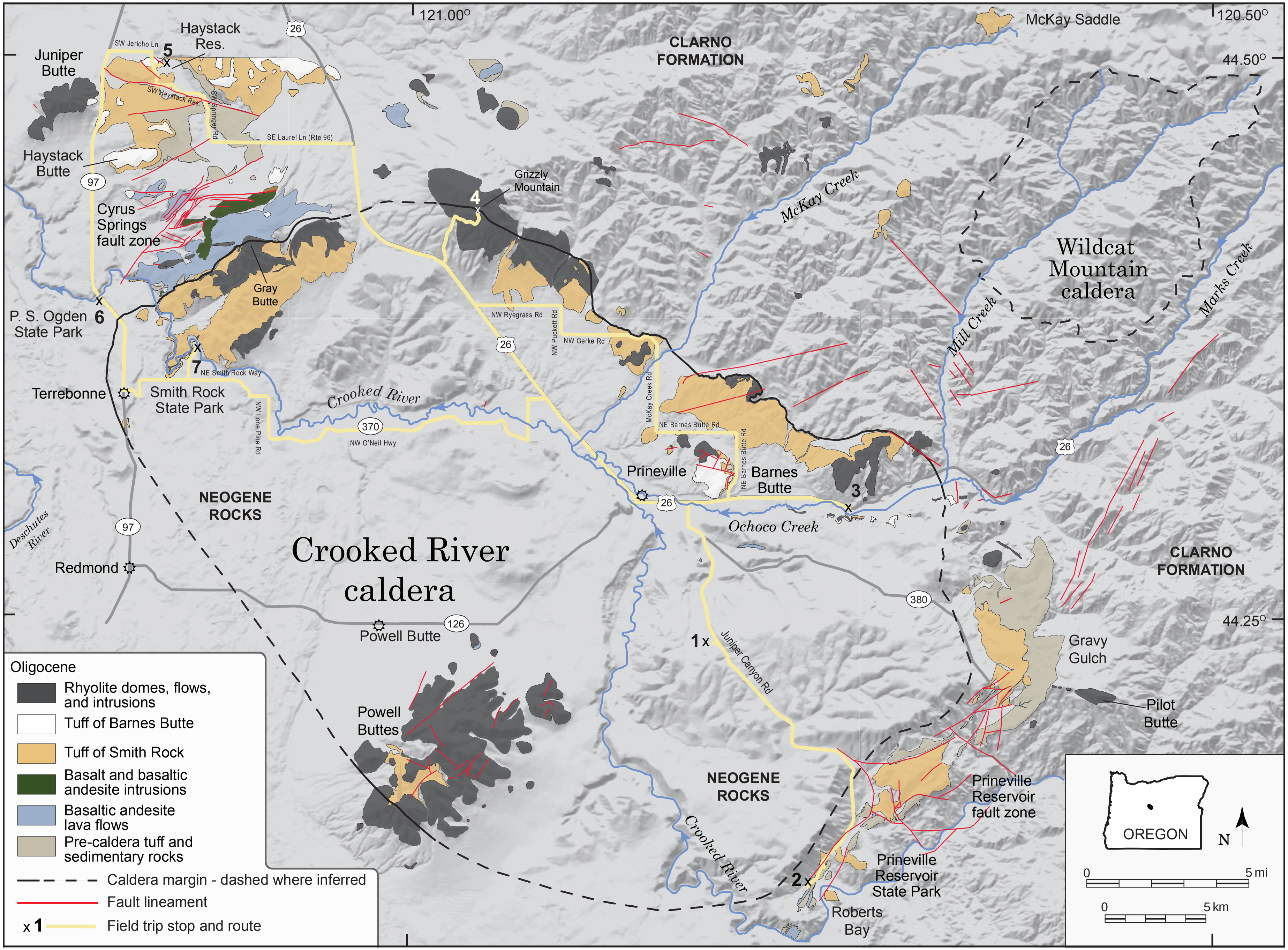

Figure 2. Simplified geologic map of the Crooked River caldera labeled with field trip route and associated stops 1 through 7. See facing page for additional description.

FIELD TRIP GUIDE

Note: Road logs are reported in miles [black-boxed numbers] to match most car odometers. GPS coordinates, recorded in longitude and latitude (NAD 27, deg.dddd), are given for each field stop. Compass directions to points of interest are given in azimuthal format. Metric system units are used for all scientific measurements; corresponding standard U.S. units are given in parentheses.

Objectives of this field trip

This field guide is for a one-day trip through the western part of the Lower Crooked Basin and provides an overview of the Crooked River caldera. Emphasis in the guide is placed on the general stratigraphy of the caldera and the geologic factors that control regional groundwater flow, mineralization, and landslide deposits in the Lower Crooked Basin. Discussion includes how the caldera and its deposits relate to the regional stratigraphy of the John Day Formation. Additionally, the field trip route visits Prineville Reservoir, Smith Rock, and Peter Skene Ogden state parks where key features of the caldera geology can be seen. Field trip mileage begins and ends at the Ochoco National Forest Office in Prineville.

Figure 2 (facing page), additional description: Simplified geologic map of the Crooked River caldera labeled with the field trip route and associated stops numbered 1 through 7. The main volcanic units are identified on the map. Rhyolite domes form prominent highs that encircle the basin and intrude the Tuff of Smith Rock. The caldera is inset into a deeply eroded section of middle to late Eocene andesite and dacite domes and lavas exposed along northeast margin of the caldera. On the northwest and southeast, the caldera margin is defined by faulted late Eocene to early Oligocene ash-flow tuffs, Fe- and Ti-rich lavas, and sedimentary strata. Neogene rocks obscure the southwest margin between Terrebonne and Powell Buttes. The structural fabric at the northwest and southeast margins of the caldera is perpendicular to the Sisters-Brothers fault zone and is related to caldera forming events. The northeast trending Cyrus Springs fault zone (Smith and others, 1998) is defined by lack of stratigraphic continuity from north to south. Strata south of the fault zone dip 20°–35° south, are cut by numerous dikes within and parallel to fault zone, and have been hydrothermally altered. Smith and others (1998) constrain the onset of structural disruption along this fault zone between 28 and 30 Ma. The southeastern margin of the caldera is defined by ~N45°E striking and northwest-dipping (45°–55° NW) early Oligocene strata that are cut by northeast trending faults near Prineville Reservoir. Arcuate lineaments that mimic the structural margin of the caldera also offset Eocene rocks in the Ochoco Mountains to the north.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 1

En route to stops 1 and 2 the field trip passes through middle Miocene to Pliocene lavas of the Prineville Basalt and the Deschutes Formation that unconformably overlie the Oligocene caldera stratigraphy. Basalt lavas of the Miocene to Pliocene Deschutes Formation were erupted from vents within the Lower Crooked Basin, while the older middle Miocene Prineville Basalt was likely erupted farther south. Lavas erupted during both the Prineville and Deschutes volcanic episodes flowed north, following ancestral channels of the Crooked River that were incised into the underlying stratigraphy of the Crooked River caldera. Local basalt eruptions and inundation of the Crooked River with basalt lavas ceased during the middle Pliocene. Subsequent erosion has removed much of the basalt cover in the basin and has now exhumed Crooked River caldera-related rocks to their present stratigraphic level.

Begin field trip mileage:

0.0 *Start field trip at U.S. Forest Service (USFS) complex on east end of Prineville and proceed left onto US 26.*
0.9 *Left turn onto Combs Flat Road.*
2.3 *Right turn (south) onto Juniper Canyon Road.*

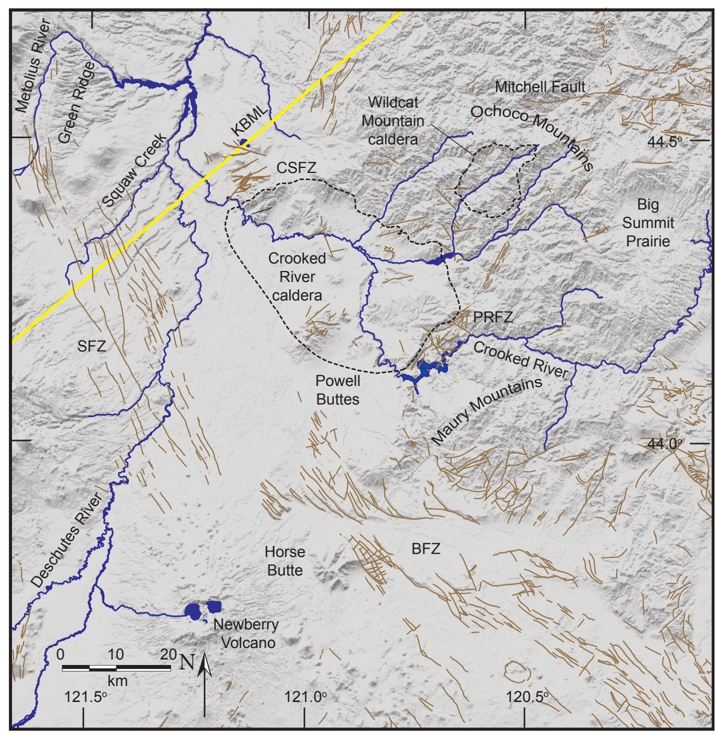

Figure 3. Fault lineament map of central Oregon with caldera structures delineated in the Lower Crooked Basin. The Crooked River caldera is coincident with the junction of the northwest trending Brothers fault zone (BFZ) and the north-northwest trending Sisters fault zone (SFZ). Northeast trending fault zones, including the Cyrus Springs fault zone (CSFZ) (Smith and others, 1998) and Prineville Reservoir fault zone (PRFZ), define the northwest and southeast margins of the caldera. The Cyrus Springs fault zone is coincident in location and trend with the Klamath-Blue Mountain gravity-anomaly lineament (KBML) (Riddihough and others, 1986).

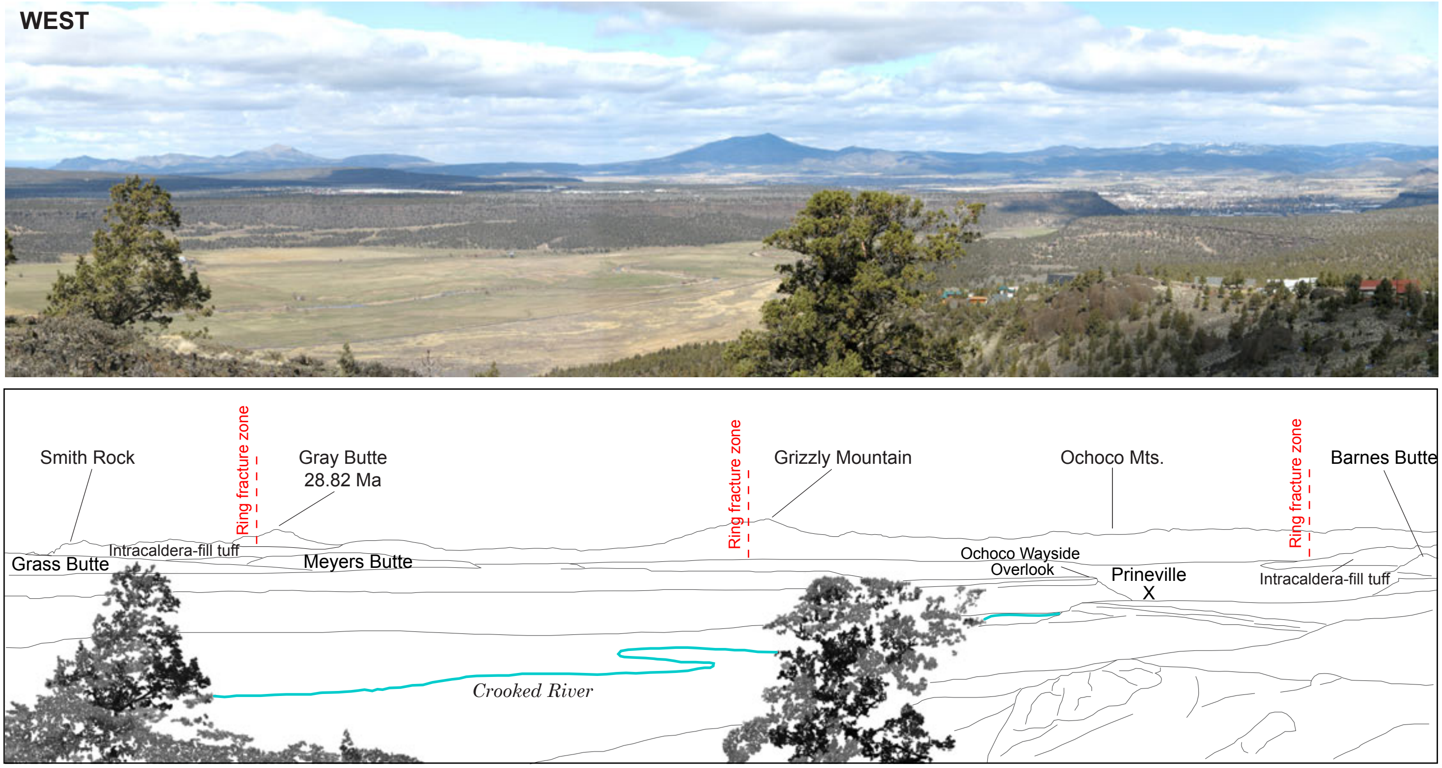

Figure 4. View looking north from stop 1 (continued on next page). Line drawing highlights parts of the Crooked River caldera visible from Bonnie Road.

5.7 *Right turn onto Bonnie Lane.*
6.0 *Stop 1, along Bonnie Lane.*

STOP 1. GEOLOGIC OVERVIEW

GPS coordinates: –121.8108, 44.2402

Stop 1 provides an overview of the Lower Crooked Basin and the main components of the Crooked River caldera (Figure 4). The Crooked River caldera is the major vent feature of the Lower Crooked volcanic field, an area of ~1,500 km^2 (580 mi^2) in the western part of the Lower Crooked Basin underlain by Oligocene silicic tuff and rhyolite dome complexes, and tholeiitic basalt, and basaltic andesite and andesite lavas and intrusions (Figure 2). Although previous workers (Swanson, 1969; Robinson and Stensland, 1979; Robinson and others, 1984, 1990) have correlated these rocks with various members of the John Day Formation, lithologic distribution, geochemistry, geochronology, and structure now delineate these rocks as a discreet, mappable volcanic field. The field is entirely preserved within the arcuate peripheral fault zone of the Crooked River caldera and is entirely Oligocene in age (Figures 2 and 3). Mafic rocks within the Lower Crooked volcanic field are distinctly tholeiitic, with enriched Fe and Ti contents and relatively low amounts of Al. Silicic rocks in the Lower Crooked volcanic field are characterized by elevated trace-element abundances for Ba (barium), Zr (zirconium), Y (yttrium), and Nb (niobium) and, generally, have higher abundances for the light rare-earth elements (LREE) of La (lanthanum) and Ce (cerium) (see Table 3).

The Crooked River caldera is characterized by a combination of thickly ponded silicic pumice-lithic ash-flow tuff, nearly vertical caldera-bounding faults, rhyolite dome complexes that surround the structure, and a corresponding regional relative gravity low. Middle Eocene to early Oligocene stratigraphy exposed outside the caldera is everywhere absent within the inferred ring-fracture. All these features are consistent with caldera formation (Williams, 1941; Smith, 1960; Smith and Bailey, 1968; Lipman, 1976, 1984, 1997; Christiansen, 2001). The caldera developed through five stages: (1) a series of Fe- and Ti-rich tholeiitic basaltic andesites and andesites compositionally similar to icelandite erupted from volcanic centers between Haystack and Prineville reservoirs between 36 and 30 Ma. These lavas and intrusions apparently coincide with the onset of volcanism in the Lower Crooked volcanic field. (2) Eruption of the Oligocene Tuff of Smith Rock accompanied the major subsidence phase of the Crooked River caldera at 29.56 Ma. (3) Large (20–80 km^2; 8–31 mi^2) fields of rhyolite lavas, domes, and intrusions were emplaced along the structural margin between ca. 28.8 and 25.8 Ma when major volcanic activity in the field ceased. Rhyolite domes and flows are prominently exposed at Powell Buttes (SSW, 240°, not visible; 28.3, 25.8 Ma), Gray Butte (NW, 310°; 28.82 Ma), Grizzly Mountain (NNW, 330°; no age data), Barnes Butte (NNW, 355°; 27.94 Ma), Ochoco Reservoir (NE, 35°; 27.54 Ma), and Pilot Butte (ESE, 100°; no age data), (Figures 2–4; Tables 2 and 3). (4) The Tuff of Barnes Butte

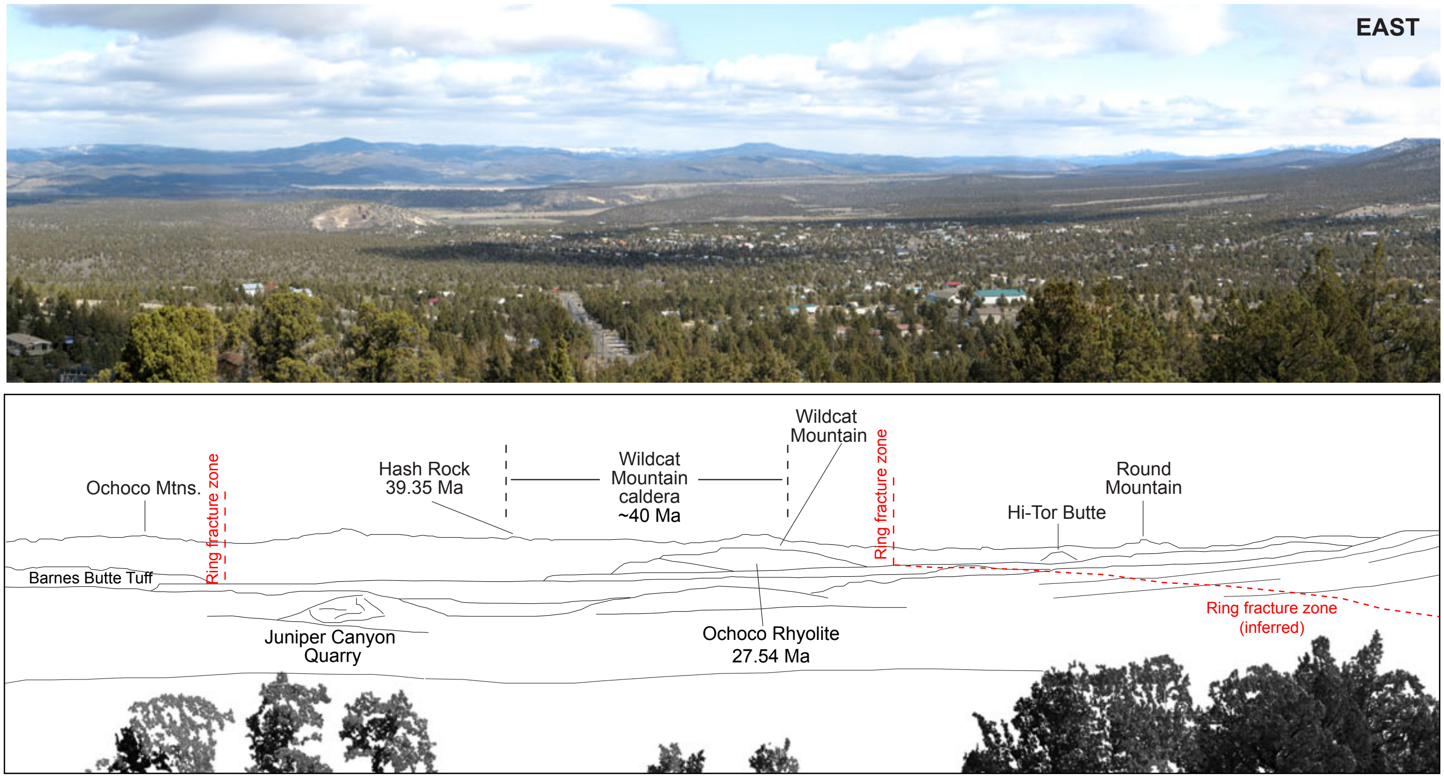

Figure 4, continued. View looking north from stop 1.

erupted between 29.56 and 27.97 Ma from a now obscure vent source in the southeast part of the Crooked River caldera. (5) Large hot-springs subsequently formed both within and around the periphery of the caldera. These deposited massive quartz and calcite veins (± cinnabar) along ring-fractures and peripheral fault structures as well as finely laminated to massive mudstones, siliceous pool sinter, and sinter breccia along the caldera wall.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 2

6.3 *Return east on Bonnie Lane. Right turn (south) onto Juniper Canyon Road. Drive south to stop 2.*

12.5 Traveling south, the field trip route leaves the ridge capping middle Miocene Prineville Basalt and drops down into the Antelope Creek drainage, where a northwest-dipping section of Oligocene ash-flow tuffs and interbedded Fe-rich basaltic andesite lavas is exposed. The ridge line to the left (east) is capped by outflow tuff from the Crooked River caldera. The skyline to the south is formed by northwest-dipping ash-flow tuffs that predate eruption of the caldera.

15.5 *Right turn on County Boat Ramp Road.* From mile points 15.5 to 16, Oligocene sedimentary rocks are exposed in road cuts on the right.

16.0 Fe- and Ti-rich basaltic andesite lava that overlies the early Oligocene Tuff of Antelope Creek.

16.9 *Stop 2, at Prineville Reservoir county boat ramp.*

STOP 2. PRE-CALDERA VOLCANIC STRATIGRAPHY

GPS coordinates: –121.7491, 44.1329

The northwest tilted section exposed at the Prineville County boat ramp consists of a pre-caldera succession of rhyolite tuffs, interbedded tholeiitic basaltic andesite lavas, and volcaniclastic sedimentary rocks that lie along the southeast caldera margin (Figure 5). Two early to middle Oligocene ash-flow tuffs, visible from the boat ramp, are part of the "southern" facies of the John Day Formation of Robinson and Brem (1981) (Figure 1). Although these ash-flow tuffs are compositionally similar to tuffs erupted from the Crooked River caldera, they are older and erupted from vents that are yet unknown (Table 3). The lower part of the section is formed by the Tuff of Eagle Rock, a strongly welded, sparsely feldspar-phyric, locally rheomorphic pumice-lithic tuff that is up to 50 m thick along the banks of the reservoir. Robinson and others (1990) report a K/Ar age of 32.1 ± 0.7 Ma (plagioclase) for this tuff near Eagle Rock, 10 km (6 mi) northeast of the boat ramp. The younger Tuff of Antelope Creek is a sparsely sanidine-phyric, devitrified, strongly welded and locally rheomorphic ash-flow tuff that is up to 30 m thick. The Tuff of Antelope Creek is geochemically similar to a thick crystal- and micro-pumice-rich fallout tuff exposed beneath Carroll Rim in the Painted Hills for which Retallack and others (2000) report a single crystal $^{40}Ar/^{39}Ar$ age of 29.75 ± 0.02 Ma.

Lavas interbedded with the ash-flow tuffs near the boat ramp mark the transition in the Lower Crooked Basin between the older Eocene calc-alkaline volcanism of the Ochoco volcanic field and the younger bimodal basalt and rhyolite volcanism associated with the Crooked River caldera (Figure 2). These lavas consist of both mafic and intermediate flows that are exposed along both the northwest and southeast margins of the caldera. Intermediate-composition rocks consist of tholeiitic basaltic andesite and andesite lavas, with chemical compositions similar to that of icelandite (Table 3). Petrographic and chemical characteristics of the intermediate flows indicate compositions similar to those reported by Robinson and Brem (1981) and Robinson and others (1990) for trachyandesites in Member B of the John Day Formation. Intermediate lavas are compositionally similar to a 30.8 ± 0.5 Ma intrusion (K/Ar, whole rock; Robinson and others, 1990) exposed along the northwest margin of the caldera north of Gray Butte and a 30.1 ± 1.1 Ma basaltic andesite lava (K/Ar, whole-rock; Evans and Brown, 1981) encountered in a geothermal test well that was drilled just west of Powell Buttes (Brown and others, 1980). The intermediate lavas are interbedded with a poorly exposed series of more mafic aphyric to sparsely olivine-phyric basalts north and west of Gray Butte (Table 3). Similar composition basalt lavas have not been found at Prineville Reservoir. Geochemical analyses of basalts indicate compositions similar to those reported by Robinson (1969), Robinson and Brem (1981), and Robinson and others (1990) for alkali olivine basalts found in Members E, F, and G north of the Lower Crooked volcanic field (Table 1).

The stratigraphic section exposed at the boat ramp lies within the Prineville Reservoir fault zone, a northeast trending structural zone on the southeastern margin of the caldera (Figure 2). The main zone of deformation is ~7 km (4 mi) wide by 16 km (10 mi) long and defines a northeast trending homocline pervasively cut by faults with both normal and reverse sense of displacement. Beds within the homocline generally strike N45°E and dip 45°–55° northwest back into the caldera (Figures 2 and 5). Outflow facies of the Tuff of Smith Rock overlie the deformed Oligocene section, separated by an angular unconformity. East of Prineville Reservoir, along O'Neil Creek, the outflow tuff is ponded against the tilted structural block and is itself faulted and warped with a northwest verging dip. The Tuff of Smith Rock is the youngest unit deformed in the fault zone. Combined stratigraphic and structural relationships within the Prineville Reservoir fault zone suggest that deformation of the Oligocene section of tuff and basaltic andesite occurred synchronously with formation of the Crooked River caldera and deposition of outflow facies of the Tuff of Smith Rock.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 3

18.3 *Return to Juniper Canyon Road. Left turn (north) onto Juniper Canyon Road.*

30.9 *Left turn on Combs Flat Road.*

32.3 *Right turn on US 26.*

36.4 A gravel quarry and prospect two thirds of the way up the cliff-face on the right exposes a brick orange outcrop of strongly welded, hydrothermally altered Tuff of Barnes Butte. Cavities in the tuff contain blood-red, opaque to translucent opal and white to black chalcedonic quartz. The alteration zone marks part of the caldera margin.

37.6 *Stop 3, at Ochoco Dam.*

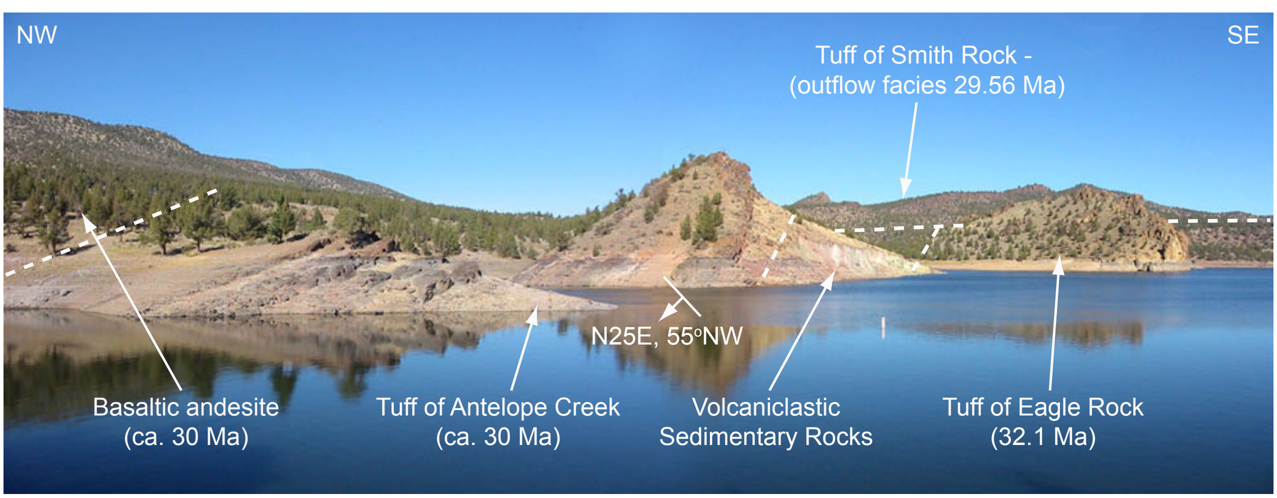

Figure 5. Northwest-dipping early Oligocene strata exposed near the Prineville Reservoir county boat ramp at stop 2. The exposed section includes two thick rhyolite tuffs interbedded with Fe- and Ti-rich basaltic andesite and volcaniclastic sedimentary rocks. Dashed white lines are approximate contacts between units. Schematic strike and dip symbol indicates the structural orientation of early Oligocene strata.

STOP 3. SOUTHEASTERN CALDERA MARGIN AND THE OCHOCO RESERVOIR RHYOLITE

GPS coordinates: –121.7235, 44.2998

Stop 3 provides a look at the Rhyolite of Ochoco Reservoir and a discussion of the geologic foundation of Ochoco Dam (Figure 6). The Rhyolite of Ochoco Reservoir, exposed north of stop 3, is a south-dipping, purple to gray, massive, platy to columnar jointed, sanidine-phyric rhyolite that erupted along the southeast margin of the Crooked River caldera. The rhyolite forms a relatively flat-topped, tabular body with a relatively consistent thickness that Waters and Vaughan (1968) interpreted as a rheomorphic ash-flow tuff. Basal flow-breccias, a lack of pumice or other pyroclastic textures (e.g., eutaxitic fabric), and complex internal flow-banding, combined with the tabular habit and association with a thick section of sedimentary rocks suggest that the rhyolite was emplaced as a lava that erupted and ponded in moat settings near the southeastern margin of the Crooked River caldera. The rhyolite has an $^{40}Ar/^{39}Ar$ age of 27.54 ± 0.36 Ma (Table 2; McClaughry and Ferns, 2006b). However, this age is discordant with the rhyolite's stratigraphic position beneath the Tuff of Barnes Butte, which is intruded by a 27.97 ± 0.32 Ma rhyolite dome at Prineville (Table 2). The present structural tilt of the rhyolite to the south may be a result of deformation during eruption of the Tuff of Barnes Butte at ~28.5 Ma or may be related to lower to middle Miocene faulting in the area.

Ochoco Dam, located ~10 km (6 mi) east of the city of Prineville, was completed in 1920 for irrigation and flood control as part of the United States Bureau of Reclamation (USBR) Crooked River Project (Carter, 1998; Kunzer, 1998). Since its completion, the dam has suffered from persistent seepage problems beneath the right abutment (north side). Deteriorating site conditions since construction resulted in the temporary emptying of the reservoir in 1993 (Carter, 1998). Water storage resumed in 1995 after modifications to increase bank stability and decrease seepage along the right abutment had been completed. Additional flood protection was provided through modifications to the left abutment spillway (Carter, 1998; Kunzer, 1998).

Operational problems at the Ochoco Reservoir dam site are intimately linked to site geology (Carter, 1998). Quaternary landslide deposits line both margins of Ochoco Reservoir and form the foundations upon which the dam structure is built. The construction site was chosen where landslide deposits formed the greatest topographic restriction in the valley. The left abutment (south side) of the dam is constructed upon rock-fall and debris flow deposits derived from the 3.56 Ma Basalt of Combs Flat of the Deschutes Formation (McClaughry and Ferns, 2006b). These deposits originate from over steepened, tension-cracked cliff-faces in the basalt that calve and topple or rotate listrically along fractured columnar joint margins. The right abutment of the dam is founded upon landslide deposits composed of intermixed rhyolite and tuffaceous siltstone derived from tension-cracked, southerly dipping, cliff-forming outcrops of the Rhyolite of Ochoco Reservoir and underlying sedimentary rocks interpreted as caldera moat-fill (Figure 6). Persistent seepage beneath the right abutment is linked to sinkholes developed in poorly sorted landslide deposits that have variable permeability and material strength.

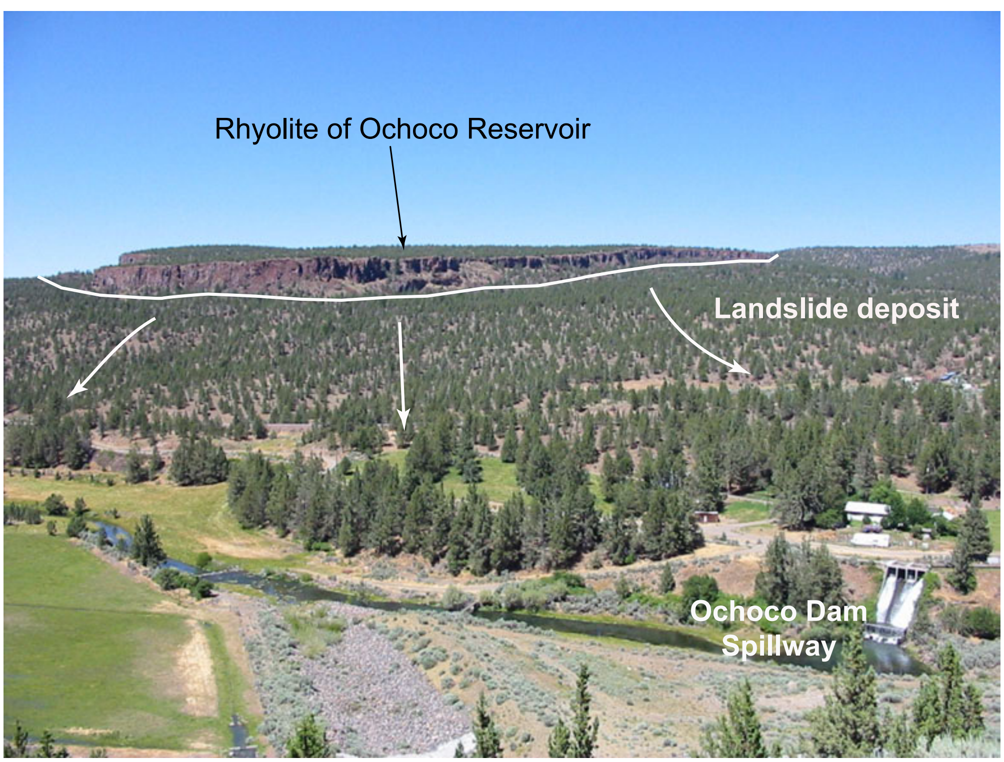

Figure 6. View north across Ochoco Creek to large, south-dipping, cliff-forming outcrops of the rhyolite of Ochoco Reservoir. The right abutment of the dam and spillway visible in the photo is founded upon a flanking, large active landslide complex that is sourced in the rhyolite. White arrows indicate general direction of transport of material in the landslide complex. Flow of Ochoco Creek is to the left (west) in the photograph.

GEOLOGIC HIGHLIGHTS AND ROAD LOG EN ROUTE TO STOP 4

37.6 *Left turn on US 26, travel west to Barnes Butte Road.*

41.7 *Right turn on Barnes Butte Road.*

42.8 *Intersection with Wainright Road.* Barnes Butte is visible on the left. The southern part of the butte is capped by the Tuff of Barnes Butte, an ash-flow tuff erupted from within the southeastern confines of the Crooked River caldera between 29.56 and 27.97 Ma. It is not clear whether eruption of the Tuff of Barnes Butte resulted in the formation of a second collapse structure or whether it erupted from another type of vent structure (e.g., ignimbrite fissure [Aguirre-Diaz and Labarthe-Hernandez, 2003]). No topographic expression of a subsidiary caldera ring-structure is clearly defined. The northern part of Barnes Butte is a rhyolite dome complex, isotopically dated at 27.97 ± 0.32 Ma ($^{40}Ar/^{39}Ar$ whole rock; Table 2; McClaughry and Ferns, 2006a), that intrudes the overlying Tuff of Barnes Butte. The rhyolite intrusion is geochemically indistinguishable from the Tuff of Barnes Butte, identifying this area as the eruptive source for the tuff (Table 3).

43.8 Outcrops of the intracaldera facies of the Tuff of Smith Rock.

46.3 *Right turn on McKay Creek Road.*

47.3 Pistachio green to buff-colored intracaldera facies of the Tuff of Smith Rock forms all low-lying hills on right and straight ahead. Small domal knobs forming protuberances in the field on the right are the upper parts of rhyolite domes that intrude the intracaldera ash-flow tuff.

48.6 *Intersection of McKay Creek Road and Gerke Road. Left (straight) on Gerke Road.* East-southeast of this point, Old Dry Creek runs along the caldera margin.

49.6 Between these mileage points, the field trip passes very near the margin of the Crooked River caldera. The knob on the left consists of a thick section of intracaldera facies of the Tuff of Smith Rock intruded by rhyolite. Road cuts on the right expose tuff and tuffaceous sediments that may have been deposited as caldera moat-fill.

51.1 *Continue due west on Gerke (Lamonta) Road*

52.1 *Right turn on NW Puckett Road. In 0.9 miles the road turns sharply left and becomes Ryegrass Road.*

53.0 to 55.8 Intracaldera facies of the Tuff of Smith Rock against the front of Grizzly Mountain contains exposures of lacustrine sedimentary rocks and hydrothermal hot-spring breccia and sinter.

55.8 *Right turn on US 26.*

57.4 *Right turn on Grizzly Mountain Road.*

60.2 *Stop 4, on the lower summit of Grizzly Mountain.*

STOP 4. RING-FRACTURE RHYOLITE DOMES

GPS coordinates: –121.9588, 44.4297

Grizzly Mountain, a post-caldera rhyolite dome and flow field along the northeast margin of the Crooked River caldera, is the highest standing point of the caldera at 1,733 m (5,685 ft). The lower summit location of stop 4 affords one of central Oregon's most scenic and relatively unknown vistas. Grizzly Mountain received its auspicious name in the 1870s purportedly due to its "grizzled" color under the sun of central Oregon, not due to any incidents involving grizzly bears (McArthur, 1992).

Rhyolite dome complexes are often associated with calderas after their formation (e.g., Smith and Bailey, 1968; Lipman, 1984; Christiansen, 2001). Ring fracture domes are often emplaced close to or above caldera-bounding faults. Other domes may occur aligned along regional structural trends or scattered randomly within a caldera (Lipman, 1984; Self and others, 1986). Following collapse of the Crooked River caldera, large (20 to 80 km^2 [8 to 31 mi^2]) fields of rhyolite flows, domes, and dikes, geochemically similar to the Tuff of Smith Rock, were emplaced along the structural margin of the caldera and intruded central portions of the intracaldera ash-flow tuff (Figure 7; Table 3). These include the rhyolite domes and flows at Grizzly Mountain as well as other domes and flows at Powell Buttes, Gray Butte, Barnes Butte, and Ochoco Reservoir. Satellite domes form Juniper Butte and Pilot Butte, outside the northwest and southeast caldera margins, respectively. Radiometric ages of the rhyolite dome complexes range from ca. 28.8 Ma to 25.8 Ma (Table 2 {before References section]); no rhyolites have yet been identified that were emplaced prior to caldera formation. Elongation of rhyolite dikes and dome complexes parallel to the caldera margin and their coincidence with an isostatic gravity low bounding the intracaldera tuff suggests the rhyolites were largely erupted from ring-fracture fault fissures. All rhyolites were apparently emplaced within the boundaries of syncollapse structural deformation, defined by the peripheral circumferential fault zone preserved in the surrounding country rock (Figure 2).

Figure 7. Flow-banded rhyolite exposed near the summit of Grizzly Mountain.

The arcuate ring-fractures of the caldera that allowed emplacement of rhyolite intrusions also served as conduits for upward movement of hot fluids after the main subsidence phase of the caldera had ended. Many of the rhyolite dome fields are associated with hydrothermal alteration and hot spring style mercury (Hg) mineralization; the rhyolite domes have been sites of past mineral exploration and limited resource production. Most notably, Barnes Butte was the site of a ca. 1940s mercury mine developed in heavily silicified rhyolite (Brooks, 1963). Powell Buttes was variably explored as a potential uranium target in the 1940s and 1950s, and geothermal potential was explored there in the 1980s (Brown and others, 1980). Isochron ages of basalt samples taken from hydrothermal alteration zones range from 29 to 25 Ma, suggesting the timing of alteration (Smith and others, 1998). Numerous other locations along the ring fracture of the caldera also show evidence of quartz and calcite veining, hydrothermal explosion breccias, siliceous sinter, and well-laminated, silicified mudstone (Figure 8). Thormahlen (1984) and Gray and Baxter (1986) found detectable amounts of gold (Au), silver (Ag), and arsenic (As) in these deposits. The character and spatial association of these deposits within and peripheral to the caldera are consistent with deposition in geyser and mudpot fields (e.g., modern Yellowstone caldera). Today, elevated temperature wells (>21º C, 70º F) continue to be drilled in the Prineville area. These relatively warm-water wells are generally confined within or along the inferred caldera margin, although their modern heat source is unknown.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 5

63.0 *Return to US 26. Right turn (north) onto US 26. Drive north to stop 5.*

68.3 *Left turn on SE Laurel Lane (route 96 on the Crooked River National Grassland).*

71.4 Historic Gray Butte Cemetery on the right.

72.2 The Tuff of Rodman Springs is exposed in a low-lying hill on the right. Smith and others (1998) obtained a $^{40}Ar/^{39}Ar$ age of 32.49 ± 0.30 Ma for this ash-flow tuff (Table 2). The high ridge in the distance to the left is the north slope of Gray Butte, a ring-fracture rhyolite dome that intrudes the Tuff of Smith Rock and therefore postdates the eruption of the Crooked River caldera. Smith and others (1998) obtained a $^{40}Ar/^{39}Ar$ age of 28.82 ± 0.23 Ma for the Rhyolite of Gray Butte. The lower, north slopes of Gray Butte and the topography that intervenes between there and Laurel Lane consist of an older south-dipping section of middle Eocene to lower Oligocene basalt to andesite intrusions and lavas and interbedded sedimentary rocks that host well-known fossil floras (Robinson and Stensland, 1979; Ashwill, 1983; Smith and others, 1998). Robinson and others (1990) report a K/Ar age of 30.8 ± 0.5 Ma from a basalt intrusion exposed in this stratigraphic section 3.2 km (2 mi) south of Gray Butte Cemetery.

72.6 *Right turn on Springer Road (SW King Lane).* Prominent mesas to the west and north-northeast are capped by orange, crudely columnar-jointed ledges formed by the Tuff of Barnes Butte. This ash–flow tuff postdates initial caldera-forming eruptions in the Crooked River caldera and may be correlative to the Member H tuff for which Smith and others (1998) determined an $^{40}Ar/^{39}Ar$ age of 27.62 ± 0.63 Ma at Haystack Reservoir (Table 2).

73.9 The field trip route here crosses part of the Cyrus Springs fault zone (Smith and others, 1998), a northeast trending, 800-m-wide composite shear zone coincident in location and trend with the Klamath-Blue Mountain gravity-anomaly lineament (Figure 3). The Cyrus Springs fault zone is defined by a break in stratigraphy across the structure; the fault zone juxtaposes the lowest John Day Formation ash-flow tuff (Member A) on the south against much younger outflow tuff from the Crooked River caldera on the north. Strata south of the fault zone are capped by the 32.49 ± 0.30 Ma Tuff of Rodman Springs, dip 20°–35° south, are cut by numerous basalt to rhyolite dikes within and parallel to the fault zone, and have been hydrothermally altered (Gray Butte cinnabar prospect; Brooks, 1963). Strata on the north of the fault zone form a broadly folded, north-northwest trending homocline. Intrusions and hydrothermal alteration pervasive on the south of the fault zone are notably absent in strata on the north (Smith and others, 1998). Faults within the zone generally strike N45°–60°E, but some faults in the southeastern part of the zone wrap to east-west orientations. On the basis of regional lineament mapping, the Cyrus Springs fault zone is now considered to be part of an arcuate set of faults that encircle the

Figure 8. Sinter and pool deposits related to hot spring activity are spatially distributed along the caldera margin. (a) Massive, brecciated siliceous sinter deposit exposed south of Grizzly Mountain. (b) Well-laminated, silicified mudstone exposed southeast of Grizzly Mountain.

Crooked River caldera. Smith and others (1998) constrain activity along the Cyrus Springs fault zone between ca. 28 and 30 Ma, coincident with collapse of the Crooked River caldera.

77.2 *Right turn on Fishing Pier Road.*

77.5 *Stop 5, at Haystack Reservoir.*

STOP 5. OUTFLOW TUFF OF THE CROOKED RIVER CALDERA

GPS coordinates: –121.1547, 44.4967

Three geographic lobes of outflow facies of the Tuff of Smith Rock are distributed clockwise from northwest to southeast around the caldera. These include the Haystack Reservoir, McKay Saddle, and Roberts Bay lobes (Figure 2; Tables 2 and 3). Middle Miocene and younger volcanic and sedimentary rocks conceal any outflow lobes that might be present on the west. The well-preserved tuffs at Haystack Reservoir were first described as the Tuff of Haystack Reservoir by Smith and others (1998), who correlated them with Member G of the "western" facies of the John Day Formation (Peck, 1964).

The Haystack Reservoir lobe of the Tuff of Smith Rock is as much as 30 m thick and consists of at least three distinct cooling units preserved between the Cyrus Springs fault zone and Haystack Reservoir (Figures 2 and 9). The lower unit at the fishing pier consists of 5 to 7 m (16.4–23.0 ft) of densely welded crystal-vitric tuff. Phenocrysts in the tuff include alkali feldspar and plagioclase now altered to cores of white chalky clay. The densely welded tuff is succeeded upward by a nonwelded section of light green, gray, and light purple, 1- to 3-m-thick (3.3–9.8 ft) beds of plane-bedded and cross-bedded to massive, pumice- and accretionary-lapilli bearing ash-flow tuffs. The bedded lower tuff has an $^{40}Ar/^{39}Ar$ age of 29.53 ± 0.09 Ma. (Table 2; Smith and others, 1998). The upper unit, exposed in the gravel pit above the fishing pier, consists of a dark red-brown, intensely welded ash-flow tuff. The welded tuff typically contains 1 to 5 percent crystals of sanidine, plagioclase, and quartz. It has an $^{40}Ar/^{39}Ar$ age of 29.57 ± 0.17 Ma (Smith and others, 1998; Table 3). The distribution of the welded tuff, combined with flow directions determined by surge cross beds indicates a source vent to the south-southwest of Haystack Reservoir (Smith and others, 1998). Radiometric ages determined for the tuffs at Haystack Reservoir are indistinguishable from a 29.56 ± 0.17 Ma ($^{40}Ar/^{39}Ar$) age for the McKay Saddle lobe of the Tuff of Smith Rock and John Day Formation Member G tuffs exposed north of the Crooked River caldera that have $^{40}Ar/^{39}Ar$ ages of 29.61 ± 0.10 and 29.54 ± 0.10 Ma (Table 2).

Figure 9. North-dipping, bedded section of outflow tuff exposed near the fishing pier at Haystack Reservoir (stop 5). The lower tan deposits consist of non-welded pumice-crystal tuff with an $^{40}Ar/^{39}Ar$ age of 29.53 ± 0.09 Ma. The uppermost, red-colored deposit is a densely welded crystal-vitric tuff with an $^{40}Ar/^{39}Ar$ age of 29.57 ± 0.17 Ma.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 6

77.8 *Right turn on SW Haystack Drive.*

78.2 *Left turn on Jericho Lane.* The high, flat ridge to the south of Jericho Lane is capped by densely welded to rheomorphic outflow facies of the Tuff of Smith Rock.

79.6 *Left turn on US 97.*

81.3 The field trip route here traverses the saddle between Juniper Butte on the west and Haystack Butte on the southeast. Juniper Butte is an Oligocene rhyolite dome that formed as an outlier along the circumferential peripheral fault zone that surrounds the Crooked River caldera. The prominent mesa at Haystack Butte is capped by the Tuff of Barnes Butte; this tuff is underlain by outflow facies of the Tuff of Smith Rock and sedimentary rocks.

83.7 The field trip route between mile point 83.7 and 87.0 travels across the surface of the upper Miocene Basalt of Tetherow Butte, part of the overlying Deschutes Formation. Smith (1986a,b) reports $^{40}Ar/^{39}Ar$ ages of 5.31 ± 0.05 Ma and 5.43 ± 0.05 Ma for this basalt. The flows were erupted from Tetherow Butte, 5.5 km (3.5 mi) northwest of Redmond.

87.3 Crossing the Crooked River Gorge and the highway bridge that was completed in September, 2000. The US 97 highway bridge spans the Crooked River Gorge, 91 m (300 ft) above river level, with a concrete arch span of 125 m (410 ft). The current bridge replaced the old Conde B. McCullough Steel arch bridge that was built in 1926 and that is now designated as a historic landmark.

87.5 *Right turn into Peter Skene Ogden State Park.*

87.6 *Stop 6, at Peter Skene Ogden State Park.*

STOP 6. NORTHWEST MARGIN OF THE CROOKED RIVER CALDERA

GPS coordinates: –121.1928, 44.3929

Stop 6 visits Peter Skene Ogden (P. S. Ogden) State Park on the northwest margin of the Crooked River caldera. Peter Skene Ogden State Park is named for an explorer and fur trapper for the Hudson Bay Company during the 1820s, who was the first to describe and name many of the features in central and eastern Oregon (McArthur, 1992). Two geologic domains are visible from the park.

The ridge visible on the east, from the highway bridge at Peter Skene Ogden State Park, is underlain by a southeast-dipping section of middle Eocene to middle Oligocene rocks that form part of the remnant northwestern wall of the Crooked River caldera (Figure 10). This structural block dips 28°–45° southeast, back toward the interior of the caldera, where the block is abruptly terminated by the primary caldera-bounding ring-fault. The base of the section is composed of calc-alkaline basalts and basaltic andesites of the Clarno Formation. These lavas are overlain by the John Day Formation, which here includes Fe- and Ti-rich basalts and andesites, interbedded volcaniclastic sedimentary rocks, and tuff. The volcaniclastic sedimentary rocks in this section host the well-known Gray Butte fossil floras, including the Kings Gap, Sumner Spring, Nichols Spring, Canal, and Trail Crossing floras. These floras are considered by Ashwill (1983) and Smith and others (1998) to be consistent with a middle Eocene to middle Oligocene age for the host strata. The section is capped by the ca. 30 Ma, yellow-altered, welded Tuff of Antelope Creek. This tuff is thicker and more strongly welded where it is more widely exposed in a deformed northwest tilted section along the southeastern margin of the caldera; it is absent within the arcuate ring-fracture. The younger intracaldera facies of the 29.56 Ma Tuff of Smith Rock is inset into this southeast-dipping section and forms the high ridge to the right of the prominent yellow-colored hoodoos (Figure 10). Because the Tuff of Smith Rock is ponded against and onlaps the southeast-dipping section, structural tilt is interpreted to have occurred during caldera collapse and eruption of the tuff. Gray Butte, the high peak in the background to the east, is part of a 28.82 Ma, postsubsidence rhyolite dome complex that intrudes the Tuff of Smith Rock along the ring-fracture.

The younger feature is the modern Crooked River Gorge, whose steep walls are composed of a thick intracanyon basalt lava that entered into the ancestral Crooked River drainage about 780,000 years ago. This basalt now serves as the anchor points for the U.S. 97 highway bridge. The intracanyon basalt was erupted from vents on the north flank of Newberry Volcano, located 72 km (45 mi) to the south of the state park. The lava flowed north across a broad plain extending from Newberry Volcano to Redmond (Sherrod and others, 2004). The lava entered the Crooked River at several sites northwest of O'Neil and at Smith Rock, approximately 10 km (6 mi) southeast of the present highway bridge. At Smith Rock these basalt lavas entered a broad, shallow channel cut into Oligocene rocks of the Crooked River caldera and are less than 30 m (100 ft) thick. Downstream of Smith Rock, the Newberry basalt was confined as an intracanyon flow within a steep-walled ancestral Crooked River Gorge, incised into a thick succession of older interbedded lavas, ash-flow tuffs, and sedimentary rocks of the late Miocene and Pliocene Deschutes Formation. Intracanyon basalt is more than 100 m (328 ft) thick at P. S. Ogden, where it is inset between canyon walls formed in the upper Miocene Basalt of Tetherow Butte on the north (5.31, 5.43 Ma) and the Pliocene (3.56 Ma) Basalt of

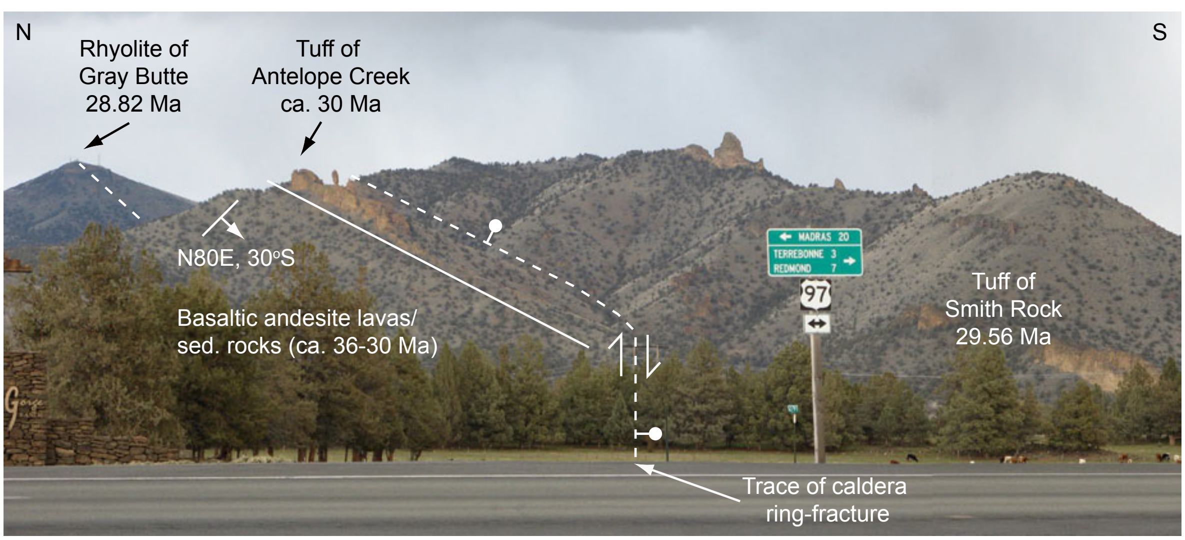

Figure 10. View east to southeast dipping section of early Oligocene strata from the old U.S 97 bridge at Peter Skene Ogden State Park at Stop 6. Intracaldera facies of the 29.56 Ma Tuff of Smith Rock are inset into and onlap the older deformed strata. Gray Butte in the distance is a 28.82 Ma rhyolite intrusion that crosscuts the Tuff of Smith Rock. Dashed white line demarcates the structural margin of the caldera. Arrows indicate the relative motion of the downthrown block within the caldera ring-fracture. Schematic strike and dip symbol indicates the structural orientation of early Oligocene strata.

Redmond on the south. Downstream of P. S. Ogden, Newberry lavas descended into the ancestral Crooked River Canyon forming a prominent bench that extends at least another 8 km (5 mi) to Lake Billy Chinook. The modern Crooked River has since incised a steep-walled canyon into the Newberry Basalt.

P. S. Ogden State Park is coincidentally the location where the elevation of the regional water table first corresponds with the streambed of the Crooked River; therefore groundwater discharges to the river from permeable rock units downstream from this point (Gannett and others, 2001). The amount of groundwater discharge (~1100 cfs) between P. S. Ogden State Park and Opal Springs downstream is largely controlled by the relatively high permeability of some of the Deschutes Formation units as compared to the older Clarno and John Day age units exposed near the surface upstream from stop 6 (Stearns, 1931; Lite and Gannett, 2002; Sherrod and others, 2002).

The contrasting permeability of the major rock units along the lower Crooked River drainage is also important as a regional boundary to groundwater flow. The John Day and Clarno formations, exposed near or at the surface east of P. S. Ogden State Park, are considered the lower boundary of the regional groundwater flow system in the Lower Crooked Basin and throughout much of the adjoining upper Deschutes Basin on the west (Lite and Gannett, 2002; Sherrod and others, 2002). These rocks typically exhibit low permeability due to the abundance of devitrified rhyolite, tuff, and tuffaceous sedimentary rocks that are altered to clay and zeolite (Lite and Gannett, 2002; Gannett and others, 2004). Most of the water wells that produce out of the John Day and Clarno formations in the Lower Crooked Basin have very low yields except where permeability is locally increased by secondary porosity (fractures). In some cases, wells sourced in John Day Formation rocks have been reported to contain detectable amounts of arsenic. The more productive sources or groundwater in the Lower Crooked Basin unconformably overlie the rocks of the John Day and Clarno Formations. These units include the Prineville Basalt, Deschutes Formation, and post-Deschutes Formation rocks.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 7

87.7 *Right turn onto US 97.*

88.2 Coyote Butte on the east is composed of intracaldera facies of the Tuff of Smith Rock. The caldera margin here is inferred to swing between the butte and US 97.

89.1 Crossing the inferred ring-fracture zone of the Crooked River caldera now buried beneath Neogene basalt lavas.

90.6 *Left turn on B Ave/Smith Rock Way in Terrebonne.*

91.3 *Left turn (north) on 1st Street.*

91.8 *Road turns abruptly right (east) and becomes NE Wilcox Avenue.*

92.6 Intracaldera ash-flow tuff and intrusive rhyolite dikes form the prominent cliffs and spires on the left.

93.3 *Left turn on Crooked River Drive.*

93.9 *Stop 7, at Smith Rock State Park.*

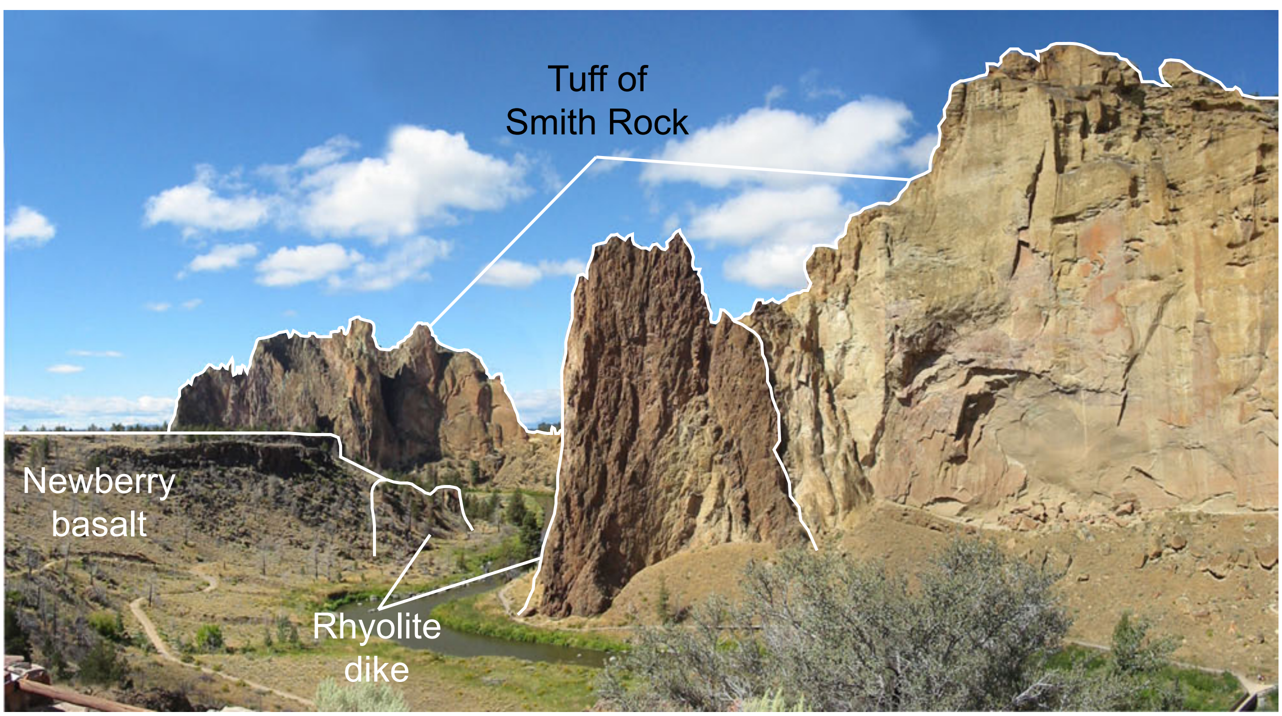

Figure 11. Exposure of intracaldera facies of the Tuff of Smith Rock intruded by rhyolite dikes at Smith Rock State Park. Quaternary basalt from Newberry Volcano is inset into the incised Paleogene surface.

STOP 7. INTRACALDERA TUFF OF THE CROOKED RIVER CALDERA: THE SMITH ROCK TUFF

GPS coordinates: –121.1335, 44.3706

Nestled in the northwest corner of the Lower Crooked Basin is Smith Rock, a picturesque set of sheer rock walls and case-hardened tuff spires that are well known to thousands of rock climbers, hikers, geologists, and tourists who travel to central Oregon each year (Figure 11). Close examination of the tuff reveals its explosive origins. Smith Rock proper, which forms the sheer rock massif at the state park, is named for John Smith, former sheriff of Linn County and Indian agent at Warm Springs Indian Agency. Smith first described the prominent rock formation during one of his expeditions in central Oregon between 1855 and 1859 (McArthur, 1992).

Until recently, the age, origin, and regional stratigraphic relationships of the Tuff of Smith Rock have been enigmatic, largely due to limited regional geologic mapping. Previous workers (Williams, 1957; Robinson and Stensland, 1979; Obermiller, 1987; Smith and others, 1998; Sherrod and others, 2004) considered the Tuff of Smith Rock to be an exceptionally thick tuff deposit of limited areal extent. The tuff was thought to be a conformable deposit upon the Rhyolite of Gray Butte and a south-southeast dipping section of Eocene and Oligocene strata. On the basis of K/Ar ages of uncertain quality, Obermiller (1987) interpreted the Tuff of Smith Rock as part of a middle Miocene silicic tuff cone. Smith and others (1998) demonstrated the unit was Oligocene in age, but they concurred with Obermiller (1987) that the Tuff of Smith Rock formed as a silicic tuff cone and was conformable upon the Rhyolite of Gray Butte. Results from regional detailed geologic mapping indicate that the Tuff of Smith Rock is a more widespread, relatively flat-lying, ash-flow tuff that inset in older middle Eocene to middle Oligocene strata. Pre-caldera stratigraphy, into which the tuff is ponded, may be as young as ca. 30 Ma west of Gray Butte; basaltic andesite recovered from drill core along the inferred caldera margin near Powell Buttes has a reported K/Ar age of 30.1 ± 1.1 Ma (whole rock, Evans and Brown, 1981). Mapped contact relations also demonstrate that the Tuff of Smith Rock is not conformable upon the 28.82 Ma Rhyolite of Gray Butte but is instead intruded by that unit. These stratigraphic and age relationships constrain the age of the intracaldera facies of the Tuff of Smith Rock to between ca. 29 and 30 Ma. Smith and others (1998) reported a fission-track age of 29 ± 3.0 Ma for the intracaldera ash-flow tuff at Smith Rock State Park; outflow facies of the tuff at McKay Saddle, Haystack Reservoir, Teller Flat, and Antelope return radiometric ages of ca. 29.6 Ma.

The intracaldera facies of the Tuff of Smith Rock forms an arcuate belt of discontinuous exposures that extends from the type section at Smith Rock State Park (Robinson and Stensland, 1979) to Ochoco Reservoir (Figure 2). At Smith Rock State Park, the intracaldera facies weathers to spectacular spires up to 200 m (650 ft) tall (Figure 11); along the northeast margin and interior of the caldera, similar tuff deposits degrade to form rounded, low-elevation hills. The intracaldera facies is predominantly a massive, unstratified, matrix-supported, pumice-rich, sparsely sanidine-phyric, rhyolite tuff that weathers tan to yellow brown. Locally, the tuff is altered to light green and maroon and is case-hardened by zeolite alteration. Bedding features in the Tuff of Smith Rock are generally indistinct, but horizontal to gently dipping (<5°) lithic-rich lenses and associated fine-grained ash horizons are intercalated with the pumice-rich tuff in exposures along the Crooked River at Smith Rock State Park and in Skull Hollow. These discontinuous lithic-rich lenses are interpreted as lithic lag-breccias that are indicative of pulsating or surging pyroclastic flows (Figure 12). Rare clasts of limestone, some bearing Permian fusulinids (Thompson and Wheeler, 1942), occur as xenoliths within the tuff, suggesting that the Tuff of Smith Rock erupted through a Paleozoic limestone basement. Geochemical samples analyzed from the intracaldera facies of the Tuff of Smith Rock closely compare to those determined for rhyolite dome complexes, which intrude the tuff along the margin and in central areas of the caldera (Figure 11 and Table 3).

The intracaldera ash-flow tuff is typically in complex, high-angle to vertical contact with country rock, and water-well logs within the caldera indicate that the tuff thickens to hundreds of meters immediately away from these contacts (Figure 13). On the basis of regional mapping and water well log analysis of the intracaldera facies, the Tuff of Smith Rock has a minimum intracaldera thickness of 0.5 km. Bulk volume estimates of the

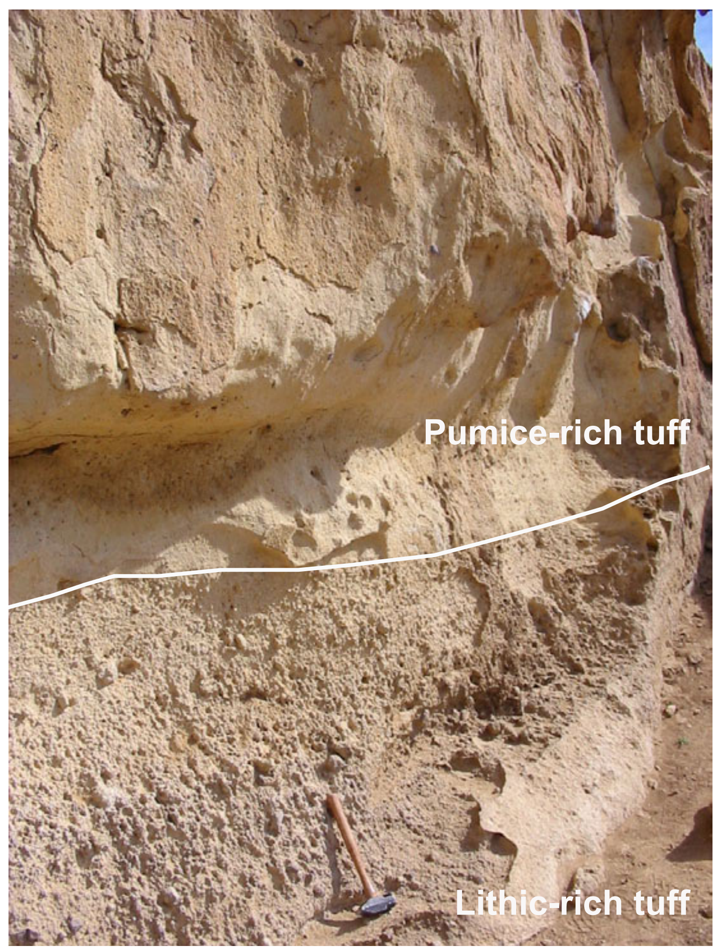

Figure 12. Close-up outcrop view of the intracaldera facies of the Tuff of Smith Rock at Smith Rock State Park. The tuff is greater than 0.5 km thick and consists of a monotonous section of pumice-lithic tuff intercalated with lithic-rich lenses and fine-ash.

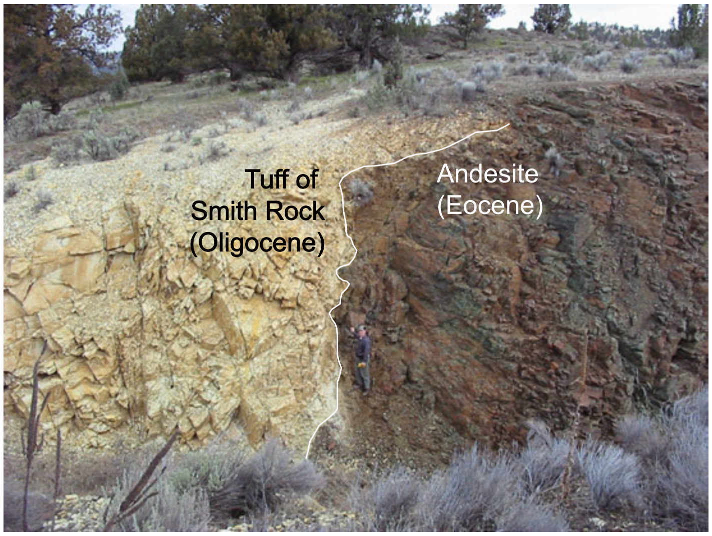

Figure 13. Caldera ring-fault exposed on the northeast caldera margin where pumice-lithic intracaldera facies of the Oligocene Tuff of Smith Rock is separated from older Eocene andesite country rock by a complex, unfaulted, high-angle contact. The tuff is not faulted and onlaps the country rock surface. The country rock is pervasively cut by a series of regularly spaced shear zones that parallel the caldera margin. Note person near the middle of the photo for scale.

intracaldera facies indicate more than 580 km^3 (139 mi^3) of tuff were erupted during caldera formation. This is a minimum estimate as it does not account for correlative outflow tuff deposits exposed outside the caldera ring fault. Outflow facies are exposed discontinuously around the periphery of the caldera, distributed in three geographic lobes at Haystack Reservoir, McKay Saddle, and Prineville Reservoir (Figure 2). Distal welded ash-flow tuff deposits, up to 5 m (16.5 ft) thick, have been traced as far north as the town of Antelope, 58 km northeast of Smith Rock (Figure 1; Tables 2 and 3).

94.5 *Exit the park and make a left turn on NE Wilcox Avenue.*
96.7 *Left turn on Smith Rock Way.*
97.3 *Right turn onto NW Lone Pine Road.*
98.6 *Left turn on O'Neil highway.*
107.3 *Left turn on Elliot Road.*
108.6 *Right turn on Elliot Lane.*
109.2 *Right turn on US 26.*
113.5 *Left turn onto US 26/NW 3rd Street at the US 26-OR 126 junction in Prineville.*
115.9 *Ochoco National Forest Office in Prineville.* **End of field trip.**

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$^{40}Ar/^{39}Ar$ age determinations were prepared and analyzed by John Huard at the College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis. X-ray fluorescence (XRF) geochemical analyses were prepared and analyzed by Stanley Mertzman, Franklin and Marshall College, Lancaster, Pennsylvania, except for those analyses with the prefix PAT, which were analyzed at Washington State University. Analytical procedures for the Franklin and Marshall X-ray laboratory are described by Boyd and Mertzman (1987) and Mertzman (2000) and are available online at http://www.fandm.edu/x7985. Analytical procedures for Washington State University are described by Johnson and others (1999). Geochemical analytical results, shown in Table 3, have been normalized on a volatile-free basis and recalculated with total iron expressed as FeO*.

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Table 2. Summary of radiometric age determinations for Crooked River caldera stratigraphic units.

Geologic Unit			Sample	Geologic Unit and Geographic Area	UTM North	UTM East	Material Dated	Method	Age (Ma)	Reference
Crooked River Caldera	Member H Tuff		GS095-134	rhyolite tuff (Member H) at Haystack Reservoir	4928680	646560	alkali feldspar	$^{40}Ar/^{39}Ar$	27.62 ± 0.63	6
Crooked River Caldera	Rhyolite Intrusions / Flows		1.15VII.05	rhyolite lava north of Ochoco Reservoir	4908454	682626	whole rock	$^{40}Ar/^{39}Ar$	27.54 ± 0.36	1
Crooked River Caldera	Rhyolite Intrusions / Flows		4B.12VII.05	rhyolite intrusion at Barnes Butte	4909935	674019	whole rock	$^{40}Ar/^{39}Ar$	27.97 ± 0.32	2
Crooked River Caldera	Rhyolite Intrusions / Flows		648-623Bb	sanidine-phyric rhyolite, summit of Powell Buttes	4895300	661690	Sanidine	K/Ar	25.8 ± 0.2	3
Crooked River Caldera	Rhyolite Intrusions / Flows		PB-5/AH-34	aphyric rhyolite northeast of Powell Buttes summit	4895610	662480	anorthoclase	K/Ar	28.3 ± 1.0	4
Crooked River Caldera	Rhyolite Intrusions / Flows		GSO95-41	rhyolite vitrophyre at Gray Butte	4918390	650260	alkali feldspar	$^{40}Ar/^{39}Ar$	28.82 ± 0.23	6
Crooked River Caldera	Tuff of Smith Rock	Outflow Tuff	448 LCJ 07	Tuff of Smith Rock at McKay Saddle	4932290	687550	alkali feldspar	$^{40}Ar/^{39}Ar$	29.56 ± 0.17	this report
Crooked River Caldera	Tuff of Smith Rock	Outflow Tuff	GSO-95-133	Tuff of Smith Rock at Haystack Reservoir, lower tuff	4928490	646710	alkali feldspar	$^{40}Ar/^{39}Ar$	29.53 ± 0.09	6
Crooked River Caldera	Tuff of Smith Rock	Outflow Tuff	GSO95-132	Tuff of Smith Rock at Haystack Reservoir, upper tuff	4928570	646560	alkali feldspar	$^{40}Ar/^{39}Ar$	29.57 ± 0.17	6
Crooked River Caldera	Tuff of Smith Rock	Outflow Tuff	GSO95-144	John Day Formation, Member G tuff near Teller Flat, 22.5 km (14 mi) northwest of Haystack Reservoir	4945500	661200	alkali feldspar	$^{40}Ar/^{39}Ar$	29.61 ± 0.10	6
Crooked River Caldera	Tuff of Smith Rock	Outflow Tuff	GSO95-136	John Day Formation, Member G tuff along Antelope Cr.eek, 44 km (27.5) mi northwest of Haystack Reservoir	4968030	667890	alkali feldspar	$^{40}Ar/^{39}Ar$	29.54 ± 0.10	6
Crooked River Caldera	Tuff of Smith Rock	Intra-Caldera Tuff	—	Tuff of Smith Rock at Smith Rock State Park?	—	—	zircon	fission-track	29 ± 3.0	6
Crooked River Caldera	Pre-caldera Basaltic Andesite		DOGMI-Bas81-2/ UT-225	basaltic andesite (310 m depth) in borehole northwest of Powell Buttes	4894200	655700	whole rock	K/Ar	30.1 ± 1.1	4
Crooked River Caldera	Pre-caldera Basaltic Andesite		10-6-78-2	basaltic andesite intrusion northeast of Gray Butte	4921590	651660	whole rock	K/Ar	30.8 ± 0.5	3, 5
Member E & F Tuff			648-625A	rhyolite tuff at Eagle Rock	~4896180	~687830	plagioclase	K/Ar	32.1 ± 0.7	3, 5
Member E & F Tuff			GS095-130	rhyolite tuff at Rodman Springs	4924910	649930	alkalifeldspar	$^{40}Ar/^{39}Ar$	32.49 ± 0.30	6

References are 1, McClaughry and Ferns (2006b); 2, McClaughry and Ferns (2006a); 3, Robinson and others (1990); 4, Evans and Brown (1981); 5, Fiebelkorn and others (1983); 6, Smith and others (1998).

Table 3. Representative geochemical analyses from Crooked River caldera stratigraphic units.

	Precaldera Rocks				Tuff of Smith Rock						Postcaldera Rhyolite Domes and Lavas									Tuff of Barnes Butte
	Tuff of Eagle Rock	Tuff of Antelope Creek	Basaltic Andesite	Basalt	Intra-caldera Tuff	Outflow Tuff														
Sample	18 LC 06	PAT PR11	16 LC 06†	RC95 -76§	24 LCJ 06	22 LCJ 06	448 LCJ 07	394 LCJ 07	PAT TF1	PH95 376†	95-BE-31#	RC95-70B§	PAT GR1	08-PJ -05	7.29VI. 05	15 P 05	1.15VII. 05	520 LCJ 08	PAT BB1	PAT OR2A
Geographic Area	Prineville Res.	Prineville Res.	Prineville Res.	Gray Butte	Smith Rock	Owl Creek	McKay Saddle	Haystack Res.	Teller Flat	Ante-lope	Juniper Butte	Gray Butte	Grizzly Mtn.	Powell Buttes	Powell Buttes	Powell Buttes	Ochoco Res.	Pilot Butte	Barnes Butte	Ochoco Res.
UTM N	4889220	4888930	4889168	4917728	4914036	4902169	4932290	4928481	4945844	4969320	4926158	4919692	4922320	4897123	4894249	4890217	4908454	4898960	4910352	4906892
UTM E	680850	680285	680322	647398	648479	688720	687550	646612	661269	669430	641646	651261	662943	663910	662320	660600	682626	691900	674100	681043
Age (Ma)	32.1	ca. 30	ca. 30	ca. 30			29.56	29.57	29.61	29.54		28.82		28.30	25.80		27.54		27.97	
Oxides, weight percent																				
SiO_2	78.97	76.46	55.39	49.99	76.67	77.79	76.25	78.11	76.65	75.21	78.60	76.83	77.87	79.26	74.93	76.23	75.74	78.36	78.05	78.18
Al_2O_3	10.96	11.51	14.16	15.52	12.06	11.57	13.02	10.84	11.50	12.81	10.92	12.40	11.99	11.55	11.62	8.69	11.92	11.80	11.27	11.61
TiO_2	0.18	0.29	2.00	2.58	0.24	0.14	0.24	0.15	0.29	0.32	0.13	0.25	0.22	0.14	0.28	0.33	0.28	0.16	0.16	0.15
FeO*	2.06	3.55	13.56	11.84	2.76	1.81	1.25	1.92	2.80	2.20	1.63	1.31	1.35	1.06	4.24	7.14	3.17	1.03	1.80	1.15
MnO	0.02	0.08	0.27	0.20	0.05	0.02	0.02	0.03	0.04	0.03	0.01	0.01	0.01	0.01	0.04	0.21	0.05	0.01	0.02	0.01
CaO	0.29	0.90	6.08	10.14	0.48	0.16	0.50	0.10	0.29	0.77	0.12	0.37	0.18	0.09	0.29	0.13	0.19	0.13	0.14	0.17
MgO	0.15	0.18	2.26	5.84	0.23	0.16	0.13	0.11	0.05	0.57	0.16	0.10	0.02	0.05	0.14	0.11	0.09	0.09	0.09	0.08
K_2O	3.87	3.48	1.60	0.37	4.24	4.57	4.11	8.40	5.00	6.01	5.01	4.31	4.36	4.32	4.68	4.46	4.55	4.21	5.98	4.95
Na_2O	3.42	3.50	3.74	2.90	3.21	3.62	4.43	0.33	3.32	2.05	3.41	4.39	3.93	3.49	3.72	2.64	3.96	4.15	2.47	3.64
P_2O_5	0.07	0.04	0.92	0.63	0.07	0.05	0.05	0.02	0.06	0.03	0.03	0.03	0.06	0.04	0.05	0.05	0.05	0.05	0.02	0.06
LOI	1.59	3.57	2.70	**N.D.	2.10	0.97	0.92	2.03	1.98	6.84	**N.D.	**N.D.	2.08	0.70	1.67	1.18	0.44	0.81	3.20	2.30
Trace Elements, parts per million																				
Ni	7	2	4	49	2	5	0	0	0	16	9	15	1	2	6	3	4	1	7	0
Cr	0	1	7	157	0	0	1	1	6	4	0	8	2	0	0	0	0	7	4	2
Sc	2	4	30	34	3	2	3	0	4	4	0	5	3	1	1	0	3	7	1	2
V	13	11	148	280	9	13	14	17	32	8	4	3	0	8	10	32	9	12	14	4
Ba	960	974	374	367	1035	604	1120	111	416	221	309	905	994	963	516	250	765	975	503	520
Rb	118	84	45.7	7.0	134.3	134.9	130.8	180.0	155.4	192.0	179.0	132.0	128.4	115.0	111.9	136.3	118.0	133.3	134.8	124.4
Sr	43	122	291	329	43	19	47	8	18	28	14	46	40	10	17	15	29	18	13	11
Zr	490	484	243	186	512	384	596	420	583	582	373	519	546	462	826	1185	771	455	335	341
Y	120.2	76.3	61.1	40.0	113.7	61.4	113.2	89.6	89.5	103.0	99.0	64.0	86.2	63.1	105.7	145.0	110.8	85.9	66.8	69.3
Nb	64.7	35.6	20.9	23.0	53.8	53.0	71.9	53.6	44.7	56.0	49.0	68.0	57.0	45.0	70.2	93.1	64.6	75.6	40.0	40.5
Ga	23.7	24.6	24.9	19.0	21.6	24.1	25.9	29.7	24.5	28.0	30.0	27.0	25.3	23.0	29.3	30.9	25.1	20.5	21.0	22.9
Cu	0	1	4	46	0	0	0	5	6	7	2	3	2	0	5	7	3	2	5	4
Zn	131	126	120	101	180	115	168	124	122	110	111	135	115	43	155	159	128	50	99	93
Pb	2	10	2	**N.D.	7	8	8	28	14	17	14	16	14	3	11	22	11	1	11	12
La	68	45	29	**N.D.	59	59	68	60	61	**N.D.	81	**N.D.	71	30	68	93	87	96	54	54
Ce	148	78	59	**N.D.	139	128	172	108	134	**N.D.	130	**N.D.	146	68	155	197	186	200	103	111
Th	16.0	7.8	3.2	4.0	18.7	13.7	16.1	20.3	16.4	20.0	15.0	18.0	16.2	12.0	13.3	17.0	14.4	15.2	12.4	14.9
U	5	3	0	**N.D.	5	5	5	5	4	**N.D.	**N.D.	18	3	5	2	1	5	3	4	5
Co	1	0	31	**N.D.	0	0	0	0	**N.D.	**N.D.	**N.D.	0	**N.D.	0	4	10	1	1	0	0

Note: Major element determinations have been normalized to a 100% total on a volatile-free basis and recalculated with total iron expressed as FeO*. Oxides as weight percent; trace elements as parts per million. **N.D. = no data or element not analyzed. Coordinates in Universal Transverse Mercator (UTM NAD 27). †Hammond (2008), §Smith and others (1998), #Smith and others (1996).

Field trip guide to the Neogene stratigraphy of the Lower Crooked Basin and the ancestral Crooked River, Crook County, Oregon

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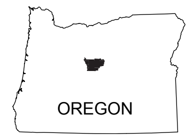
Overview: This field trip along the wild and scenic Crooked River between Ochoco Wayside State Park and Bowman Dam provides an overview of the Neogene basalt stratigraphy in the Lower Crooked Basin. Emphasis is placed on the interaction between basalt lavas and the development of the ancestral Crooked River. The geologic factors that influence regional groundwater flow in the Lower Crooked Basin and control landslide deposits along the Crooked River Canyon are discussed. This field trip is 73 km (45 mi).



INTRODUCTION

The Lower Crooked Basin of central Oregon, drained by the northwest flowing Crooked River, has been a long-lived catchment for the episodic emplacement of volcanic flows and sedimentary detritus. The Crooked River is a long-established stream drainage in the basin, whose paleogeographic development is intimately related to volcanism that has occurred in the Lower Crooked Basin since ca. 30 Ma. The geographic position of the Crooked River reflects entrenchment into the Oligocene Crooked River caldera, a northwest elongated, ~41 km × 27 km (25 mi × 17 mi), semi-elliptical structure that forms a topographically low basin centered on Prineville (McClaughry and Ferns, 2007a; McClaughry and others, 2009). Since at least the middle Miocene, the distribution of ancestral channels of the Crooked River in the Lower Crooked Basin has been controlled by (1) the structural and topographic margin of the caldera, (2) high-standing, erosionally resistant rhyolite domes along the margin of the caldera that restrict lateral migration of the channel, and (3) the periodic eruption and spread of locally derived basalt lavas that have choked the drainage and impeded canyon incision.

Lavas of the middle Miocene Prineville Basalt (Uppuluri, 1974; Tolan and others, 1989; Hooper and others, 1993), middle Miocene tuffaceous sedimentary rocks equivalent to the Simtustus Formation (Smith 1986b), and late Miocene to Pliocene strata of the Deschutes Formation (Smith, 1986a) all accumulated in the west part of the Lower Crooked Basin during the Neogene. Lavas of the 15.7 Ma Prineville Basalt, likely erupted in the southern part of the Lower Crooked Basin (Hooper and others, 1993), are exposed from Bowman Dam north to the Columbia Plateau. The thickest sections of Prineville Basalt lavas in the Lower Crooked Basin are interbedded with sedimentary rocks of the Simtustus Formation and infill topographic lows that had developed within the Crooked River caldera during the early to middle Miocene. The distribution of these lavas and associated sedimentary rocks may mark the early south-to-north channel course of the ancestral Crooked River.

Since at least 9 Ma, the Crooked River south of Prineville has been entrenched in approximately the same position, barricaded between topographic highs created by the middle Miocene Prineville Basalt and rocks of the Oligocene Crooked River caldera (Figure 1). Channel migration has further been limited during this time period by a series of basalt lavas of the Deschutes Formation that have repeatedly inundated the Crooked River drainage. The Deschutes Formation consists of a diverse succession of interbedded sedimentary and pyroclastic rocks and intracanyon lavas that preserve a partial record of the early High Cascade eruptive episode that occurred between ~ 10 and 4.5 Ma (Taylor, 1981; Priest and others, 1983; Smith and others, 1987). The formation is characterized at its type section in the Deschutes Basin west of Madras as a succession of volcaniclastic sedimentary rocks and widespread ash-flow tuff deposits, with fewer basalt lavas. Lavas are increasingly abundant in the formation in the vicinity of major eruptive centers stationed near the Cascade Range crest on the west and in areas east and southeast of the Deschutes Basin. Rocks correlated with the Deschutes Formation in the Deschutes Basin were largely emplaced between ca. 7.4 and 4.0 Ma on a broad apron that prograded eastward from principal source areas in the early High Cascade Range (Smith 1986a, 1987, 1991). Influx of sediment, pyroclastic material, and lavas onto the active arc-adjacent plain in the Deschutes Basin ceased coincidently with the uplift of Green Ridge at ca. 5.42 Ma (Smith, 1987).

Correlative strata exposed eastward in the Lower Crooked Basin are dominated by intracanyon basalt lavas and contain an overall paucity of interbedded sedimentary and pyroclastic rocks. Detailed mapping and geochemical correlation of Deschutes Formation basalt lavas indicate the presence of at least 20 mappable flow packages in the Lower Crooked Basin. These basalt lavas were erupted from as many as 14 known vents located between Tetherow Butte (near Redmond) on the northwest and Alkali Butte (17 km [8.5 mi] southeast of Bowman Dam) on the south. Vents generally correspond with the structural margin of the Oligocene Crooked River caldera, and their distribution may have been in part controlled by these zones of weakness. Basalt lavas are typically open-textured, distinctly olivine-phyric, and are characterized by average (n = 46) major element compositions of 49.9 wt. % SiO_2, 16.1 wt. % Al_2O_3, 1.6 wt. % TiO_2, 11.3 wt. % FeO*, and 7.3 wt. % MgO (McClaughry and Ferns, 2007b; Table 1 [located before References section]). The thickest accumulation of Deschutes basalt is exposed in the modern Crooked River Canyon south of Prineville, where lavas are juxtaposed against or fill channels incised into the middle

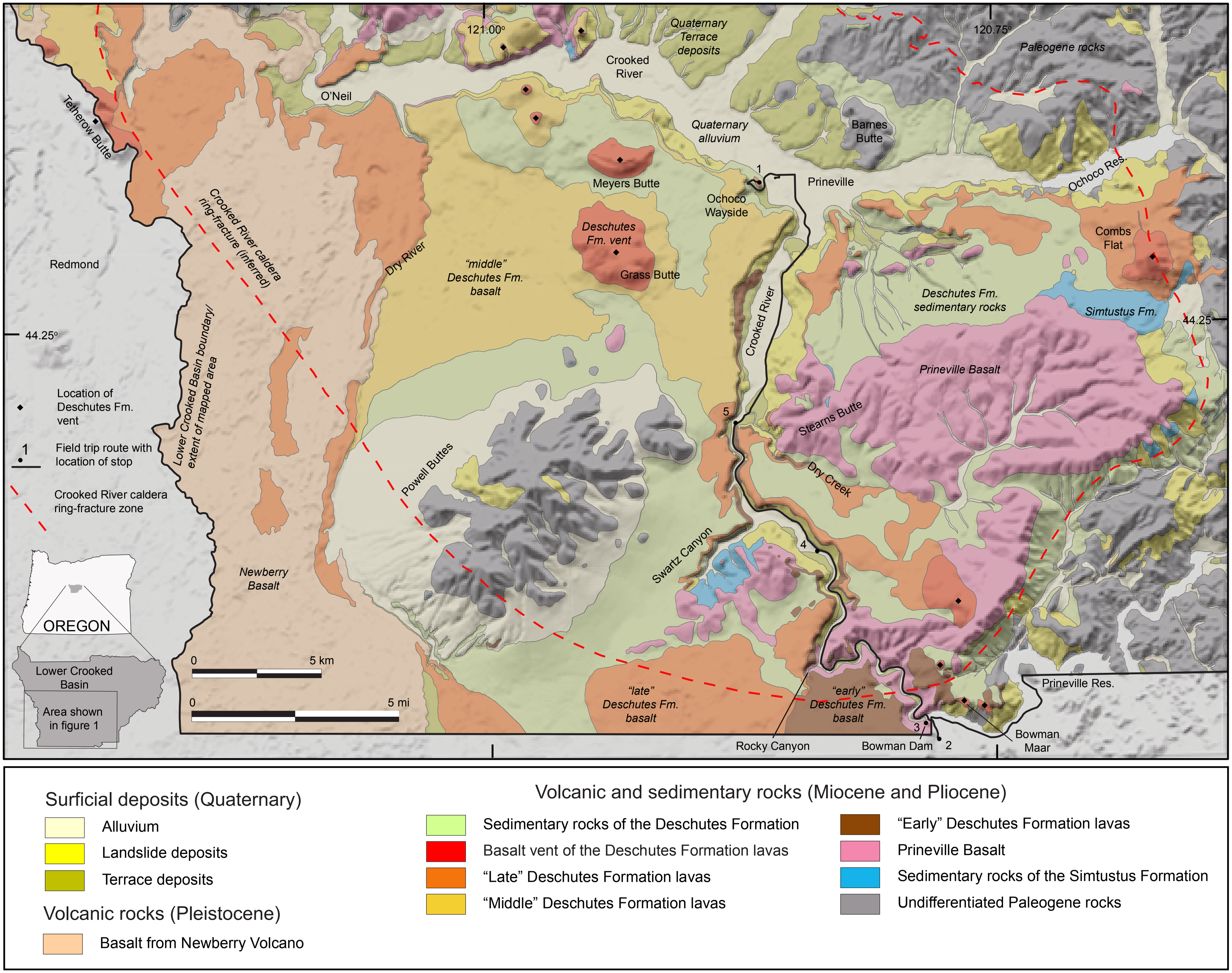


Figure 1. Simplified overview geologic map of the Crooked River between Bowman Dam and Prineville, Oregon. Numbers indicate stops described in this field guide.

Miocene (15.7 Ma) Prineville Basalt. These locally erupted basalt lavas record the Neogene development of a longitudinal, north-flowing river that closely approximated the present-day drainage of the Crooked River.

Isotopic ages obtained from intracanyon basalt lavas indicate the Deschutes Formation is as young as ~3.4 Ma and may be as old as 9 Ma in the Lower Crooked Basin. Basalt packages are informally divided here into the "early," "middle," and "late" Deschutes Formation on the basis of stratigraphic position relative to the 7.05 Ma Rattlesnake Ash-Flow Tuff (Streck and Grunder, 1995) and temporal relations with the onset of faulting along Green Ridge in the Deschutes Basin around 5.42 Ma (Smith, 1986a). In the Lower Crooked Basin, only the "middle" Deschutes Formation is temporally correlative with the type section west of Madras, which is bracketed between the 7.42 Ma Pelton Basalt Member and the 3.97 Ma Round Butte Basalt Member (Smith, 1986a).

FIELD TRIP GUIDE

Note: Road logs are reported in miles [black-boxed numbers] to match most car odometers. GPS coordinates, recorded in longitude and latitude (NAD 27, deg.dddd), are given for each field stop. Compass directions to points of interest are given in azimuthal format. Metric system units are used for all scientific measurements; corresponding standard U.S. units are given in parentheses.

Objectives of this field trip

This field guide for a half-day trip along the wild and scenic Crooked River between Ochoco Wayside State Park and Bowman Dam provides an overview of the Neogene basalt stratigraphy in the Lower Crooked Basin. Emphasis in the guide is placed on the interaction between basalt lavas and the development of the ancestral Crooked River. The geologic factors that influence regional groundwater flow in the Lower Crooked Basin and that control landslide deposits along the Crooked River Canyon are also discussed. Field trip mileage begins and ends at the Crook County Library in Prineville.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 1

Begin field trip mileage:

0.0 *The field trip begins at the Crook County Library. Turn right onto W Second Street*. The library sits on Quaternary alluvium deposited by the modern Crooked River.

0.1 *Turn left onto NW Hardwood Street. In one block, turn left again at the stop light onto NW Third Street (US Highway 26) and proceed west.*

0.3 *Bear left, through the US Highway 26/OR Highway 126 interchange, and proceed west toward Redmond on OR Highway 126.* The highway crosses the Crooked River and ascends the canyon wall.

0.5 Sedimentary rocks of the Deschutes Formation are exposed along OR Highway 126 in the road cut on the right. This is the thickest accumulation of late Miocene and Pliocene sedimentary rocks observed at any location within the Lower Crooked Basin. Elsewhere in the basin, there is an overall paucity of sedimentary rocks interbedded with basalt lavas. Traveling west up the grade, the route passes by poorly consolidated beds of conglomerate and sandstone. Clast-size, sorting, and large-scale trough cross-beds in the conglomerate and sandstone indicate that these rocks were most likely deposited within the active ancestral Crooked River channel. Near the turnoff to the overlook, the sedimentary rocks grade laterally to well-bedded, planar-stratified, fine-grained sandstone and siltstone. These deposits were likely emplaced in overbank floodplain settings marginal to the main ancestral river channel. Both the coarse- and fine-grained sedimentary units are capped by basalt lavas of the Deschutes Formation.

1.2 *Turn right onto the access road to the overlook at the Ochoco Wayside State Park*. The access road ascends onto the Basalt of Stearns Ranch, part of the Deschutes Formation.

STOP 1. OCHOCO WAYSIDE STATE PARK VIEWPOINT

GPS coordinates -120.8633, 44.3003

Stop 1 at Ochoco Wayside State Park offers a panoramic vista of the Lower Crooked Basin and views of two geologic domains that exert a fundamental influence on groundwater resources in the basin (Figure 2). These geologic domains include Oligocene rocks of the Crooked River caldera and overlying strata of the Simtustus Formation, Prineville Basalt, and Deschutes Formation.

The western part of the modern Lower Crooked Basin is centered on the 29.56 Ma Crooked River caldera, a large eruptive center marked by a thick succession of intracaldera tuff encircled by prominent rhyolite dome complexes (McClaughry and Ferns 2007; McClaughry and others, 2009). Three of these rhyolite domes, Powell Buttes (225°), Grizzly Mountain (340°) and Barnes Butte (55°), are visible from Ochoco Wayside. The intracaldera tuff reaches depths of at least 300 m (1,000 ft) below land surface near Prineville and has generally very low permeability, resulting in a poor regional aquifer. The tuff is a regional hydrologic boundary, restricting productive aquifers at Prineville to younger, overlying Neogene and Quaternary units. The primary water producing zones in the Lower Crooked Basin are hosted in the Prineville Basalt, Deschutes Formation, and in terrace gravels that unconformably overlie rocks of the Crooked River caldera near Prineville. The Simtustus Formation is generally fine-grained and thus usually a low-yielding aquifer unit. Stop 1 provides an overview of the Deschutes Formation basalts and terrace gravels. The Prineville Basalt and Simtustus Formation are discussed at stops 3 and 4, respectively.

Detailed geologic mapping of Deschutes Formation basalt lavas indicates that the Crooked River between Bowman Dam and Prineville has held the same general geographic position since at least the middle to late Miocene. During the late Miocene to middle Pliocene basalt lavas of the Deschutes Formation entered the ancestral Crooked River at numerous points between Bowman Dam and O'Neil and flowed downstream as channel-confined intracanyon flows through a narrow gorge formed in the Prineville Basalt (Figure 1). These channel-confined flows emptied into a stagnant, low gradient basin at Prineville. None of the basalt lavas exposed in this part of the Lower Crooked Basin correlate with those that line the modern Crooked River Canyon downstream of O'Neil, suggesting that Prineville was the terminus point for many if not all of these small volume lavas.

The once channel-confined basalt lavas of the Deschutes Formation exposed above Prineville now form topographically inverted, rimrock-forming ridge caps that define ancestral channels of the Crooked River. Several topographically inverted, ridge-capping basalt lavas are visible from Ochoco Wayside State Park and illustrate the cut-and-fill nature of Deschutes-age

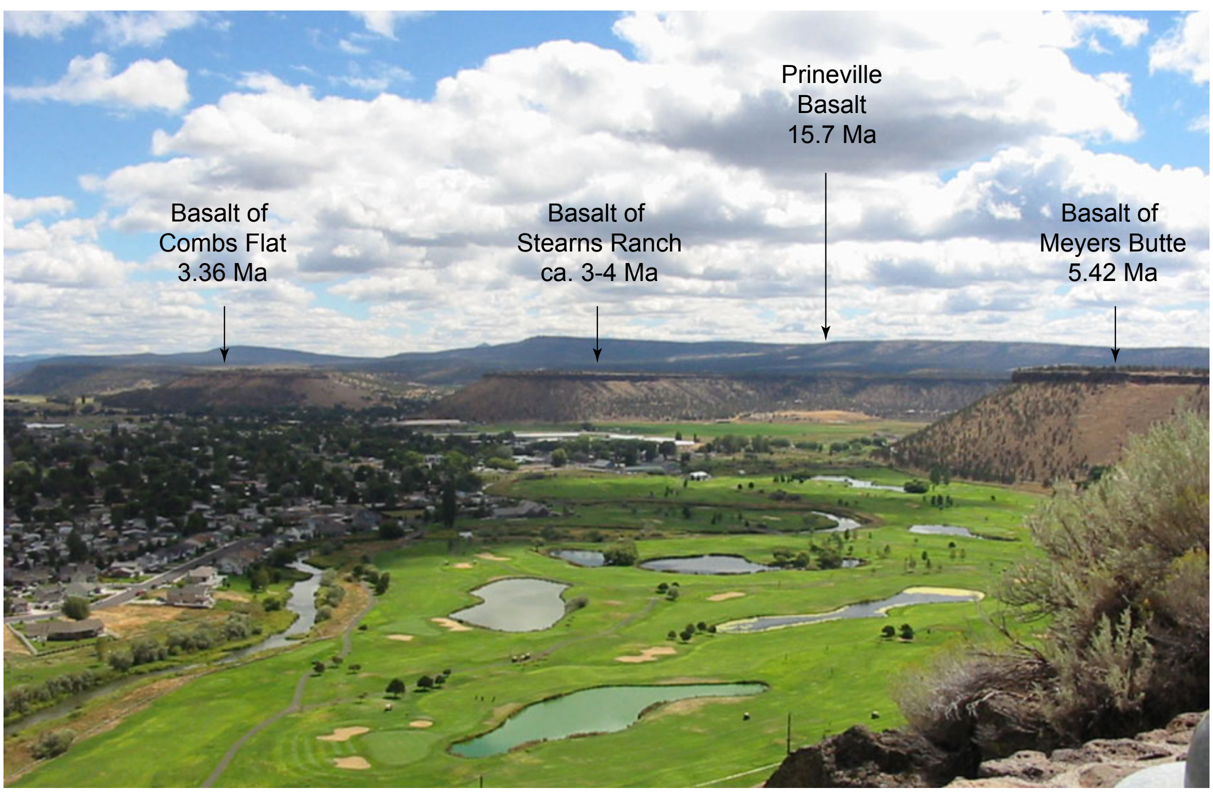


Figure 2. View east across the city of Prineville from Ochoco Wayside State Park. Topographically inverted basalt lavas of the Deschutes Formation trace the course of ancestral channels of the Crooked River. The high skyline on the east is composed of the Prineville Basalt.

basalts in the Lower Crooked Basin (Figure 2). The 3.36 ± 0.08 Ma (Smith, 1986a) Basalt of Combs Flat, part of the "late" Deschutes Formation, is visible to the southeast (100°). This lava erupted from a vent complex located at the eastern end of Combs Flat and flowed west down a paleochannel incised into an irregular surface of late Miocene and early Pliocene Deschutes Formation sand and gravel (Figure 1). The ca. 3-4 Ma Basalt of Stearns Ranch, part of the "late" Deschutes Formation, is visible to the southeast (115°) and forms the rimrock beneath Ochoco Wayside State Park. The vent for the Basalt of Stearns Ranch can be traced to a broad shield, located southeast of Dry Creek, near Prineville Reservoir (Figure 1). The 5.42 ± 0.11 Ma ($^{40}Ar/^{39}Ar$, whole rock; Ferns and McClaughry, 2006b) Basalt of Meyers Butte, part of the "middle" Deschutes Formation, forms a plateau exposed to the southeast (130°), south (180°) and west (270°) of Ochoco Wayside. These flows were erupted from a vent complex at Meyers Butte, west of Ochoco Wayside, and flowed northward and eastward into the ancestral Crooked River channel.

Much of the city of Prineville is situated on unconsolidated to poorly consolidated, moderately to well sorted, massive to stratified deposits of gravel, sand, silt, and clay preserved as remnants of abandoned fluviatile terraces along the Crooked River upstream of Smith Rock (Figure 1). In the Prineville Valley, terrace deposits are in excess of 90 m (300 ft) thick and form a broad, gently sloping plain covering ~50 km^2 (19 mi^2) (Figure 1). Upper surfaces of the terraces are as much as 6 to 90 m (20 to 180 ft) above the current base level of the Crooked River. The highest terrace levels are preserved at an elevation of 954 m (~3,130 ft) between the summit of Grizzly Mountain and US Highway 26, northwest of Prineville. Terraces may have been deposited in multiple episodes from late Miocene through middle Pleistocene time in response to repeated damming of the Crooked River by basalt lavas that entered the canyon near O'Neil, west of Prineville. The basalt impoundments elevated the base level for sediment deposition in the Prineville Valley and may have resulted in the formation of temporary lakes (Robinson and Price, 1963; Sherrod and others, 2004).

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 2

2.0 *Return to OR 126 via the viewpoint access road. Turn left onto OR 126 and proceed east back toward Prineville.*

3.5 *In Prineville, turn right onto the Crooked River Highway (OR 27). Travel 20.3 miles south on the Crooked River Highway to the Powder House Cove Boat Ramp.* From Prineville south to mile point 16.5, the Crooked River Highway follows the Crooked River upstream through a basalt-lined canyon whose walls are formed largely by Deschutes Formation basalt lavas (Figure 1). Between mile point 16.5 and Bowman Dam the lower walls of the canyon are composed of thick lavas of the Prineville Basalt capped by thin rimrock-forming basalt lavas of the Deschutes Formation.

23.8 *Follow the Crooked River Highway across Bowman Dam to the south bank of the Crooked River and continue south along the edge of Prineville Reservoir.*

23.9 *Turn left onto the entrance road for the Powder House Boat Ramp and drive to the large parking area near the reservoir at the east end of the boat launch area.* Restrooms are available.

STOP 2. POWDER HOUSE COVE: BOWMAN MAAR VIEWPOINT

GPS coordinates -120.7787, 44.1048

Bowman Maar is a deeply dissected hydromagmatic vent complex that is well exposed on the north rim of Prineville Reservoir northeast (35°) of stop 2 (Figure 3). A maar is a special type of volcanic vent that forms when ascending magma interacts with ground or surface water. The result is a low-relief, bowl-shaped crater that is composed of tuff and cinders that are rapidly ejected from the vent and pile up around the rim. Bowman Maar is one of at least 14 volcanic vents that erupted basalt lavas into the Lower Crooked Basin during the late Miocene and Pliocene.

The bowl-shaped volcanic edifice that defines Bowman Maar is filled with massive to distinctly stratified tuff and palagonite breccia that dip steeply back toward the center of the vent. Tuff beds are generally tan to yellow and contain abundant centimeter-sized accretionary lapilli. Horizons of granule- to pebble-sized breccia are interlayered with the tuff. Clasts in these deposits consist of black scoria, olivine-phyric basalt, rhyolite tuff, basaltic andesite and well-rounded, stream-worn cobbles of aphyric basalt up to 20 cm (7.9 in) in diameter (Figure 4). Outsized clasts of olivine-phyric basalt that occur within the vent facies have a maximum diameter of 64 cm (25.2 in).

Pyroclastic rocks preserved within the maar are crosscut by numerous olivine-phyric basalt dikes and are capped by a relatively thin basalt lavas, ramparts of welded spatter, and abundant scoria and fluidal bombs. This vent was the eruptive center for the Basalt of Bowman Maar, which forms a ridge-capping plateau above the Prineville Basalt northwest of Bowman Dam and on the south side of the Crooked River west of the spillway (Figure 1). Remnants of the basalt are found downstream as intracanyon lavas hanging on paleocanyon walls formed in the Prineville Basalt near the mouth of Swartz Canyon (stop 4), and are in section beneath the Rattlesnake Ash-Flow Tuff near the mouth of Dry Creek (stop 5). Bowman Maar and its associated lavas are considered to be late Miocene in age, as these units lie stratigraphically beneath the 7.05 ± 0.01 Ma Rattlesnake Ash-Flow Tuff (Streck and Grunder, 1995) and the Basalt of Hoffman Dam and above the 8.76 ± 0.24 Ma (McClaughry and Ferns, 2007c) Basalt of Quail Valley Ranch.

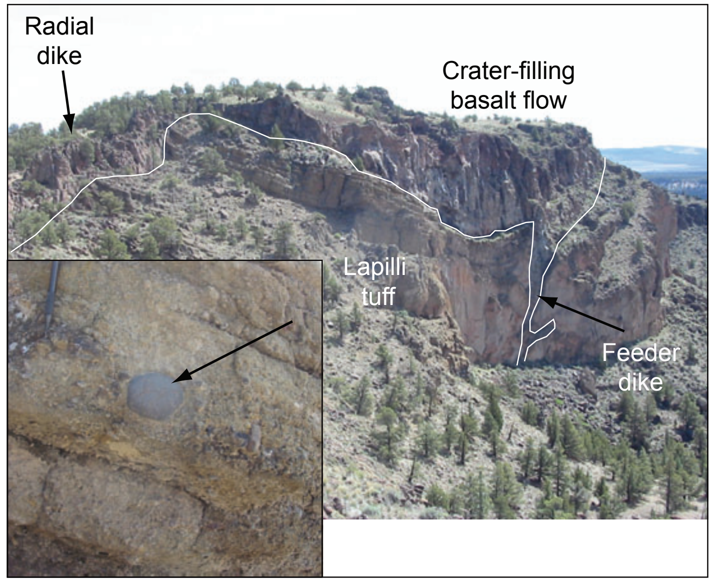


Figure 4. Bowman Maar is filled by a thick section of internally dipping lapilli tuff and an overlying crater-filling basalt lava. Inset photograph shows one of many well-rounded stream cobbles that were incorporated in primary lapilli tuff deposits inside the crater. The lithology of the cobble (approximately 10 cm ([3.9 in] wide) is Prineville Basalt. En-echelon basalt dikes intersect the maar complex.

Bowman Maar formed along the southwestern extension of the Prineville Reservoir fault zone, a complex zone of normal and reverse faults that accommodated synvolcanic deformation around the periphery of the Crooked River caldera in the Oligocene (McClaughry and others, 2009). The trace of the fault zone is now buried beneath a large landslide deposit that obscures the stratigraphic relationships between the older section of Oligocene ash-flow tuff and overlying middle Miocene rocks of the Simtustus Formation and the Prineville Basalt (Figure 3). Well-rounded stream cobbles contained within vent deposits indicate the maar complex erupted within an active channel of the ancestral Crooked River or on an adjacent floodplain.

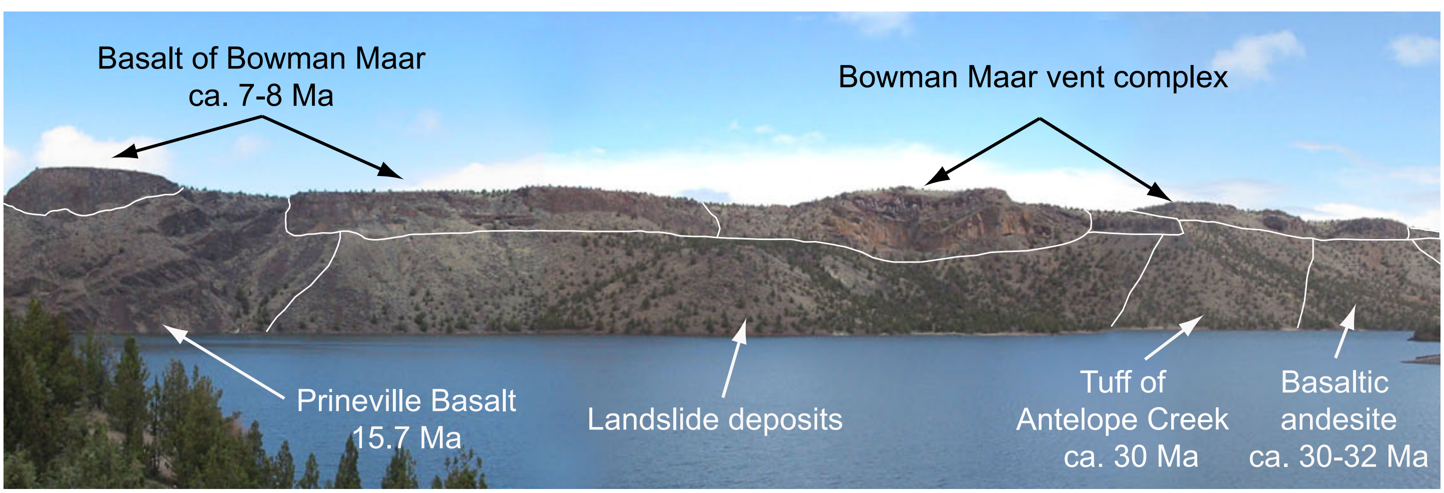


Figure 3. View northeast across Prineville reservoir toward Bowman Maar. Bowman Maar is a late Miocene hydrovolcanic eruptive center that formed above structurally deformed Oligocene rocks that predate eruption of the Crooked River caldera and the middle Miocene Prineville Basalt. Lavas erupted from the maar unconformably overlie the older, deformed strata.

Return to the Crooked River Highway. Turn right and proceed north to Bowman Dam.

24.2 *Turn left into the parking area on the left (south) abutment of Bowman Dam.*

STOP 3. LEFT ABUTMENT OF BOWMAN DAM: PRINEVILLE BASALT

GPS coordinates -120.7844, 44.1103

Stop 3 provides a view of the Prineville Basalt as defined by Uppuluri (1974), Smith (1986a), Tolan and others (1989), and Hooper and others (1993). Here a pillow delta, formed when lava flowed down an incline into a standing body of water, is exposed at the base of one of the Prineville Basalt lavas (Figure 5).

The Prineville Basalt is one of the westernmost units of the Columbia River Basalt Group and consists of a series of dark gray to black, fine-grained, aphyric and sparsely plagioclase-phyric, iron-rich basalt and basaltic-andesite lavas, characterized by unusually high concentrations of phosphorous (1.25–2.02 wt. % P_2O_5) and barium (1695–3202 ppm Ba). Hooper and others (1993) identified three chemical types for the Prineville Basalt: a Bowman Dam chemical type; high-silica chemical type; and high titanium-phosphorous chemical type. In the Lower Crooked Basin the Prineville Basalt forms a high plateau between Combs Flat and the Crooked River and is again exposed between Lone Pine Flat and the Crooked River west of the city of Prineville. The largest number of individual lavas and thickest section of Prineville Basalt occurs in the Crooked River Canyon west Bowman Dam, where the succession attains a maximum composite thickness of 210 m (690 ft). The type section near Bowman Dam consists of a vertical section of at least six lavas (Smith, 1986a). These lavas are generally flat lying except on the north side of Bowman Dam, where a large fault block of Prineville Basalt dips ~30° to 45° to the southwest. According to Hooper and others (1993), the lower two Bowman Dam type lavas display reversed magnetic polarity while the capping Bowman Dam type lava displays normal magnetic polarity; the intervening two lavas were found to have indeterminate polarity. Outcrop exposures are massive to hackly- and columnar-jointed with lesser amounts of spheroidal weathering. Pillow basalt, like that exposed here at Bowman Dam, is common, particularly where basalt lavas conformably overlie and invade early to middle Miocene sedimentary rocks equivalent to the Simtustus Formation (Smith, 1986b). The invasive relationship with underlying sedimentary rocks is recognized by the occurrence of crude pillows, chilled rinds, and admixed baked siltstone.

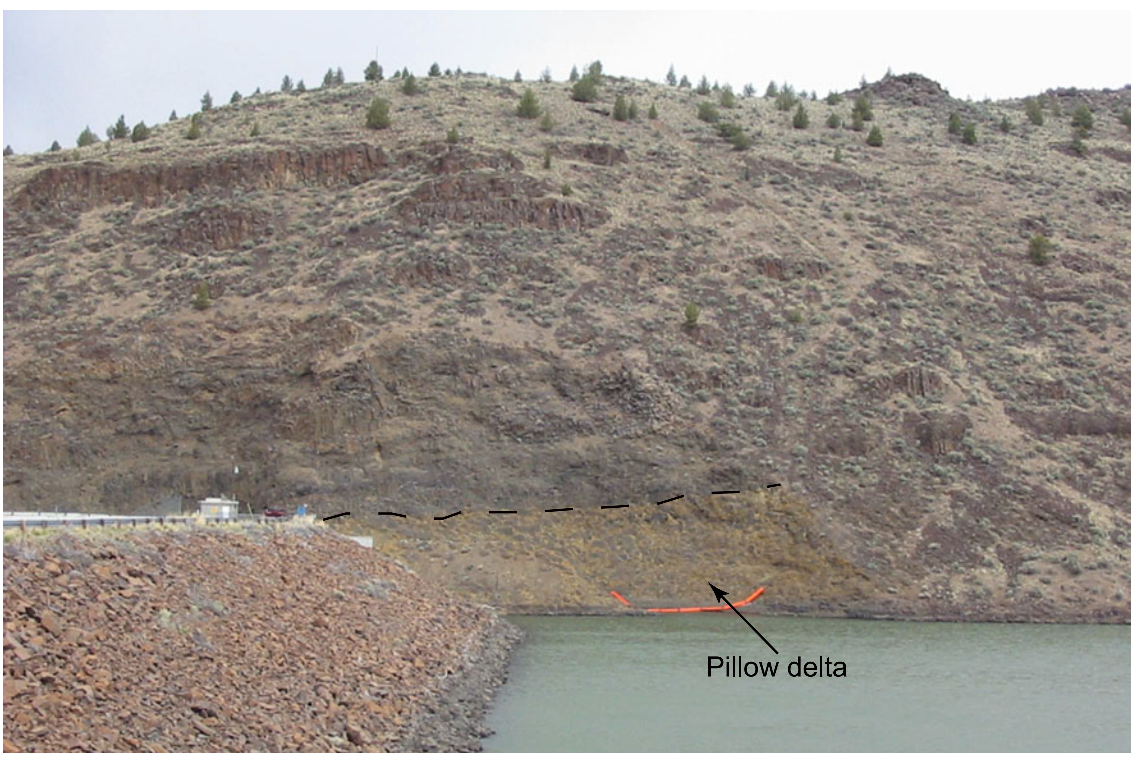


Figure 5. Pillow delta exposed at the base of a thick section of Prineville Basalt along the right abutment of Bowman Dam near stop 3.

A middle Miocene age for the Prineville Basalt is based on a $^{40}Ar/^{39}Ar$ age of 15.7 ± 0.1 Ma (Smith, 1986a) on the basal lava at Pelton Dam in the Deschutes Basin and intertonguing relationships between reversed magnetic polarity Bowman Dam type flows and R2 Grande Ronde Basalt lavas north of the Deschutes Basin (Hooper and others, 1993). The basalt is distinguished geochemically from similarly aged lavas of the Grande Ronde Basalt and the overlying basalt lavas of the Deschutes Formation by the remarkably high incompatible element concentrations of phosphorous (P_2O_5) and barium (Ba) (Figure 6). Prineville Basalt lavas are also typically more glassy, contain fewer recognizable crystals and, in general, are finer-grained than the average Deschutes Formation basalt lavas.

The Prineville Basalt is considered by Swanson and others (1979), Tolan and others (1989), and Smith (1986a) to be equivalent to the Columbia River Basalt Group while Hooper and others (1993) regard the Prineville Basalt as a separate interfingering unit. Presumably equivalent lavas are thought to be exposed in the valley of the Clackamas River (160 km [100 mi] northwest), and at least one lava has been traced down the canyon of the John Day River nearly to its mouth at the Columbia River (190 km [120 mi] northeast) (Hooper and others, 1993). No vents, as indicated by dikes, scoria, welded spatter, or tephra deposits, have been found for the Prineville Basalt, but the thickness of the succession near Bowman Dam indicates that area as the most probable eruptive site (Hooper and others, 1993).

Lavas of the Prineville Basalt and to an extent the age-equivalent sedimentary rocks of the Simtustus Formation are the primary water-producing units for residential areas that have been recently expanding between Stearns Butte on the north and the Crooked River on the south. The Prineville Basalt is identified in well logs by chemistry where available and is often described in water well logs as broken basalt intermixed with brown clay. Presumably, this description refers to the characteristic burrowing of Prineville Basalt lavas into underlying sedimentary rocks or the pillowed nature of the base of many of the lavas.

Merge right onto the Crooked River Highway and proceed north across Bowman Dam. Drive 8.3 miles to stop 4.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 4

24.7 The Basalt of Hoffman Dam forms the prominent plateau above the Prineville Basalt across the river to the west.

24.9 Outcrops of the central parts of individual Prineville Basalt lavas are often marked by narrow columns that end in blocky entablatures. Such outcrops often weather to fist-sized angular blocks.

28.6 Both the Hoffman Dam and underlying Bowman Maar lavas are visible near the top of the cliff on the south side of the river. The cliff at the top of the ridge north of the river is an erosional remnant of the Hoffman Dam lava that filled an old channel cut into the underlying Prineville Basalt.

29.3 Rocky Canyon is incised into a thick section of three Deschutes Formation lavas on the southwest side of the river. These flows include from bottom to top, the Basalt of Bowman Maar, the Basalt of Hoffman Dam, and the Basalt of Dry River.

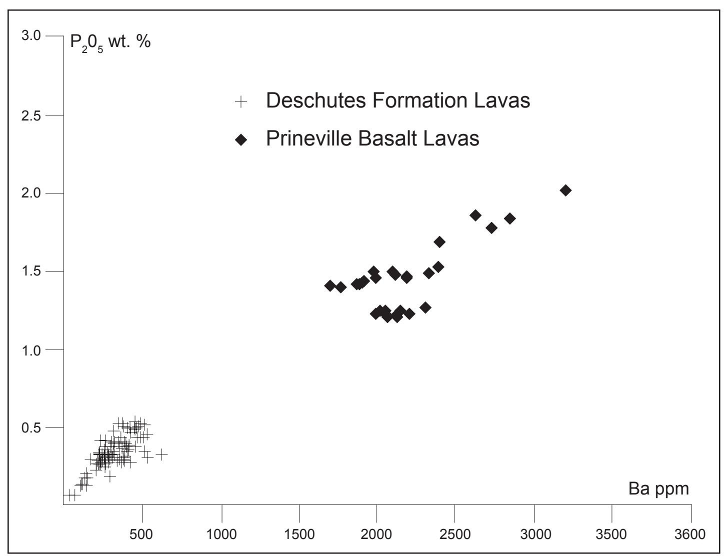


Figure 6. Variation plot of phosphorous (weight percent P_2O_5) versus barium (parts per million Ba) for Deschutes Formation Basalt lavas and the Prineville Basalt in the Lower Crooked Basin. The Prineville Basalt is distinguished from overlying lavas of the Deschutes Formation by its unusually high concentrations of phosphorous (P_2O_5) and barium (Ba).

The Basalt of Bowman Maar, part of the "early" Deschutes Formation, consists of a series of dark gray, diktytaxitic, olivine- and plagioclase-phyric lavas. These lavas compose the cliff- and bench-forming rimrock north-northeast of Bowman Dam and are layered beneath the Basalt of Hoffman Dam at the mouth of Rocky Canyon (Figure 7). Intracanyon lavas are found as far north as the mouth of Dry Creek where they sit stratigraphically beneath the Basalt of Hoffman Dam (stop 5). The basalt is directly juxtaposed against an older Prineville Basalt paleocanyon wall in Devils Canyon and at the mouth of Swartz Canyon. The Basalt of Bowman Maar was erupted from a north-northwest trending fissure and series of vents exposed 1.6 km (1 mi) east-northeast of Bowman Dam. Basalt lavas traveled west and north along an ancestral Crooked River drainage nearly identical to the modern river course (Figure 1).

The Basalt of Hoffman Dam directly overlies the Basalt of Bowman Maar and consists of dark gray, open-textured, diktytaxitic, olivine-, clinopyroxene-, and plagioclase-phyric basalt lavas (Figure 7). Lavas form part of the rimrock along the Crooked River west of Bowman Dam and are exposed as thick intracanyon lavas between Hoffman Dam and Prineville. Near Hoffman Dam, the lava succession may be more than 180 m (590 ft) thick where the lava is juxtaposed against and onlaps paleocanyon walls formed in the Prineville Basalt (Figure 8).

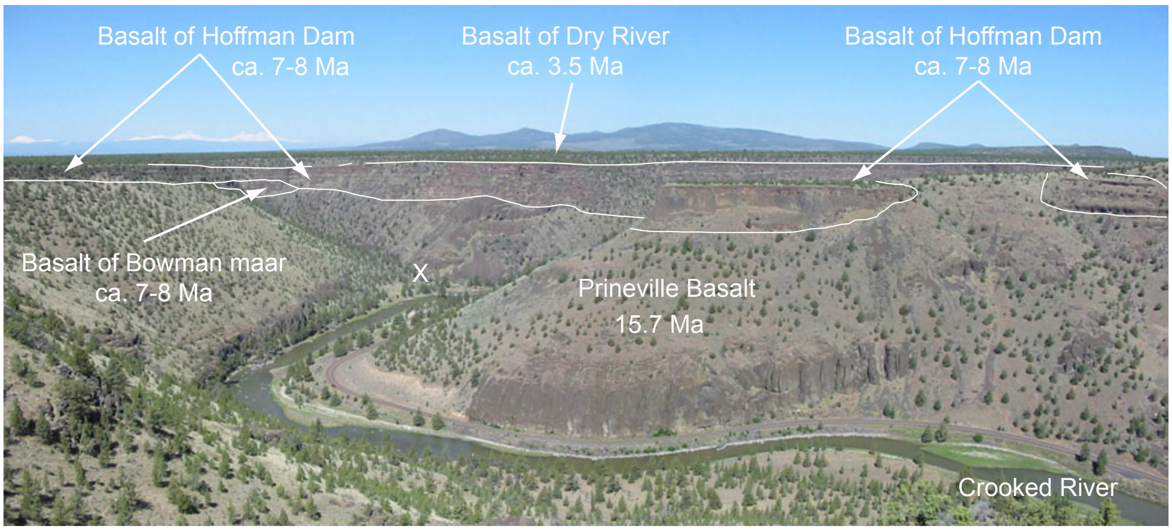


Figure 7. Well-exposed lavas of the Prineville Basalt and overlying intracanyon, olivine-phyric lavas of the Deschutes Formation that line the Crooked River Canyon. Lavas of the Prineville Basalt reach a maximum composite thickness of 210 m (690 ft) at this locality and thin abruptly to the north and south. View is to the northwest toward the mouth of Rocky Canyon (marked by ×). The Oligocene Powell Buttes rhyolite dome complex and the High Cascades are visible on the horizon.

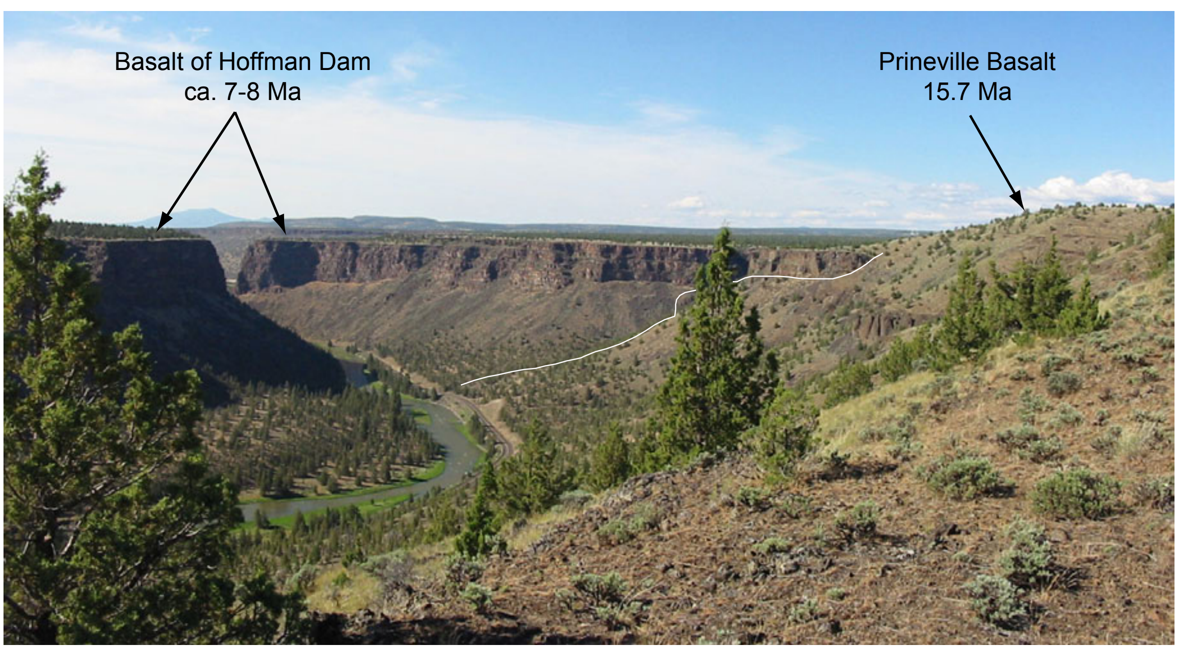


Figure 8. Thick, intracanyon lavas of the Basalt of Hoffman Dam juxtaposed against paleocanyon walls composed of Prineville Basalt.

Vents for the Basalt of Hoffman Dam are unknown but are inferred to be located to the south near Horse Butte (~9 km [5.75 mi] southwest of this location). Distribution of the lavas indicates that flows traveled north away from their source vents and formed a broad lobe. Flows emptied into an ancestral Crooked River drainage near Rocky Canyon and traveled downstream confined within a channel nearly identical to the modern river course. Both the Basalt of Bowman Maar and the Basalt of Hoffman Dam are considered to be late Miocene on the basis of stratigraphic position above the 8.76 ± 0.24 Ma (McClaughry and Ferns, 2007c) Basalt of Quail Valley Ranch and below the 7.05 ± 0.01 Ma Rattlesnake Ash-Flow Tuff.

The basalt succession at the head of Rocky Canyon is capped by the ca. 3.5 Ma Basalt of Dry River, part of the "late" Deschutes Formation, which consists of diktytaxitic, aphyric to olivine- and plagioclase-phyric basaltic andesite lavas (Figure 7). The Basalt of Dry River consists of extensive lavas that form the rimrock on the west side of the Crooked River Canyon between Swartz Canyon and the mouth of Dry Creek. These lavas also form a broad plain on the west side of Powell Buttes and the rimrock of the Crooked River east of O'Neil and west of the mouth of the Dry River. Lavas are found as far north and west as Redmond and extend south in a broad hummocky plain to their inferred vent area near Horse Butte. The Basalt of Dry River is considered to be Pliocene on the basis of stratigraphic position above the 5.42 ± 0.11 Ma Basalt of Meyers Butte.

29.8 From mile point 29.8 just north of Rocky Canyon nearly to Prineville, most of the canyon wall of the Crooked River is composed of lavas of the Deschutes Formation; lower contacts are concealed by landslide deposits. Unlike the Prineville Basalt, lavas of the Deschutes Formation typically break apart into large blocks that calve and topple or rotate listrically along fractured columnar joint margins and cascade downward from over-steepened, tension-cracked cliff-faces. In many places along the length of the Crooked River Canyon basalt blocks coalesce to form large, unconsolidated landslide deposits that mantle steep slopes. Older basalt slide deposits have vegetated and soil-mantled upper surfaces; more recent deposits lack vegetation and soil and in places may be confused for tumuli-capped intracanyon lavas. Clast-size in the deposits averages 1–3 m (3.3–9.8 ft) across; the maximum intact landslide blocks may exceed 300 m (985 ft) across. Note the large landslide block of basalt in the canyon to the left.

31.0 The canyon narrows abruptly to the north of this mile point, where a thick succession of intracanyon lavas of the Basalt of Hoffman Dam form the east wall of the Crooked River Canyon. Thick intracanyon lavas thin abruptly east of the modern Crooked River Canyon where flows are juxtaposed against and onlap paleocanyon walls formed by the Prineville Basalt (Figure 8). The Basalt of Hoffman Dam is here capped by younger Pliocene lavas of the Basalt of Stearns Ranch. Stearns Ranch lavas were erupted from a small shield volcano preserved on top of the plateau, 4.4 km (2.7 mi) east of the field trip route.

31.8 Terrace gravels are exposed on the left side of the highway, beneath younger landslide deposits.

32.1 The highway emerges from the Wild and Scenic portion of the Crooked River Canyon.

32.5 *Pull off onto the right side of the highway.* The outcrop for stop 4 is exposed just to the north of the narrow parking area.

STOP 4. BASALT OF QUAIL VALLEY RANCH AND SIMTUSTUS FORMATION

GPS coordinates -120.8333, 44.1698

The oldest of the "early" Deschutes Formation lavas exposed in the Lower crooked Basin, the Basalt of Quail Valley Ranch, forms a distinct, southward-dipping bench on the west, where it hangs on a paleocanyon wall formed in the Prineville Basalt (Figure 9). The Basalt of Quail Valley Ranch consists of gray, diktytaxitic, glomeroporphyritic, plagioclase-, clinopyroxene-, and olivine-phyric basalt. The basalt is considered to be late Miocene on the basis of a $^{40}Ar/^{39}Ar$ (whole rock) age of 8.76 ± 0.24 Ma (McClaughry and Ferns, 2007c). Vents for the Basalt of Quail Valley Ranch are unknown.

The outcrop along the road consists of white to tan, moderately indurated tuff that stratigraphically underlies the middle Miocene Prineville Basalt. The unit here is mantled by a large landslide deposit and terrace gravel related to the modern Crooked River. The tuff is composed of a mixture of rhyolite lithics, feldspar grains, pumice, relict glass (?) fragments, and concretions (Figure 10a). Correlative tuff and sedimentary deposits elsewhere in the Lower Crooked Basin are exposed beneath and are locally interbedded with the middle Miocene Prineville Basalt. Sedimentary deposits are characterized by massive bedding, cut-and-fill channel forms, rip-up fragments, and locally abundant burrow traces.

Although previously mapped as John Day Formation, we consider the tuff exposed along the road here to be part of a younger succession that is in part coeval in age with the Prineville Basalt (Waters and Vaughan, 1968; Swanson, 1969). Unlike the bulk of the John Day Formation, these rocks are weakly altered and, in places, make marginal aquifers. A middle Miocene age for the upper part of the unit is inferred on the basis of interdigitated contact relations with the Prineville Basalt and middle Miocene vertebrate fossils that have reportedly been recovered from these deposits near Eagle Rock. Contact relations with the Prineville Basalt are often marked by palagonite breccia and by detached basalt pillows that are totally enclosed within the tuffaceous sedimentary rocks (Figure 10). The quenched basalt textures and invasive character of the basalt pillows indicate the Prineville Basalt interacted with standing water, wet unconsolidated sediment, or a combination thereof (Figure 10b).

On the basis of interbedded stratigraphic relations, early to middle Miocene sedimentary rocks in the Lower Crooked Basin are considered to be correlative to the Simtustus Formation (Smith, 1986b). The Simtustus Formation, as originally defined by Smith (1986b) along the Deschutes River near Madras, is restricted to sedimentary rocks that are clearly interbedded with

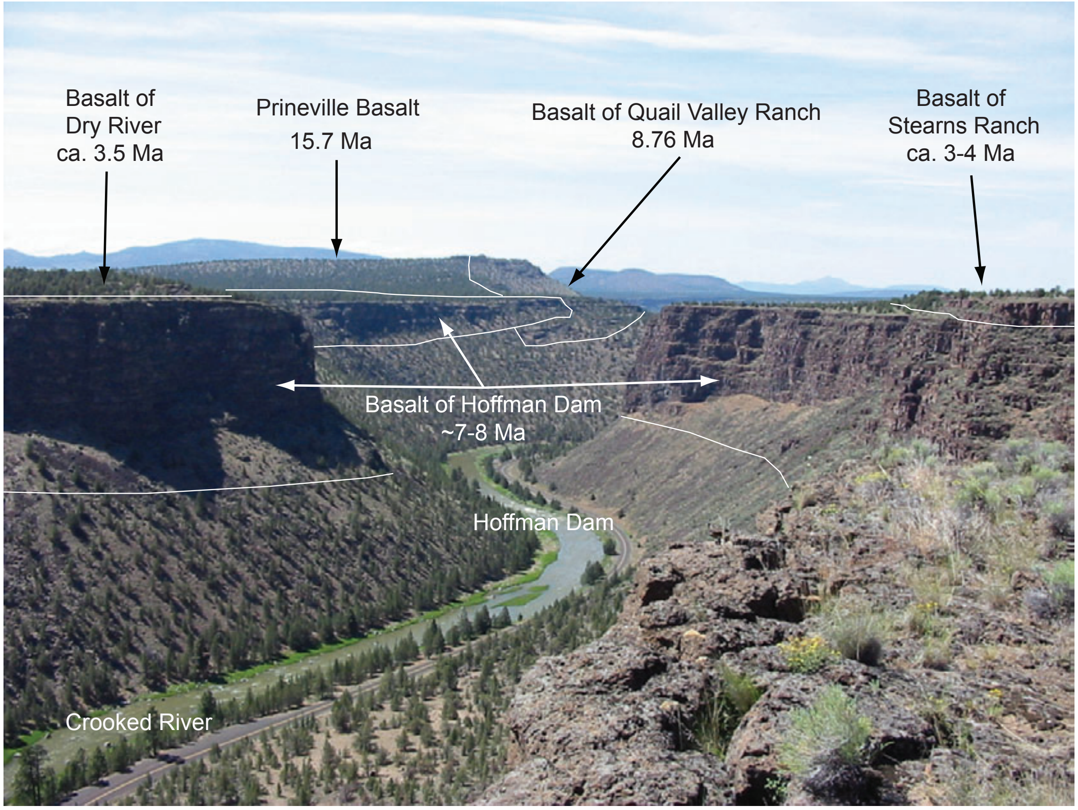


Figure 9. Thick, intracanyon Deschutes Formation lavas exposed near Hoffman Dam and stop 4. View is to the north-northwest. The 8.76 Ma Basalt of Quail Valley Ranch is the oldest Deschutes lava recognized in the Lower Crooked Basin and is here juxtaposed against a Prineville Basalt paleocanyon wall. The southeast dip on the Basalt of Quail Valley Ranch is the only good evidence for deformation of the Deschutes Formation in the Lower Crooked Basin.

Figure 10. (a) Outcrop of tuffaceous sedimentary rocks equivalent to the Simtustus Formation exposed along the Crooked River Highway at stop 4. (b) Detached pillows of the Prineville Basalt encased in similar tuffaceous sedimentary rocks in the Lower Crooked Basin.

or overlie the Prineville Basalt. Similar stratigraphic relations for middle Miocene sedimentary rocks in the Lower Crooked Basin suggest a permissible correlation of these rocks to the Simtustus Formation in the Deschutes Basin.

This is the only place where there is good evidence for deformation of the Deschutes Formation in the Lower Crooked Basin. Tuff beds exposed in the road outcrop strike ~ N 60° E, and dip ~20° SE. A similar strike and dip can be inferred for the Basalt of Quail Valley Ranch, suggesting that faulting in this part of the basin occurred after emplacement of this lava. The trace of the fault may be marked by Swartz Canyon, with the highstanding ridge of Simtustus Formation sedimentary rocks and the Prineville Basalt preserved as an upthrown fault block.

Continue north on the Crooked River Highway.

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 5

33.3 The landslide block on the left is mantled by terrace gravels.

34.2 The mouth of Swartz Canyon comes into view on the left. Thin, blocky to rounded, outcrops of Rattlesnake Ash-Flow Tuff are exposed sporadically about midway up the canyon wall on both sides of the Crooked River Canyon between this mileage point and stop 5 (Figure 11). Springs are emitted from the upper contact of the tuff, which in many places presents a barrier to groundwater flow.

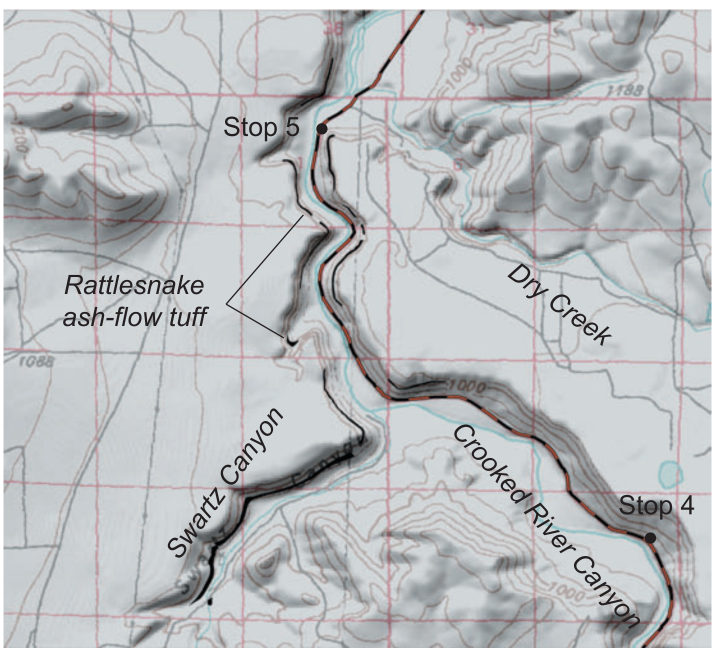


Figure 11. The 7.05 Ma Rattlesnake Ash-Flow Tuff interbedded with a section of Deschutes Formation lavas in the Crooked River Canyon at stop 5. The Rattlesnake Ash-Flow Tuff was erupted from a vent to the southeast in the Harney Basin and became partially channelized by the ancestral Crooked River south of Prineville. Most of the Deschutes lavas exposed between this location and Bowman Dam are older than the Rattlesnake Ash-Flow Tuff.

36.3 Stearns Dam

37.3 *Stop 5. Pull off of the highway into parking area on the left.*

STOP 5. BASALT SECTION INTERBEDDED WITH RATTLESNAKE ASH-FLOW TUFF

GPS coordinates -120.8772, 44.2155

A well-exposed stratigraphic section in the west wall of the Crooked River Canyon includes reverse polarity flows of the Deschutes Formation interbedded with the Rattlesnake Ash-Flow Tuff (Figure 12). From bottom to top the Basalt of Bowman Maar, the Basalt of Hoffman Dam, the Rattlesnake Ash-Flow Tuff, and the Basalt of Meyers Butte are exposed. A thin flow lobe of the Basalt of Dry River caps the section here but is not visible from the highway pullout.

The Rattlesnake Ash-Flow Tuff (Walker, 1979; Streck and Grunder, 1995) forms an important stratigraphic marker in the canyon wall that is easily visible on the east side of the Crooked River (Figure 11). The tuff consists of a 7- to 15-m-thick (23.0–49.0 ft) single cooling unit of light orange, vitric-pumice-lithic tuff that forms a distinct, ledge-forming marker bed exposed in the Crooked River Canyon between Swartz Canyon and the mouth of Dry Creek at stop 5 (Figure 12). The tuff is considered to be late Miocene on the basis of an $^{40}Ar/^{39}Ar$ age of 7.05 ± 0.1 Ma reported by Streck and Grunder (1995) and stratigraphic relations below the Basalt of Meyers Butte (Ferns and McClaughry, 2006b). A majority of the stratigraphic section exposed along the Crooked River Canyon south of stop 5 lies below this stratigraphic marker. The Rattlesnake Ash-Flow Tuff, one of the most far-traveled ash-flow tuffs known, was erupted in the western Harney Basin, ~ 160 km (100 mi) southeast of the Lower Crooked Basin (Streck and Grunder, 1995; Jordan and others, 2002). The ash-flow formed a thick blanket that covered at least 35,000 km^2 (13,500 mi^2) (Jordan and others, 2002) but was confined within the channel of the ancestral Crooked River as it reached the southern part of the Lower Crooked Basin.

The overlying Basalt of Meyers Butte consists of dark gray, medium-grained, sparsely olivine-microphyric lavas that caps the west side of the Crooked River Canyon between the mouth of Dry Creek and Ochoco Wayside State Park. The lava is considered to be late Miocene on the basis of a $^{40}Ar/^{39}Ar$ age of 5.42 ± 0.11 Ma from a sample north of Meyers Butte and stratigraphic position above the Rattlesnake Ash-Flow Tuff (Ferns and McClaughry, 2006). Lavas were erupted from a vent complex at Meyers Butte west of Prineville and flowed north and southeastward into the ancestral Crooked River.

Merge back onto the Crooked River Highway and return to the Crook County Library in Prineville.

Figure 12. Distribution of the Rattlesnake Ash-Flow Tuff in the Crooked River Canyon.

GEOLOGIC HIGHLIGHTS EN ROUTE TO THE CROOK COUNTY LIBRARY

37.4 A thick section of terrace gravel is exposed in the aggregate mine workings to the right, at the mouth of Dry Creek. At approximately 900 m (2,950 ft) the elevation of the top of the terrace gravels closely matches the elevation of the top of the Newberry lava where it blocked the Crooked River near O'Neil, downstream of Prineville.

37.7 Prineville Basalt is exposed at Stearns Butte, to the north and east. This flank of Stearns Butte is marked by prominent landslide deposits. Immediately to the east (right), Dry Creek cuts through the Basalt of Stearns Ranch, which here partially filled a channel that had been cut into the Prineville Basalt.

Landslide deposits exposed on the east side of the canyon result from catastrophic cliff-collapse where competent lavas overlie incompetent sedimentary rocks. Such conditions persist where (1) the contact between Prineville Basalt and underlying Simtustus Formation is exposed, (2) unconformable depositional contacts between the Deschutes Formation basalts and underlying Simtustus Formation are exposed, and (3) contacts between Deschutes Formation basalts and underlying Deschutes Formation sedimentary rocks are exposed.

37.9 Large blocks of basalt, such as the one exposed west of the field trip route at this location, have rotated listrically as they slowly slid down the canyon wall. Locally, ancient landslide deposits and large slide blocks have been partially buried by terrace gravel deposits. In this part of the Lower Crooked Basin the hummocky surfaces of large block landslides are sometimes difficult to distinguish from the original irregular tumuli-capped surface of intracanyon basalt lavas.

40.5 The prominent flat mesa ahead to the north and east is the eroded flow-top to the Basalt of Stearns Ranch. Lavas of the Basalt of Hoffman Dam are exposed at the base of the section in the west canyon wall, where they form a hummocky, irregular flow surface. Both lavas are mantled by thick lag deposits of sand and gravel of the Deschutes Formation. The rimrock on the west is the Basalt of Meyers Butte.

41.5 *Crossing a terrace gravel deposit.* The terrace is a remnant of an extensive surface of older alluvium that filled the Prineville Valley when the downstream reach of the Crooked River was blocked near O'Neil by lavas from Newberry Volcano. The modern Crooked River is still in the process of downcutting through the blocking lava between O'Neil and Smith Rock on the west. In places, the terrace deposits make a very favorable aquifer.

42.3 To the west, an "early" Deschutes Formation lava is exposed in the canyon wall. The Basalt of Huston Lake underlies the Basalt of Meyers Butte and consists of a gray, diktytaxitic, plagioclase- and olivine-phyric lava exposed between the mouth of Dry Creek and Prineville. The basalt also forms a broad plain between Dry River and Grass Buttes. The lower part of the flow in the Crooked River Canyon, south of Prineville, is composed of a large pillow delta that formed when a lobe of the Basalt of Huston Lake entered part of the ancestral Crooked River. The pillow delta here is more than 20 m (65 ft) thick and is composed of basalt pillow mounds and palagonite breccia. Detached, stretched pillows in the delta float in a yellow palagonite matrix and form well-developed steeply dipping foreset beds that trend N 80° E and plunge 40° NE. A second lobe of the Basalt of Huston Lake entered the ancestral Crooked River Canyon near the mouth of the Dry River, ~14 km (9 mi) west-northwest of Prineville. This lobe may have temporarily impounded the ancestral Crooked River drainage creating a lake at Prineville and south up the canyon. The second easterly flowing lobe of the Basalt of Huston Lake may have then flowed into this lake forming the pillow delta.

44.0 *Turn left off of the Crooked River Highway on NW Second Street.*

44.5 *Turn left onto Meadow Lake Drive and proceed to the Crook County Library Parking lot.* ***End of field trip.***

ACKNOWLEDGMENTS

This field trip guide is a product of a geologic mapping study of the Lower Crooked Basin that was partially funded by the U.S. Geological Survey National Cooperative Geologic Mapping program under assistance awards 05HQAG0037 and 06HQAG0027 during 2005 and 2006. Additional financial support from the Oregon Water Resources Department (OWRD) for geochemical and geochronological analyses is appreciated. The authors gratefully acknowledge the support of John and Lynne Breese of the Dixie Meadows Company and The Crooked River Watershed Council. Critical reviews by Rick Conrey (WSU), Ken Lite (OWRD), and Ian Madin (DOGAMI) and additional comments by Jay Van Tassell (EOU) and Deb Schueller (DOGAMI) improved the final manuscript.

$^{40}Ar/^{39}Ar$ age determinations were prepared and analyzed by John Huard at the College of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis. X-ray fluorescence (XRF) geochemical analyses were prepared and analyzed by Stanley Mertzman, Franklin and Marshall College, Lancaster, Pennsylvania. Analytical procedures for the Franklin and Marshall X-ray laboratory are described by Boyd and Mertzman (1987) and Mertzman (2000) and are available online at http://www.fandm.edu/x7985. Major-element determinations, shown in Table 1, have been normalized on a volatile-free basis and recalculated with total iron expressed as FeO*.

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Table 1. Summary table of x-ray fluorescence geochemical analyses for Deschutes Formation lavas in the Lower Crooked Basin.

	Pliocene										Miocene													
	"Late" Deschutes Formation					Round Butte Basalt Member (Deschutes Basin) erupted 3.97 Ma	Onset of faulting along Green Ridge ~ 5.42 Ma	"Middle" Deschutes Formation									Rattlesnake Ash-Flow Tuff erupted 7.05 Ma	Pelton Basalt Member (Deschutes Basin) erupted 7.42 Ma	"Early" Deschutes Formation					
Sample	196J	136P05	66 LCJ 06	RC03-9	RC03-40			SF-143b	126P05	7.13 VII.05	SF-141	SF-135	SF-140	LA-448460	DT-184b	111LCJ06			517LCJ08	115P05	114P05	1.31 VIII.05	46 LCJ 06	50 LCJ 06
UTM N	4893550	4906025	4894674	4911057	4909979			4926650	4912323	4909669	4926635	4923861	4926930	4917830	4929170	4929199			4912180	4904760	4902870	4902297	4888461	4892442
UTM E	653554	676122	670660	646205	651823			635804	660282	665091	635696	637510	635524	639980	661451	676538			663380	659810	663200	669784	676499	671627
Age (Ma)	3.31*	3.36†		3.56†				5.31†		5.42§				5.77†	6.3†									8.76**
Polarity	nd	reverse	normal	normal	rev./ nor.			normal	normal	reverse	reverse	reverse	reverse	normal	nd	nd			reverse	reverse	reverse	rev./ nor.	rev./ nor.	nd
									Cascade ash-flow tuffs (5.31 to 5.77 Ma)						Rhyolite at Cline Buttes and Steelhead Falls									
Flow unit	Alfalfa	Combs Flat	Stearns Ranch	Red-mond	Dry River			Tetherow Butte	Japa-nese Creek	Meyers Butte	un-named	un-named	un-named	Opal Springs	Willow Creek	Bottle-neck Springs			Round Butte	Huston Lake	Grass Butte	Hoff-man Dam	Bow-man Maar	Quail Valley Ranch
Oxides, weight percent																								
SiO_2	49.30	49.65	49.59	48.25	52.24			52.06	50.87	49.86	52.89	53.40	54.22	50.21	50.93	50.14			49.80	50.45	53.07	49.11	50.81	50.68
Al_2O_3	17.50	15.86	17.16	15.97	16.39			13.66	15.84	17.06	17.80	18.59	18.54	17.58	17.92	17.04			15.39	16.71	15.60	15.28	16.14	18.18
TiO_2	1.48	1.23	1.48	1.67	1.52			2.67	1.65	1.46	1.72	1.62	1.30	0.97	1.14	1.13			1.78	1.46	1.74	2.20	1.38	0.99
FeO*	9.70	9.33	11.10	11.51	10.04			13.92	9.98	10.93	9.71	8.57	8.01	8.30	10.16	9.65			9.68	10.82	9.62	12.76	9.28	9.07
MnO	0.17	0.17	0.20	0.20	0.19			0.24	0.18	0.19	nd	nd	nd	0.17	0.16	0.16			0.16	0.19	0.16	0.22	0.17	0.18
CaO	10.21	11.47	9.59	9.83	8.68			7.51	9.78	9.89	8.94	8.44	8.52	11.46	11.14	10.76			10.52	9.77	9.48	9.37	9.69	11.39
MgO	7.78	8.98	7.04	8.99	6.23			5.09	7.66	6.95	4.73	4.47	4.61	8.20	5.97	8.06			8.69	7.01	6.39	7.21	9.01	6.03
K_2O	0.36	0.75	0.48	0.37	0.96			0.62	0.79	0.41	0.80	0.92	0.79	0.39	0.28	0.46			0.68	0.41	0.92	0.57	0.61	0.42
Na_2O	3.20	2.25	3.03	2.88	3.43			3.69	2.79	2.93	3.42	3.98	4.01	2.59	2.70	2.42			2.78	2.85	2.70	2.77	2.50	2.76
P_2O_5	0.30	0.31	0.34	0.33	0.32			0.53	0.46	0.32	nd	nd	nd	0.13	0.18	0.18			0.52	0.33	0.33	0.52	0.42	0.31
LOI	nd	0.92	1.23	0.30	1.86			nd	1.08	1.02	nd	nd	nd	nd	nd	0.54			1.19	0.84	1.40	0.84	1.27	1.46
Trace Elements, parts per million																								
Ni	79	168	102	192	90			38	133	113	nd	nd	nd	125	nd	128			149	107	107	117	179	64
Cr	nd	399	106	343	77			0	255	117	nd	nd	nd	209	nd	409			342	138	242	198	385	142
Sc	nd	32	29	36	32			41	28	29	nd	nd	nd	35	nd	36			26	31	23	34	29	39
V	nd	238	259	270	240			444	226	261	nd	nd	nd	250	nd	240			256	259	223	345	225	272
Ba	201	527	313	216	381			483	524	250	nd	nd	nd	137	nd	141			510	290	617	374	379	374
Rb	5	11	8	5	15			22	11	6	nd	nd	nd	6	nd	5			8.6	6	10	9	8	5
Sr	335	768	338	239	288			386	548	341	nd	nd	nd	268	nd	553			717	347	1040	330	574	340
Zr	118	101	97	106	155			155	153	92	nd	nd	nd	73	nd	100			191	105	146	115	124	76
Y	27	23	31	34	40			38	34	30	nd	nd	nd	24	nd	21			28.2	32	29	38	26	26
Nb	9	8	6	5	7			0	12	5	nd	nd	nd	5	nd	5			9.1	6	9	7	10	8
Ga	nd	16	21	18	19			0	19	20	nd	nd	nd	17	nd	17			15.4	20	20	21	17	17
Cu	nd	65	97	77	77			0	54	86	nd	nd	nd	94	nd	34			41	91	47	99	58	102
Zn	76	67	87	96	96			0	85	85	nd	nd	nd	68	nd	84			113	90	93	106	84	70
Pb	nd	3	4	2	3			0	2	2	nd	nd	nd	5	nd	4			1	1	7	3	4	4
La	nd	18	11	5	16			0	23	11	nd	nd	nd	14	nd	13			20	12	24	14	13	10
Ce	nd	41	21	17	33			0	48	25	nd	nd	nd	5	nd	21			55	28	51	31	35	18
Th	nd	2	0	0	0			0	2	1	nd	nd	nd	1	nd	1			1	1	1	2	2	1
U	nd	0	1	0	0			0	1	0	nd	nd	nd	0	nd	1			0.5	1	1	0	1	0
Co	nd	47	46	0	0			0	43	47	nd	nd	nd	0	nd	45			39	47	38	52	41	35
Ref.	1	—	—	2	2			3	—	—	3	3	3	4	5	—			—	—	—	—	—	—

Note: Major-element determinations have been normalized on a volatile-free basis and recalculated with total iron expressed as FeO*. LOI, loss on ignition; nd, no data or element not analyzed. References for geochemical analyses, 1, Donnelly-Nolan personal communication (2008); 2, Conrey personal communication (2008); 3, Smith (1986a);4, Lite and Gannett (2002); 5, Thormahlen (1984). References for age-dates *Donnelly-Nolan (2008); †Smith (1986a); §Ferns and McClaughry (2006); **McClaughry and Ferns (2007c). Magnetic polarity determined using portable fluxgate magnetometer. Time-stratigraphic markers in the Deschutes Formation are identified by yellow shading.

DOGAMI AGENCY NEWS FOR 2008-2009

—contributed by James Roddey

MAPPING PROGRAMS

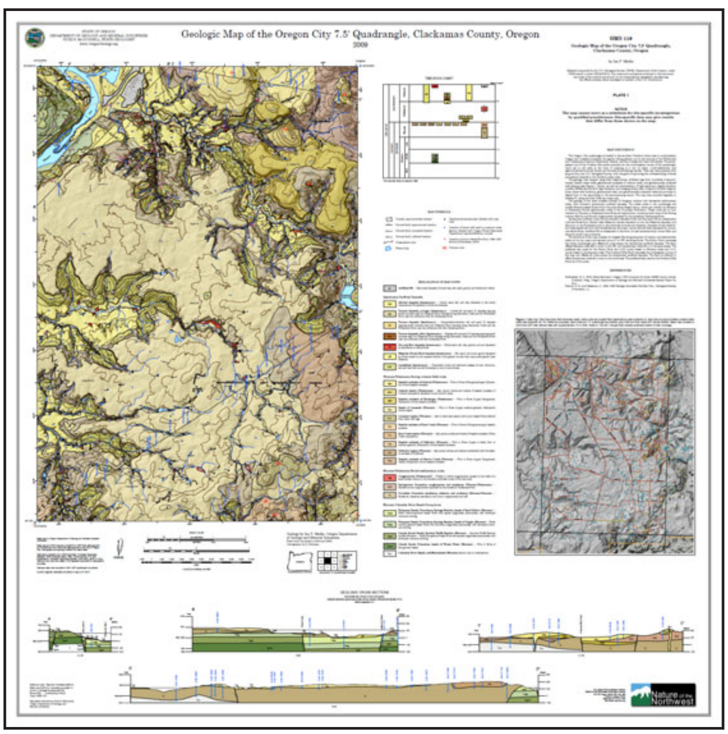
DOGAMI's Lidar Collection and Mapping Program has grown substantially over the last 2 years, thanks to the formation of the **Oregon Lidar Consortium** (OLC; http://www.oregongeology.org/sub/projects/olc/), with the ultimate goal of providing high-quality lidar elevation and topographic coverage for the entire state. Led by DOGAMI Chief Scientist Ian Madin, acquisition of lidar data that began in 2007 will soon include over 10,000 square miles of high-resolution lidar data, including the complete 362-mile-long Oregon coastline data set. In the western part of the state large portions of the Willamette Valley have been collected as well as incremental portions of the souther Klamath Basin, and other portions of eastern Oregon. OLC members include numerous USGS programs, the U.S. Forest Service, BLM, and FEMA, as well as other federal, state and local agencies including the Oregon Department of Transportation, Metro (Portland Regional Governments), the Port of Portland, state universities, local governments, and tribal governments. Two full time staff have been added to the agency to help work on this ambitious project

In December 2008 DOGAMI began releasing the first 7.5′ quadrangle geologic maps using this newly acquired high-resolution lidar data as the base topography. The geologic maps of the Linnton and Dixie Mountain quadrangles provide a view of the geology and geomorphology of the NW Tualatin Mountains (Portland Hills) that is unprecedented in its detail and scope. A geologic map of the Oregon City quadrangle using lidar-derived topographic data was released in September 2009. These new maps and data using lidar imaging are some of the most detailed and accurate topography in the United States due to accuracy of this laser-based terrain mapping program.

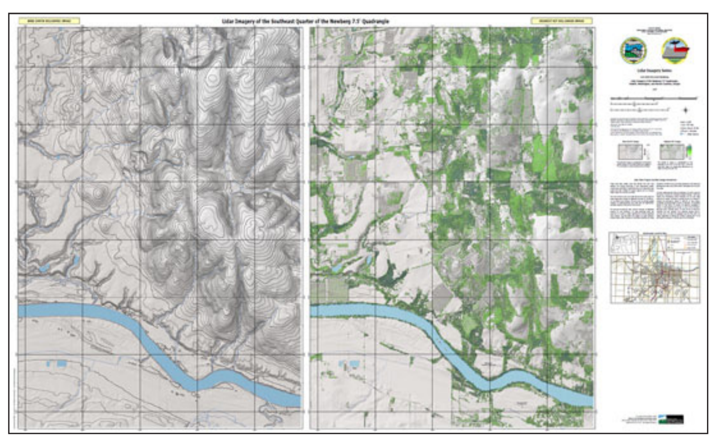
A new lidar-based digital topographic image series and a new digital elevation data series were rolled out in August 2009. The first of the new **Lidar Imagery Series (LIS)** maps are eight USGS 7.5′ quadrangles of the Portland metro area. There are four quarter-quadrant shaded relief digital elevation model (DEM) images for each quadrangle.

The initial release in the **Lidar Data Quadrangle (LDQ)** series covers most of the Portland metro area (25 USGS 7.5′ quadrangles). The data in the LDQ series, however, are designed specifically for use with specialty geographic information system (GIS) software. This release comprises the first installment of a data publication series that will eventually provide complete lidar data for most of the inhabited areas of the state.

From lidar data collected throughout the state, DOGAMI has created an interactive web site displaying bare-earth elevation data as DEM (**Lidar Data Viewer**: http://www.oregongeology.org/sub/lidardataviewer/index.htm). The interactive site is searchable by street address. As more lidar data become the data will be added to the viewer.



New 7.5-minute quadrangle maps use high-resolution lidar-based imagery as the base map. Plate 1, Geologic Map of the Oregon City 7.5' quadrangle (Geologic Map 119), by Ian P. Madin.



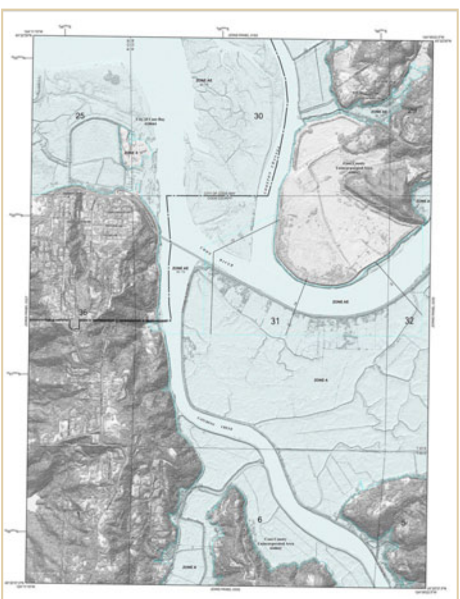
DOGAMI's new Lidar Imagery Series features bare-earth and highest hit lidar-based imagery at 1:8,000 scale. This is the SE quarter of the Newberg 7.5' quadrangle.

(Agency news, continued from page 61)

DOGAMI-FEMA pilot Risk MAP project

Another important, multi-year program currently underway is the DOGAMI-FEMA pilot Risk MAP (Mapping, Assessment, and Planning) project, begun in 2008. The Federal Emergency Management Agency (FEMA) has obligated $1,012,960 to DOGAMI under FEMA's Map Modernization Program to fund high-resolution coastal topographic data development using lidar data for flood insurance rate map redelineation, hydraulic coastal flood analysis, the integration of multiple natural hazard data layers for Coos County, and lidar data acquisition for Clatsop and Tillamook counties.

Most current FEMA flood zone maps are based on topographic data from the U.S. Geological Survey National Elevation Dataset that were constructed from 1950s–1960s era aerial photography. In this pilot project, DOGAMI has been asked to create new, lidar-based topographic maps to solve the cartographic flaws of the older maps and provide detailed three-dimensional elevation data.



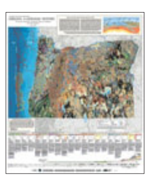
FEMA is funding DOGAMI to produce coastal topographic maps for flood insurance rate map redelineation. The maps relate flood zones to local topography using high-precision lidar.

The Oregon Geologic Data Compilation

In May 2009 DOGAMI finished a six-year project to develop a digital geologic map of Oregon and to compile this geologic information into a database for the entire state. This completed map and data, the **Oregon Geologic Data Compilation (OGDC-5)**, is the most accurate, complete, and up-to-date geologic map in Oregon's history.

By integrating the work of many individual geologic mappers into a digital data set, the compilation becomes a "living map" that can be accessed on different resolutions and can be updated as new information is added. The data are stored in a GIS format with links to a relational database.

Earlier versions of OGDC-5 are already being used throughout the state for projects and programs ranging from the identification of groundwater resources and the locations of naturally occurring hazardous materials to mapping landslides and earthquake faults. A visual web interface to the northeast, southeast, and central Oregon OGDC data is available online at http://www.oregongeology.org/sub/ogdc/. Users can view Oregon stratigraphy, rock types, and rock property theme maps on topographic and shaded relief backdrops.



Oregon sesquicentennial geologic map

While **OGDC-5** is primarily for users of GIS, the data from the compilation has been used to create the new **Oregon Sesquicentennial Geologic Map (IMS-28).** This map was created for a general audience interested in learning more about the amazing geologic history of Oregon. The Oregon Sesquicentennial Geologic Map, *Oregon: A Geologic History*, subtitled *150 Years of Statehood, 150 Million Years in the Making*, is being released to coincide with the Geological Society of America (GSA) convention being held in Portland October 18–21, 2009.

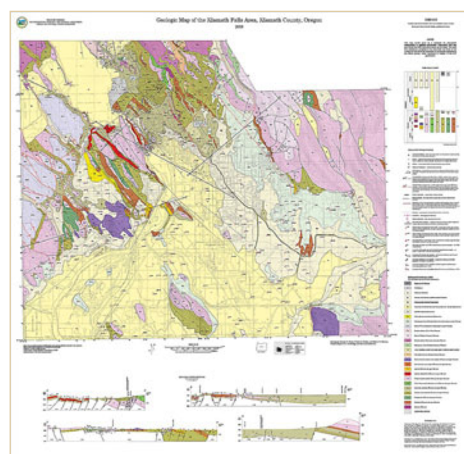
This full-color wall map contains a timeline outlining important events in Oregon's (and the earth's) geologic history. Rock unit descriptions and publicly accessible locations where each of the rock types can be seen are provided. Middle and high schools across the state will receive free copies this fall. The map will be available for purchase at the GSA convention in October and on the Nature of the Northwest website (http://www.natureNW.org). See p. 93 for ordering instructions.

Klamath Basin mapping completed

The **Geologic Map of the Klamath Falls area, Klamath County, Oregon** (GMS-118) is the first detailed, modern map of the geology of this area.

Over the years, seven DOGAMI geologists made a majority of the geologic maps that went into this publication. This compilation of 47 different geologic maps provides critical information for understanding the groundwater resources and the connections between groundwater and surface water in the upper Klamath Basin. It also identifies hundreds of newly mapped volcanoes in the area that have erupted over the past few million years into an environment of giant lakes.

Mapping efforts in the basin by DOGAMI began in the late 1990s with new mapping within the Klamath Falls urban growth boundary in support of earthquake hazard analysis. As water issues within the basin became more important, DOGAMI continued making new,



Geologic Map of the Klamath Falls area, Klamath County, Oregon (GMS-118) is the culmination of nearly a decade of geologic research and mapping in the Klamath Basin, largely in response to the water crisis.

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large-scale geologic maps in support of the hydrologic studies of the Oregon Department of Water Resources and the U.S. Geological Survey (USGS) Water Resource Department.

Umatilla Basin mapping project

DOGAMI geologists have completed a multi-year project to map an important basin in eastern Oregon. The Umatilla Basin is a large region of northeastern Oregon bounded generally by the Blue Mountains to the south and east and the Columbia River to the north. The study area comprised all of the Umatilla River drainage basin within Umatilla and Morrow counties. The major urban areas in the study area are Pendleton, Hermiston, Milton-Freewater, and Boardman. The study area also includes the U.S. Army Umatilla Chemical Depot and the lands of the Confederated Tribes of the Umatilla Indian Reservation.

Large portions of the area have been labeled critical groundwater areas by the Oregon Water Resources Department and are closed to new water well drilling. It is largely the concern over falling groundwater levels that prompted the Oregon Geologic Map Advisory Committee to make the Umatilla Basin a top priority for new geologic mapping. The new map is meant to be an initial compilation and digitization of existing data that can serve to guide and focus future in depth studies and detailed mapping. This geologic map was funded in part by the U.S. Geological Survey (USGS) National Cooperative Geologic Mapping Program.

Other DOGAMI mapping

In 2008 DOGAMI geologists also completed a major geological mapping effort in the **Lower Crooked Basin**, dedicating several years to conducting detailed mapping and compiling the best published geologic information ever available for the area. This information can be used to drive decisions about water and land use and identify areas of geological hazard. These maps can tell the geologic history of a landscape and help project what the future uses of an area might be.

In early October 2008, geologists Mark Ferns and Jason McClaughry from the Baker City Field Office presented a free public lecture in Prineville to a standing room only crowd that examined new evidence that the area around Prineville sits inside one of several ancient volcanic calderas in the area. They also led an all day technical field trip and a half-day public field trip through the Lower Crooked Basin, from Prineville Reservoir to Smith Rock State Park, to showcase the amazing geologic history of the region. These programs were presented in cooperation with the USDA Forest Service Ochoco National Forest and Crooked River Watershed Council.

Ferns and McClaughry also completed the Lebanon and Onehorse Slough 7.5′ quadrangles located in the Willamette Valley. The area was remapped at a larger scale as part of a regional effort to construct a geologic framework for the **middle and southern Willamette Valley**.

In February 2009 DOGAMI released geologic maps of the Corvallis, Wren, and Marys Peak 7.5′ quadrangles in the **central Willamette Valley** by Tom Wiley of the Grants Pass Field Office. The rocks within this mapped area reveal a rich and turbulent geologic history beginning about 50 million years ago that includes tropical islands, volcanic eruptions, epic floods, landslides, and earthquakes.

COASTAL PROCESSES AND HAZARDS

One of the most important tasks for DOGAMI is helping coastal communities understand and mitigate for the risk of possible tsunamis. Communities located in exposed, low-lying areas along the Oregon coast face the risk of inundation by tsunamis produced by earthquakes around the Pacific Rim far from Oregon, as well as local earthquakes on the Cascadia subduction zone.

As part of this important effort, DOGAMI has begun remapping the state's entire coastline for tsunami inundation using state-of-the-art computer models, coupled with laser based terrain mapping and field based geologic investigations. Coastal geologists Rob Witter and George Priest have finished 2 years of field investigations and new computer modeling that details the landward extent of sand deposits left by Cascadia tsunamis that inundated the lower Ecola Creek valley in Cannon Beach over the last 2,000 years.

From these efforts, DOGAMI, along with its many partners, including the City of Cannon Beach and the Seaside School District, have created a new tsunami evacuation brochure for Cannon Beach using this ground-breaking research. The brochure and map can be found online (http://www.oregongeology.org/pubs/tsubrochures/CannonEvac.pdf). This is the first of a new generation of tsunami evacuation brochures that will result from the remapping of the coastline for tsunami inundation. Similar efforts are now underway near Bandon.

DOGAMI has also received a generous grant from the NOAA National Tsunami Hazard Mitigation Program to accelerate mapping and outreach activities at the Oregon coast. DOGAMI assisted the City of Cannon Beach with efforts to install public education signs that feature the new tsunami evacuation map and other educational information. James Roddey, Earth Sciences Information Officer with DOGAMI was the technical advisor for the state-wide magnitude 9.0 Cascadia Peril earthquake and tsunami exercise.

DOGAMI continues as an active partner with the Northwest Association of Networked Ocean Observing Systems (NANOOS), which is a cooperative venture to establish a pilot coastal ocean

DOGAMI Coastal Field Office geologist George Priest explains the new Cannon Beach/Arch Cape tsunami evacuation map at a news conference in Portland.

(Agency news, continued from page 63)

Oregon Public Broadcasting (OPB) featured DOGAMI Coastal Geologist Rob Witter (left) in an October 2009 *Oregon Field Guide* program on new tsunami hazard research.

observatory for the estuaries and shores of Oregon and Washington. An important part of the NANOOS program is the **Oregon Beach and Shoreline Mapping Analysis Program**, with additional funding from the Oregon Department of Land Conservation and Development and the Oregon Parks and Recreation Department. 46 sites were and are being monitored along three beaches: the Clatsop Plains just north of Tillamook Head, Rockaway area beaches, and Neskowin area beaches.

The objective of this monitoring program is to document the response of Oregon's beaches to both short-term climate variability (e.g., El Niños, extreme storms) and longer-term effects associated with the changing climate of the earth (e.g., increasing wave heights, changes to storm tracks, and sea level rise), that will influence the stability or instability of Oregon's beaches over the next century.

Other projects include analysis and monitoring of a unique dynamic revetment and artificial dune for shore protection at **Cape Lookout State Park**, monitoring an active landslide that impacts part of the Pacific Coast Highway (U.S. Highway 101), and coastal erosion hazard mapping for several counties.

Another interesting project was commissioned by the U.S. Fish and Wildlife Service (USFWS) to carry out a beach monitoring study of the effects of dune lowering undertaken on the **Elk River Spit** in July-August 2006. The purpose of the dune lowering is to rehabilitate portions of the spit for the purposes of developing a Western Snowy Plover breeding habitat.

The final report (Special Paper 40) of a five-year investigation on the decades-old **Johnson Creek Landslide** in Lincoln County by DOGAMI and the Oregon Department of Transportation (ODOT) was released in 2008. The ODOT Research Program sponsored the project in cooperation with the Federal Highway Administration in order to gain a better understanding of the mechanics of large translational landslides affecting Tertiary sedimentary rocks along the U.S. west coast.

The Oregon Coastal Processes and Hazards Working Group continue to meet, chaired by the State Geologist.

GEOHAZARDS

Statewide seismic needs assessment

In 2007 DOGAMI completed the first ever Statewide Seismic Needs Assessment of Public Schools and Emergency Response Facilities (http://www.oregongeology.org/sub/projects/rvs/default.htm). Presented to the Oregon legislature in May 2007, the Statewide Seismic Needs Assessment catalogued and ranked the seismic safety of emergency and educational facilities across the state including 1,280 schools (totaling 2,369 buildings), 143 city police and fire departments, and 191 rural fire protection districts.

The assessment was the first step in a pre-disaster mitigation strategy that is now moving forward with the creation a grant program for local communities. The Oregon Seismic Rehabilitation Grant Program administered by Oregon Emergency Management (OEM) is now taking applications for grants that are available for seismic rehabilitation projects on the above described facilities. Approximately $30 million has been included in the 2009–2011 state budget and a total allocation is expected to reach over $1 billion by 2032. The eligible grant recipients through this program are directly related to DOGAMI's seismic needs assessment results.

Seismic rehabilitation

In April 2008 DOGAMI and the Oregon Public Utilities Commission (OPUC) conducted a **Critical Energy Infrastructures Workshop**, held in Salem, which brought together executives and senior engineers from critical energy and telecommunication infrastructure organizations with the goal of sharing evidence that earthquake preparedness is needed for the State's energy and telecommunication infrastructure.

The workshop also encouraged participants to look at the need for seismic vulnerability assessments of utility systems and encouraged the development and implementation of earthquake hazard mitigation plans. Workshop attendees heard from Oregon State Senate President Peter Courtney, and Regional Coordinator of the Governor's Economic Revitalization Team, Mark Ellsworth. Seven nationally recognized experts presented overviews of Cascadia earthquake hazards and risk, infrastructure vulnerability to earthquake damage, state-of-practice lifeline seismic vulnerability studies and application, and a look at vulnerability studies by the Bonneville Power Administration (BPA) and the Pacific Gas and Electric Company (PG&E).

DOGAMI wrapped up a **multi-year seismic rehabilitation project** with the Oregon University System (OUS), a $5.6 million program, funded by FEMA Pre-disaster Mitigation Program grants, to seismically rehabilitate buildings at Oregon State University, the University of Oregon, Portland State University and Western Oregon University. The seismic rehabilitation took place along with scheduled deferred maintenance of the buildings which included upgrading their energy efficiency.

A 2-day workshop in Cannon Beach and Portland in October 2009 addressed issues of tsunami risk management and

Predisaster mitigation demonstration at Oregon State University.

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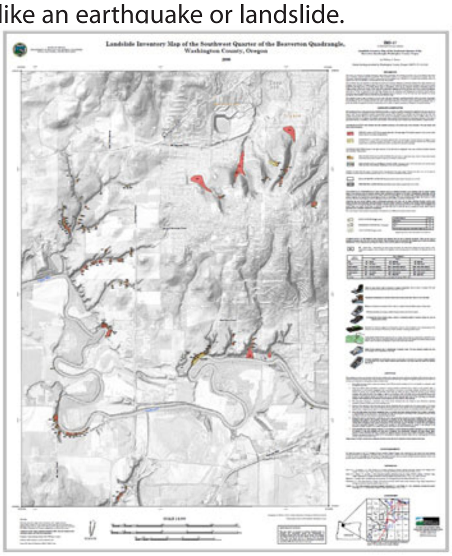
policies relating to **tsunami vertical evacuation buildings**. The workshop and field trips were sponsored by the Cascadia Region Earthquake Workgroup, the City of Cannon Beach, Oregon Department of Land Conservation and Development, the American Society of Civil Engineers, and DOGAMI.

In July, 2008, DOGAMI released **IMS-24, Geologic Hazards, Earthquake and Landslide Hazard Maps, and Future Damage Estimates for Six Counties in the Mid/Southern Willamette Valley Including Yamhill, Marion, Polk, Benton, Linn, and Lane Counties, and the City of Albany, Oregon.** This 5-year study was initiated by the Federal Emergency Management Agency (FEMA) Pre-Disaster Mitigation grant program. The three main objectives of this study were to assist communities in the development of county natural hazard mitigation plans, to identify and map potential earthquake and landslide hazards in the region and to improve the ability of the counties and local communities to perform earthquake damage and loss estimations, which is essential for requesting federal aid during natural disaster declarations. The study also made recommendations on actions to take to mitigate, prepare for and recover from a destructive natural disaster like an earthquake or landslide.



"Landslide Inventory Map of the Southwest Quarter of the Beaverton Quadrangle, Washington County, Oregon" by William J. Burns (DOGAMI Interpretive Map 27) identifies many previously unknown landslides by using high-resolution lidar-based mapping.

Lidar-based geohazards mapping

From February through April 2008, DOGAMI released a new generation of lidar-based landslide inventory maps and landslide susceptibility maps that are more accurate and comprehensive than any in the past. These new landslide maps include portions of Washington County and Oregon City and the new mapping program using lidar data has identified up to 200 times the number of landslides in areas where traditional mapping methods have been used in the past. The landslide susceptibility maps are the first of their kind in Oregon.

OUTREACH AND PUBLICATIONS

GSA in Portland

From Volcanoes to Vineyards: Living with Dynamic Landscapes is the theme of the 121st Annual Meeting of the Geological Society of America, being held at the Oregon Convention Center in Portland October 18–21. State Geologist McConnell has headed up the local organizing committee for the last year, and many DOGAMI staffers will be leading local field trips and topical sessions, presenting papers and posters, and manning the DOGAMI exhibit booth.

Highlights of the conference will include a day of activities celebrating the 200th birthday of Charles Darwin, a special display of 16 panels depicting Oregon's geologic history, originally created for a two-year display in the Oregon State Capitol, and a Science Pub Theater presentation sponsored by the Oregon Museum of Science and Industry on earthquakes in the Pacific Northwest featuring Brian Atwater of the U.S. Geological Survey and Yumei Wang of DOGAMI.

State Capitol window panels

DOGAMI was one of the lead organizations in creating a new exhibit at the State Capitol in Salem entitled **Oregon, 150 years of statehood, 150 million years in the making,** highlighting Oregon's geologic heritage and our earth sciences community during the State of Oregon's sesquicentennial.

From volcanoes and ancient fossils, to earthquakes, landslide and tsunamis, this thought provoking, first of its kind exhibit showcases Oregon's geologic history, present and future, in 16 display windows on the main floor of the Capitol. Rare gems, minerals, and fossils collected by Thomas Condon over 100 years ago and other geologic treasures are also featured in the windows.

The exhibit, which opened in January 2009, was produced by the Oregon Historical Society, in collaboration with the Oregon State University (OSU) Department of Geosciences, Oregon Paleo Lands Institute, OSU Hatfield Marine Sciences Center, Portland State University, and DOGAMI.

Tsunami risk outreach

April is **Earthquake and Tsunami Awareness Month** in Oregon and in both 2008 and 2009, DOGAMI staffers led workshops and town hall meetings up and down the Oregon coast as part of the Tsunami Road Show with presenters from OEM the National Weather Service and local emergency management agencies also participating.

In addition to duties with the Cascadia Peril exercise in April 2009, Earth Sciences Information Officer Roddey produced and co-wrote an 8-minute video on tsunami preparedness for Oregon in partnership with USGS that will be distributed to coastal communities and will be available on the OregonGeology.org website.

DOGAMI Information Officer James Roddey explains tsunami risk as part of the Tsunami Road Show in 2009.

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OregonGeology.org website

The last two years have seen some important additions to the OregonGeology.org website.

A number of interactive web map tools are now available on the DOGAMI website or partner websites. One of the most common and damaging geologic hazards in Oregon is landslides. Average annual repair costs for landslides in Oregon exceed $10 million, and severe winter storm losses can exceed $100 million. In response to this hazard DOGAMI created the **Statewide Landslide Information Database for Oregon (SLIDO)** to improve the understanding of the landslide hazard in Oregon and to create a statewide base level of landslide data. Part of the SLIDO deliverable is an interactive web map (http://www.oregongeology.org/sub/slido/index.htm).

SLIDO includes more than 15,000 landslide and landslide-related features gathered from 257 published and unpublished studies, but by no means should be considered a complete catalog of landslides in Oregon. The original studies vary widely in scale, scope, and focus; this results in a wide range in the accuracy, detail, and completeness with which the landslides are mapped. The interactive map lets you view information on location, type of landslide, and other attributes related to *only* identified landslides in Oregon.

The interactive **Geothermal Information Layer for Oregon (GTILO)** map (http://www.oregongeology.org/sub/gtilo/index.htm) lets you view information on location, temperature, and other features of thermal springs and wells (geothermal exploration, geothermal test, and water wells) as well as direct-use areas.

A **Tsunami Map Viewer** (http://www.nanoos.org/data/products/oregon_tsunami_evacuation_zones/index.php) lets you enter an address at the coast and see a map of areas with tsunami evacuation zones based on the information that you entered.

These maps join other interactive features, including the **Oregon Geologic Data Compilation (OGDC)** (http://www.oregongeology.org/sub/ogdc/index.htm), a **Lidar Data Viewer** (http://www.oregongeology.org/sub/lidardataviewer/index.htm) that allows you to view lidar data shaded-relief imagery for selected areas of Oregon and the pilot project **Portland Metro Area Lidar and Geohazards** (http://www.oregongeology.org/sub/lidar/index.htm) interactive viewer that allows you to compare the resolution of imagery generated with lidar with other kinds of mapping techniques such as 10-m shaded topographic relief (DEM), orthophoto, and topographic (DRG) maps. You can display additional overlays, such as tax lot outlines, streets, and five geohazard study maps and you can zoom directly to your address, if it is in the mapped area.

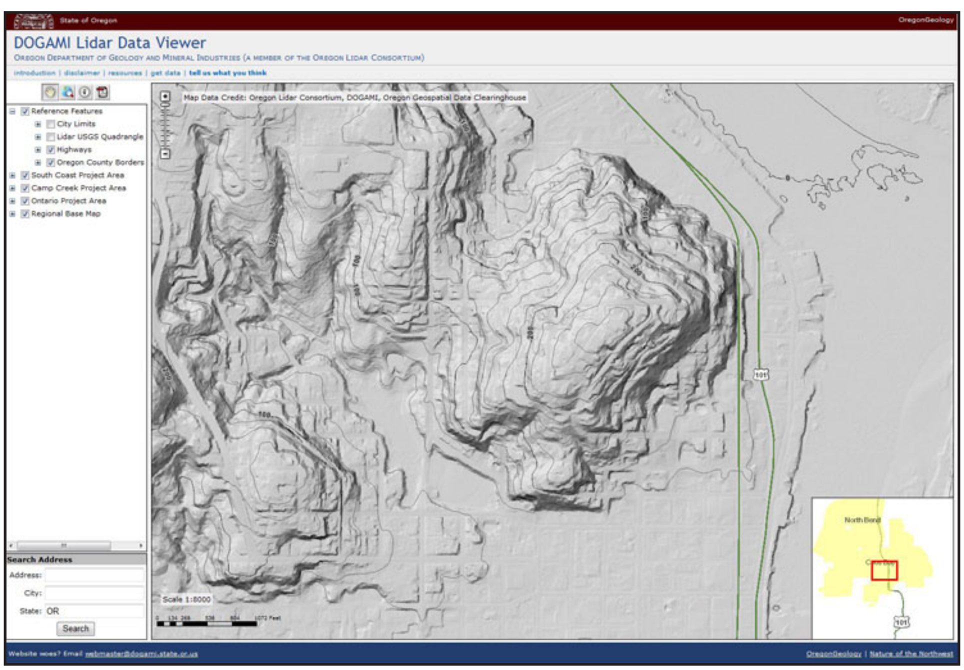
Publications

Lidar Imagery and Lidar Data Quadrangle series were introduced in 2009. Titles from these series are listed beginning on page 72 along with other recent DOGAMI publications.

The 2009–2015 DOGAMI Strategic Plan

The DOGAMI Mission: To provide earth science information and regulation to make Oregon safe and prosperous.

Members of the DOGAMI staff and DOGAMI Governing Board began meeting in fall 2007 to develop the department's new 2009–2015 strategic plan. Over the next year, meetings were held and suggestions and comments were collected from across the agency and from many of our important partners on the agency's mission, vision, goals, and future. The completed strategic plan outlines for our agency a broad and ambitious agenda for the next 6 years. The document will be an ongoing resource that guides our actions and supports our vision, which is to be "*the source of earth science information, mineral development, regulation, and guidance for Oregon while meeting the highest standards of objectivity and professionalism.*"



DOGAMI's new lidar data viewer. This screenshot shows a portion of Coos Bay at 1:8,000 scale.

(Agency news, continued from page 66)

MINERAL LAND REGULATION AND RECLAMATION

Our Mineral Land Regulation and Reclamation Program (MLRR) is the lead program for mine regulation in Oregon. MLRR administers fee-based statewide programs with authority to regulate all upland and underground mining on all lands, oil and gas drilling and geothermal resource drilling. In addition, the program implements the federal Clean Water Act General Storm water Permit and the state Water Pollution Control Facility Permit at aggregate mine sites. MLRR works with the industry and the public to minimize the impacts of mining and optimize the opportunities for reclamation and restoration. The number one issue for the program is floodplain mining and its relationship to off-site resources including the potential for habitat restoration. MLRR staff have taken a lead role in an Oregon Solutions Project on the Applegate River in southwestern Oregon to develop cooperative agreements between mining and other uses of the floodplain.

The MLRR Program has a staff of seven reclamationists with technical specialties such as fish biology, soil science, and hydrology. MLRR staff divide their time between technical communication on policy issues and field inspections and regulation. The advent of increased pricing for oil and gas has increased activity in the state for energy mineral extraction with three new Oil and Gas wells permitted since 2007 (up from one well permitted in 2003).

Cumulative acreage reclaimed totals over 5,426 acres. This means that approximately 6 square miles of Oregon once dedicated to mining is now reclaimed to a beneficial use with minimal environmental impact and consistent with surrounding land use. An awards program for mining recognizes particularly impressive success stories each year.

Mined Land Reclamation Award

The 2008 and 2009 Mined Land Reclamation Award winners are listed starting on page 69.

DOGAMI GOVERNING BOARD

In 2007 Charles Vars was chosen by the Governor to replace William Elliott, who had moved out of state. Mr. Vars is an emeritus professor in economics at Oregon State University and served as the Mayor of Corvallis.

Larry Givens joined the board in 2008 replacing Vera Simonton. Mr. Givens is currently a County Commissioner with Umatilla County. He has also served on the Umatilla County Planning Commission, and has worked as a teacher of earth sciences and geology with the Ferndale School District and as a rancher in the area. He is a graduate of Washington State University.

Long-time board member Barbara Seymour of Oceanside retired in 2009 and has been replaced with Lisa Phipps of Rockaway Beach. Ms. Phipps is the executive director of the Tillamook Estuaries Partnership, a non-profit organization dedicated to the conservation and restoration of the five Tillamook County estuaries and the watersheds that sustain them. Prior to joining the Tillamook Estuaries Partnership, Ms. Phipps was the coastal resource planner and planning manager for the Tillamook County Department of Community Development. She has served as mayor of Rockaway Beach for 5 years, currently sits on the boards of several non-profit organizations, and is the president of the Tillamook County United Way. Ms. Phipps is a graduate of Michigan State University and Vermont Law School.

DOGAMI's Governing Board at the Cannon Beach meeting September 2009. Front row: R. Charles Vars, Lisa Phipps, and Larry Givens. Back row: Steve Macnab and Don Haagensen.

PEOPLE ON THE MOVE

A reorganization of DOGAMI offices has resulted in the closing of the Grants Pass field office and the downsizing of the Baker City field office. **Mark Ferns** and **Jason McClaughry** will remain in eastern Oregon and be relocated to the Baker County Courthouse. **Tom Wiley** from the Grants Pass field office has moved to the main DOGAMI office in Portland. We are no longer operating retail sales outlets except for the **Nature of the Northwest Information Center**, which has relocated to the DOGAMI offices on the ninth floor of the Portland State Office Building.

Business Manager **Charles Kirby** retired in 2008 after 17 years with the department. **Jan Durflinger**, of the Baker City field office, also retired in 2008 after 25 years with DOGAMI. **Nancy Collins**, MLRR Storm Water Permitting Lead, left the agency in 2009.

Chip Andrus has joined the Albany office (MLRR) as a reclamationist/biologist. **John English** is the new lidar database coordinator in the Portland office. **Seay Johnson** has joined the Portland staff as a fiscal analyst, working with the lidar program. **Jed Roberts** is the new geospatial data coordinator and **Sarah Robinson** and **Matthew Tilman** have joined the department as cartographers.

Oregon State Geologist **Vicki McConnell** has been elected Vice President of the American Association of State Geologists. She also serves as Chair of the Oregon Coastal Processes and Hazards Working Group.

MLRR PROGRAM

MINED LAND RECLAMATION AWARDS

Each year the Mineral Land Regulation and Reclamation Program (MLRR) of the Oregon Department of Geology and Mineral Industries (DOGAMI), with an independent panel of experts, selects specific mine sites and operators to receive industry and Department recognition for outstanding reclamation, mine operation and salmon protection (The Oregon Plan Award). Awards, based on an operator's performance during the previous calendar year, are presented at the Oregon Concrete and Aggregate Producers Association (OCAPA) annual conference.

"We consider these awards important recognition to those owners and operators who go beyond the basic requirements of rules and regulations in operating a mine site," said Vicki S. McConnell, State Geologist and Director of DOGAMI. "By using innovative ideas and responsible techniques of reclamation they are working to minimize the impact on the environment and in the process also be good neighbors."

"The companies and government organizations we recognize with these annual awards show an understanding of the issues involved in surface mining today and are committed to protecting the undisturbed environment around the site. They also are committed to the communities where they are based," notes Gary Lynch, Assistant Director of Regulation for DOGAMI's MLRR office. "The recognition is also an encouragement to others in the mining industry to follow suit."

The Mineral Lands Regulation and Reclamation program at DOGAMI serves as a steward of the state's mineral production, while encouraging best practices within the industry. MLRR's goals include environmental protection, conservation, effective site reclamation, and operational guidance regarding other engineering and technical issues. Contact Gary Lynch, Assistant Director of Regulation, MLRR, at (541) 967-2053 for more information.

For more information on the Mined Land Reclamation program, contact Ben Mundie, telephone (541) 967-2149; email: ben.a.mundie@mlrr.oregongeology.com

MLR 2007 Award Winners

Outstanding Reclamation

S. A. Moore LLC., Deschutes County

The site of this outstanding reclamation project, Lower Bridge, is located 7 miles west of Terrebonne, along the Deschutes River, in a growing residential area. Mining for diatomaceous earth began at the Lower Bridge site in the 1920s. Over the decades of mining at the Lower Bridge site, hundreds of tons of scrap metal, equipment, and junk had accumulated. Scott Moore, having taken over from his father, began the process of cleaning up the site. By 2006, Mr. Moore had disposed of all discarded equipment and debris, literally digging up old tires and scrap metal and hauling them to recycle centers.

Scott Moore is recognized for his efforts to clean up several decades worth of refuse left by others, and in the effort, also reclaim for secondary beneficial use, areas that had not required reclamation.

Outstanding Operator

Stein Enterprises, Inc.,
Josephine County

This upland quarry is located in Wilderville, six miles south of Grants Pass. A DOGAMI operating permit was first issued in 1979.

A previous operator was found in violation of several DOGAMI and Department of Environmental Quality statutes. Stein Enterprises purchased the property in 2002 and immediately began to bring the site into compliance.

Stein Enterprises is being recognized for taking a troubled site and making it an example of the best in industry practices, while mending fences with neighbors and restoring and reclaiming land damaged by others.

Good Neighbor Award

Knife River Corporation, Western Oregon Division, Linn County

The City of Jefferson nominated Knife River Corporation, and specifically Steve Mote of Knife River, for this award.

Early in 2007, the Jefferson Cemetery Commission proposed to construct a restroom at the Jefferson cemetery. Mr. Mote not only agreed to help with the supply of concrete and gravel, but also reviewed the plans, visited the job site, and made recommendations on the type of materials best suited for this project. Mr. Mote also provided advice on the construction of the foundation stabilizing the underground vault as well as concrete for the restroom pad and gravel for the parking lot.

No Oregon Plan award was presented for 2007.

(MLR Awards, continued from page 66)

MLR 2008 Award Winners

Oregon Plan Award
3 Mile Sand & Gravel, 3 Mile Pit, Klamath County

Oregon Plan Award winner 3-Mile Sand & Gravel is recognized for their public-private partnership that has coordinated efforts to limit the spread of weeds and for their off-site volunteer work to create and enhance listed fisheries and wildlife habitat.

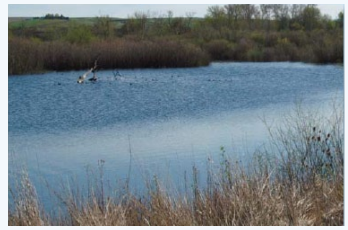
Outstanding Operator Division I

Cobb Rock, Inc., Beaverton Quarry, Washington County

Cobb Rock, Inc. was chosen as Outstanding Operator, Division I based on their long record of voluntary reclamation, a well planned and implemented operation, and their outstanding compliance record with the DOGAMI and DEQ permits issued for this site.

Outstanding Operator Division II
Cinder Butte Rock Products, Cinder Butte, Deschutes County

Cinder Butte Rock Products was chosen as Outstanding Operator, Division II for the work they have accomplished to visually and sonically screen this historic mine site from adjacent properties, reclaim mine related disturbance that was exempt from the reclamation rules, develop the cinder pit in a more orderly and neat manner, and for offering aggregate recycling services to the area.



Outstanding Reclamation
Pendleton Ready Mix Co., Mission Pit, Umatilla County

Pendleton Ready Mix has won the Outstanding Reclamation Award this year for their dedicated efforts to successfully turn the Mission Pit into a popular area for bird and wildlife viewing.

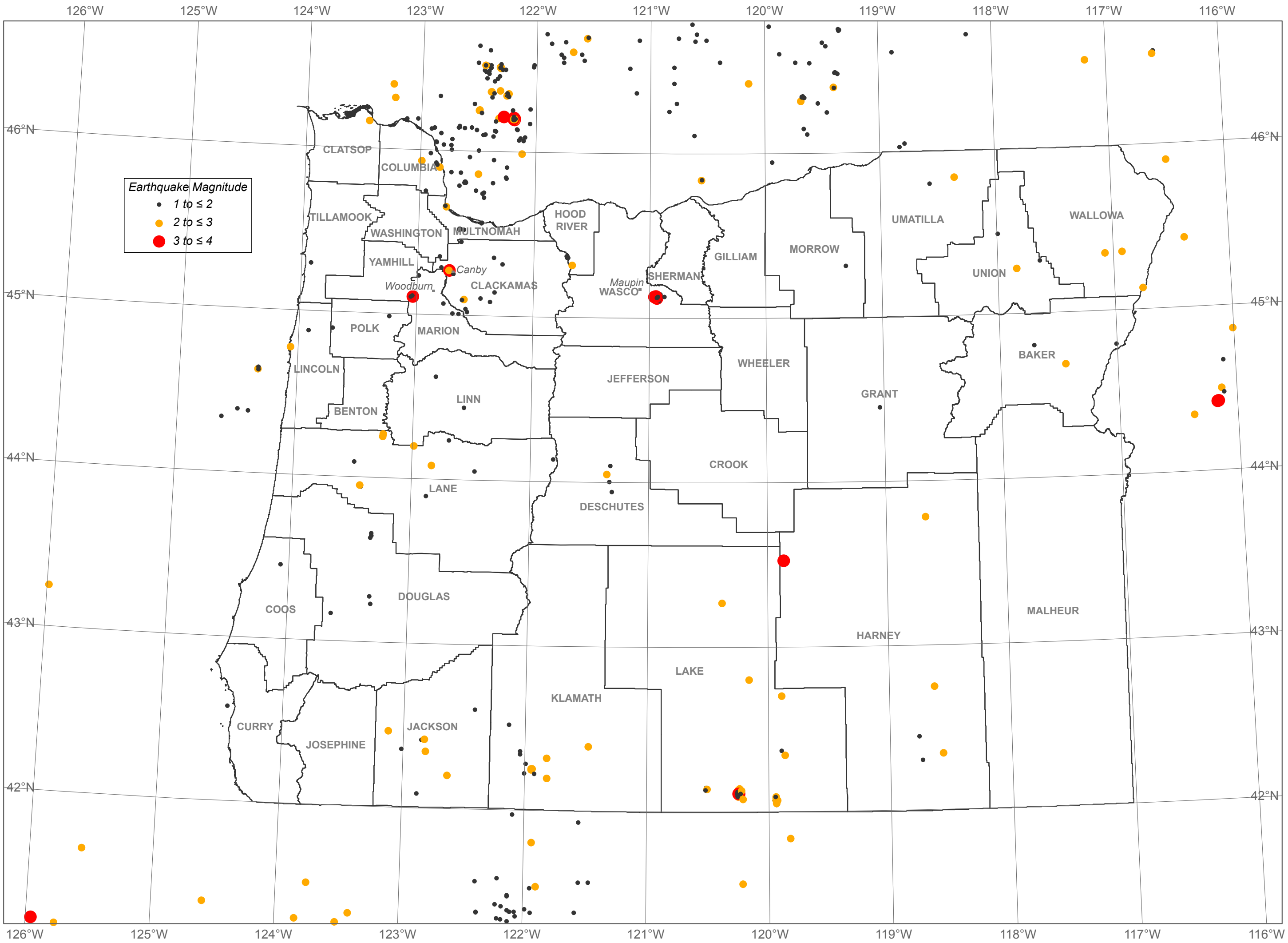
Good Neighbor Award
Turner Gravel, Inc., Turner Quarry, Marion County

Turner Gravel, Inc. received the Good Neighbor Award because of their efforts to improve their quarry operation, protect adjacent natural resources, and restore the confidence of their neighbors that a well run quarry need not be a liability.

To learn more about the MLR award winners, visit ***www.OregonGeology.org***

OREGON SEISMICITY IN 2007

Map data were generated from the ANSS/CNSS Worldwide Earthquake Catalog (http://www.ncedc.org/anss/catalog-search.html).

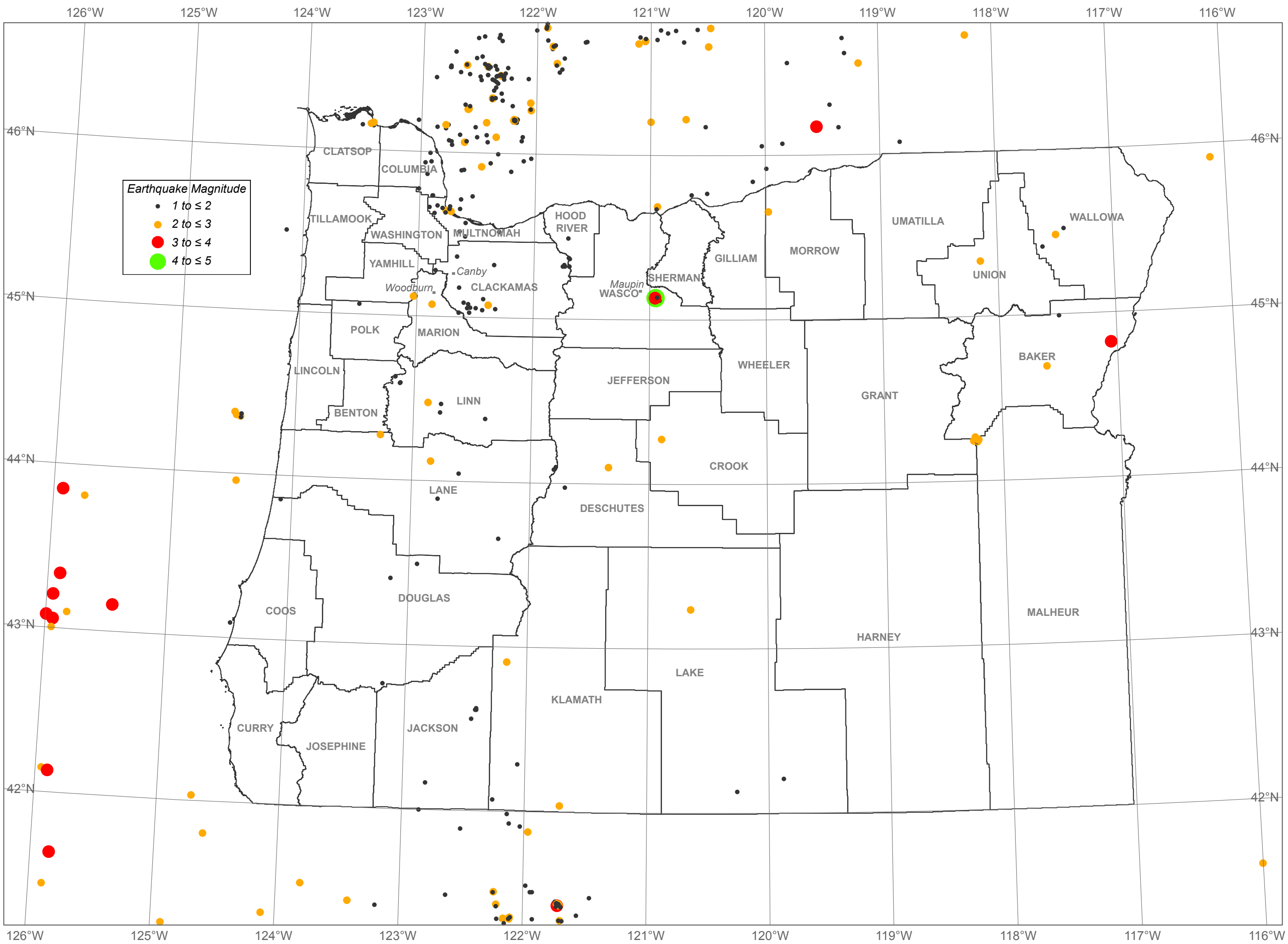


Magnitude 3+ earthquakes in Oregon:

- Thursday, January 4, magnitude 3, ESE of Maupin
- Saturday, January 20, magnitude 3, ESE of Maupin
- Thursday, March 1, magnitude 3.6, ESE of Maupin
- Sunday, April 8, magnitude 3.2, ESE of Maupin
- Thursday, April 19, magnitude 3.1, Harney County
- Wednesday, May 2, magnitude 3.3, ESE of Maupin
- Thursday, May 31, magnitude 3.4, Lake County
- Thursday, May 31, magnitude 3.2, Lake County
- Thursday, June 14, magnitude 3.8, ESE of Maupin
- Thursday, July 12, magnitude 3.2, WSW of Canby
- Monday, September 24, magnitude 3.6, WSW of Woodburn
- Wednesday, November 21, magnitude 3.3, ESE of Maupin

OREGON SEISMICITY IN 2008

Map data were generated from the ANSS/CNSS Worldwide Earthquake Catalog (http://www.ncedc.org/anss/catalog-search.html).



Magnitude 3+ earthquakes in Oregon:

- Monday, February 4, magnitude 3.3, ESE of Maupin
- Thursday, March 20, magnitude 3.1, ESE of Maupin
- Saturday, April 5, magnitude 3.6, ESE of Maupin
- Monday, April 28, magnitude 3.1, ESE of Maupin
- Sunday, June 1, magnitude 3.4, ESE of Maupin
- Friday, June 20, magnitude 3.2, ESE of Maupin
- Monday, July 14, magnitude 4.2, ESE of Maupin
- Tuesday, November 4, magnitude 3.5, Baker County
- Sunday, November 16, magnitude 3.4, ESE of Maupin
- Saturday, December 27, magnitude 3.6, ESE of Maupin

RECENT DOGAMI PUBLICATIONS

Publications are available from Nature of the Northwest, 800 NE Oregon St. #28, Suite 965, Portland, OR 97232, info@naturenw.org, (961) 673-2331; For online purchasing, go to http://www.naturenw.org, select "Store" and "Maps and Reports" and use the short identification of the publication (e.g., RMS-1) for a search.

Published in 2009

Lidar Data Quadrangle Series (LDQ), data sets require specialty software to view, $200 per DVD.

LDQ-2009-45123E1-**Forest Grove**, Forest Grove 7.5′ quadrangle, Washington County, Oregon
LDQ-2009-45123D1-**Laurelwood**, Laurelwood 7.5′ quadrangle, Washington and Yamhill Counties, Oregon
LDQ-2009-45123C1-**Dundee**, Dundee 7.5′ quadrangle, Washington and Yamhill Counties, Oregon
LDQ-2009-45122G7-**Saint Helens**, Saint Helens 7.5′ quadrangle, Columbia County, Oregon
LDQ-2009-45122F8-**Dixie Mountain**, Dixie Mountain 7.5′ quadrangle, Columbia, Multnomah and Washington Counties, Oregon
LDQ-2009-45122F7-**Sauvie Island**, Sauvie Island 7.5′ quadrangle, Columbia and Multnomah Counties, Oregon
LDQ-2009-45122E8-**Hillsboro**, Hillsboro 7.5′ quadrangle, Washington and Multnomah Counties, Oregon
LDQ-2009-45122E7-**Linnton**, Linnton 7.5′ quadrangle, Washington and Multnomah Counties, Oregon
LDQ-2009-45122E6-**Portland**, Portland 7.5′ quadrangle, Multnomah and Washington Counties, Oregon
LDQ-2009-45122E5-**Mount Tabor**, Mount Tabor 7.5′ quadrangle, Multnomah County, Oregon
LDQ-2009-45122E4-**Camas**, Camas 7.5′ quadrangle, Multnomah County, Oregon
LDQ-2009-45122D8-**Scholls**, Scholls 7.5′ quadrangle, Washington and Yamhill Counties, Oregon
LDQ-2009-45122D7-**Beaverton**, Beaverton 7.5′ quadrangle, Washington County, Oregon
LDQ-2009-45122D6-**Lake Oswego**, Lake Oswego 7.5′ quadrangle, Clackamas, Washington and Multnomah Counties, Oregon
LDQ-2009-45122D5-**Gladstone**, Gladstone 7.5′ quadrangle, Multnomah and Clackamas Counties, Oregon
LDQ-2009-45122D4-**Damascus**, Damascus 7.5′ quadrangle, Clackamas and Multnomah Counties, Oregon
LDQ-2009-45122D3-**Sandy**, Sandy 7.5′ quadrangle, Clackamas and Multnomah Counties, Oregon
LDQ-2009-45122C8-**Newberg**, Newberg 7.5′ quadrangle, Yamhill, Washington, and Marion Counties, Oregon
LDQ-2009-45122C7-**Sherwood**, Sherwood 7.5′ quadrangle, Clackamas, Washington, Marion, and Yamhill Counties, Oregon
LDQ-2009-45122C6-**Canby**, Canby 7.5′ quadrangle, Clackamas, Marion, and Washington Counties, Oregon
LDQ-2009-45122C5-**Oregon City**, Oregon City 7.5′ quadrangle, Clackamas County, Oregon
LDQ-2009-45122C4-**Redland**, Redland 7.5′ quadrangle, Clackamas County, Oregon
LDQ-2009-45122C3-**Estacada**, Estacada 7.5′ quadrangle, Clackamas County, Oregon
LDQ-2009-44122H1-**Bull of the Woods**, Bull of the Woods 7.5′ quadrangle, Clackamas County, Oregon
LDQ-2009-44122A1-**Fish Creek Mountain**, Fish Creek Mountain 7.5′ quadrangle, Clackamas County, Oregon

Lidar Imagery Series (LIS), 4 quarter quad PDFs per quadrangle on each CD, $30 per CD.

LIS-2009-45123E1-**Forest Grove**, Forest Grove 7.5′ quadrangle, Washington County, Oregon
LIS-2009-45123D1-**Laurelwood**, Laurelwood 7.5′ quadrangle, Washington and Yamhill Counties, Oregon
LIS-2009-45123C1-**Dundee**, Dundee 7.5′ quadrangle, Washington and Yamhill Counties, Oregon
LIS-2009-45122D8-**Scholls**, Scholls 7.5′ quadrangle, Washington and Yamhill Counties, Oregon
LIS-2009-45122D4-**Damascus**, Damascus 7.5′ quadrangle, Clackamas and Multnomah Counties, Oregon
LIS-2009-45122D3-**Sandy**, Sandy 7.5′ quadrangle, Clackamas and Multnomah Counties, Oregon
LIS-2009-45122C8-**Newberg**, Newberg 7.5′ quadrangle, Yamhill, Washington, and Marion Counties, Oregon
LIS-2009-45122C7-**Sherwood**, Sherwood 7.5′ quadrangle, Clackamas, Washington, Marion, and Yamhill Counties, Oregon
LIS-2009-45122C4-**Redland**, Redland 7.5′ quadrangle, Clackamas County, Oregon
LIS-2009-45122C3-**Estacada**, Estacada 7.5′ quadrangle, Clackamas County, Oregon

Oregon geologic data compilation, release 5 (statewide) [OGDC-5], compiled by Lina Ma and others, $30.

Geologic Map GMS-119, **Geologic map of the Oregon City 7.5′ quadrangle, Clackamas County, Oregon**, by Ian P. Madin, 46 p. plus appendices, 1:24,000, 1 pl., $15.

Interpretive Map IMS-28, **Oregon: A Geologic History**, by Ian P. Madin, 1 plate, 1:633,600, 1 pl., $15.

Interpretive Map IMS-27, **Landslide inventory map of the southwest quarter of the Beaverton quadrangle, Washington County**, Oregon, by William J. Burns, 1:8,000, 1 pl., $15.

Interpretive Map IMS-26, **Landslide inventory map of the northwest quarter of the Oregon City quadrangle, Clackamas County**, Oregon, by William J. Burns and Ian P. Madin, 1:8,000, 1 pl., $15.

Open-File Report O-09-03, **Preliminary digital geologic compilation map of part of northwestern Oregon**, by Lina Ma, Ray E. Wells, Alan R. Niem, Clark A. Niewendorp, and Ian P. Madin, 1:175,000, $15.

Open-File Report O-09-02, **Preliminary geologic map of the Robinson Butte 7.5′ quadrangle, Jackson County**, Oregon, by Stanley A. Mertzman and others, 40 p., 1:24,000, 1 pl., $15.

Open-File Report O-09-01, **Beach and shoreline response to an artificial landslide at Rocky Point, Port Orford, on the southern Oregon coast**, by Jonathan C. Allan and Roger Hart, 54 p., $15.

Open-File Report O-08-08, **Preliminary geologic map of the Mule Hill 7.5′ quadrangle, Klamath County, Oregon, and Siskiyou County, California**, by Stanley A. Mertzman and others, 37 p., 1:24,000, 1 pl., $15.

Special Paper SP-42, **Protocol for inventory mapping of landslide deposits from light detection and ranging (Lidar) imagery**, by William J. Burns and Ian P. Madin, 30 p., $15.

Special Paper SP-41, **Tsunami hazard assessment of the northern Oregon coast: A multi-deterministic approach tested at Cannon Beach, Clatsop County, Oregon**, by George R. Priest, Chris Goldfinger, Kelin Wang, Robert C. Witter, Yinglong Zhang, and António M. Baptista , 87 p. plus appendix, $15.

(continued on page 95)

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

by Ian P. Madin

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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.

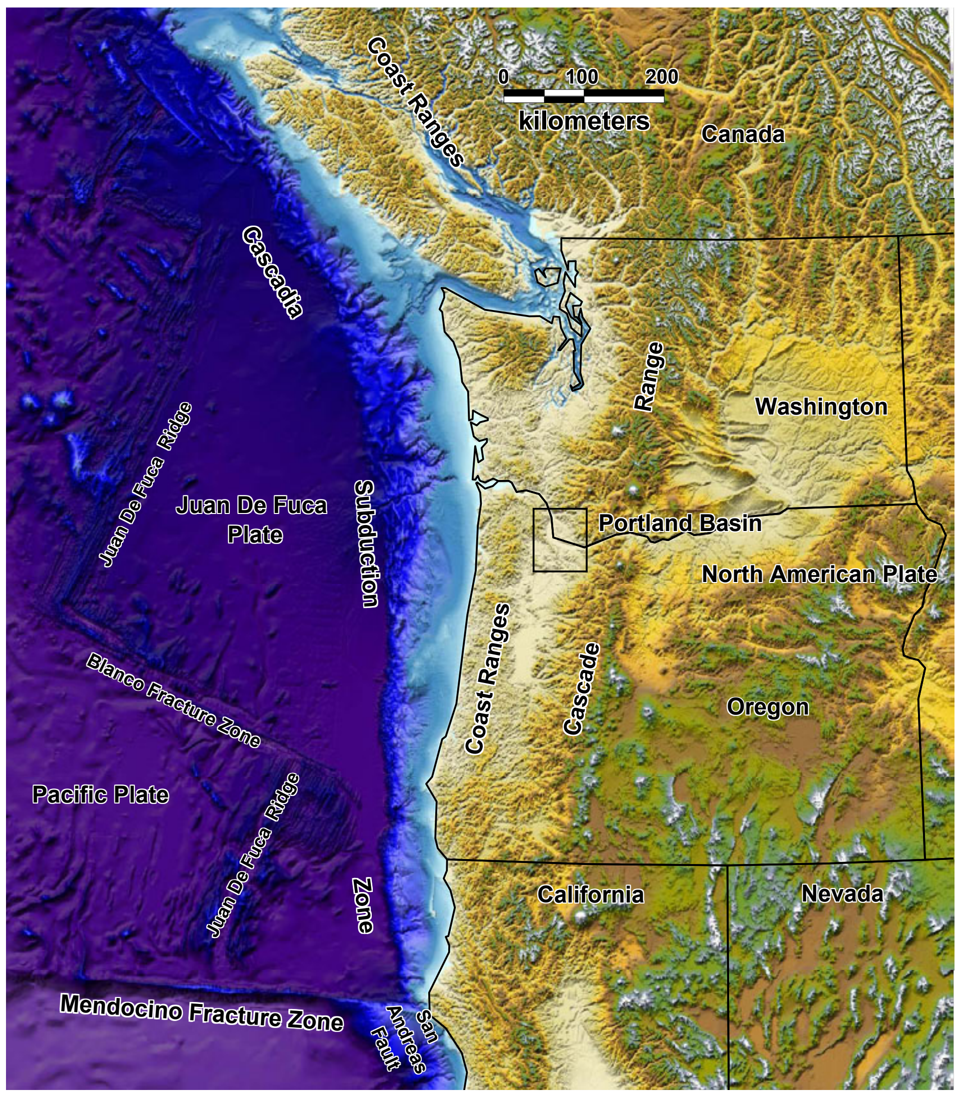

Figure 1. Regional tectonic setting of the Portland Basin within the Pacific Northwest.

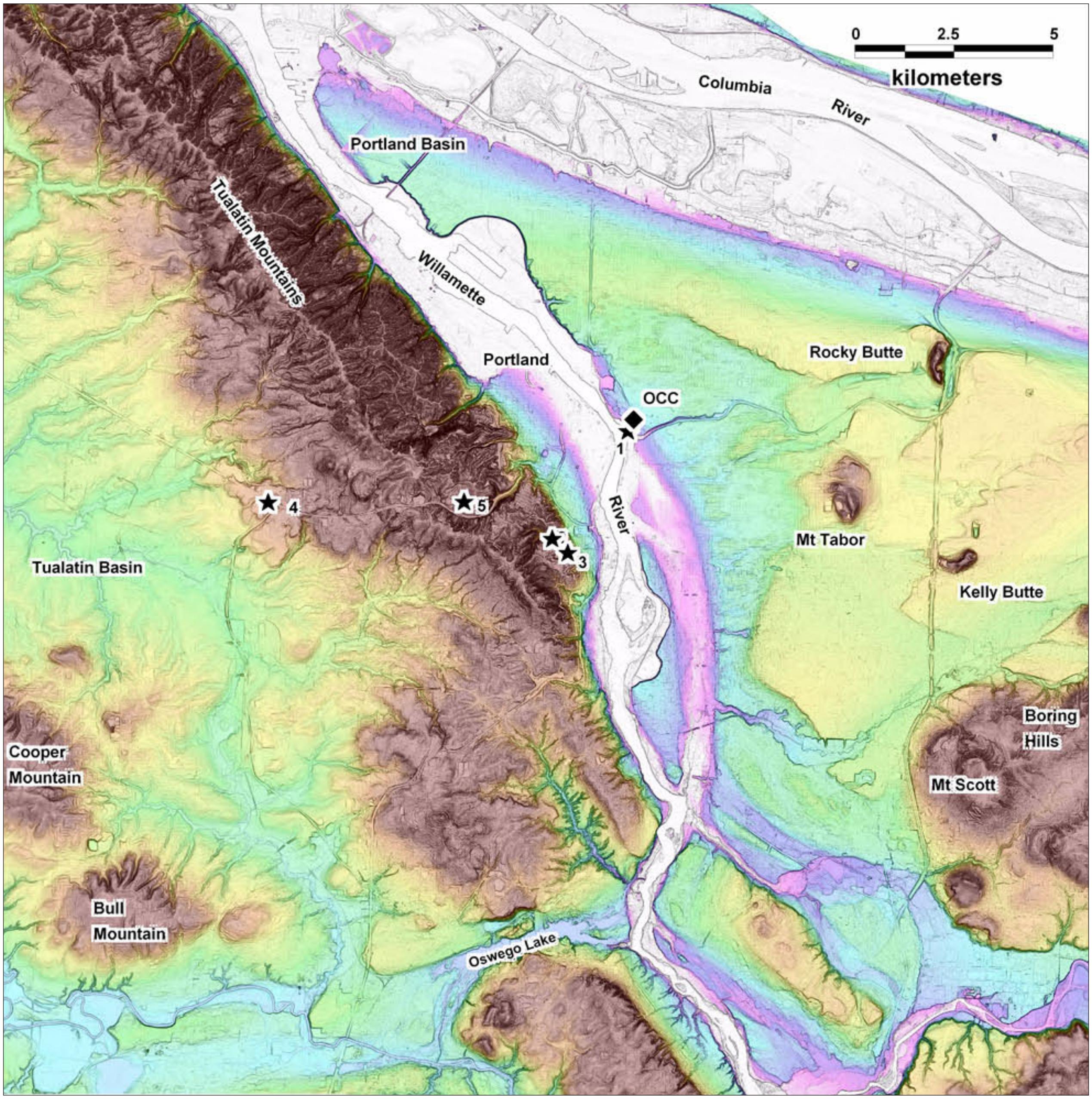

Figure 2. Lidar image of the Portland, Oregon, area, showing field trip stops (stars) and major geographic features. Image consists of an elevation color gradient over slopeshaded lidar. The peak elevation for Bretz/Missoula floodwaters was about 115 m, corresponding to the base of the brick red color. 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.

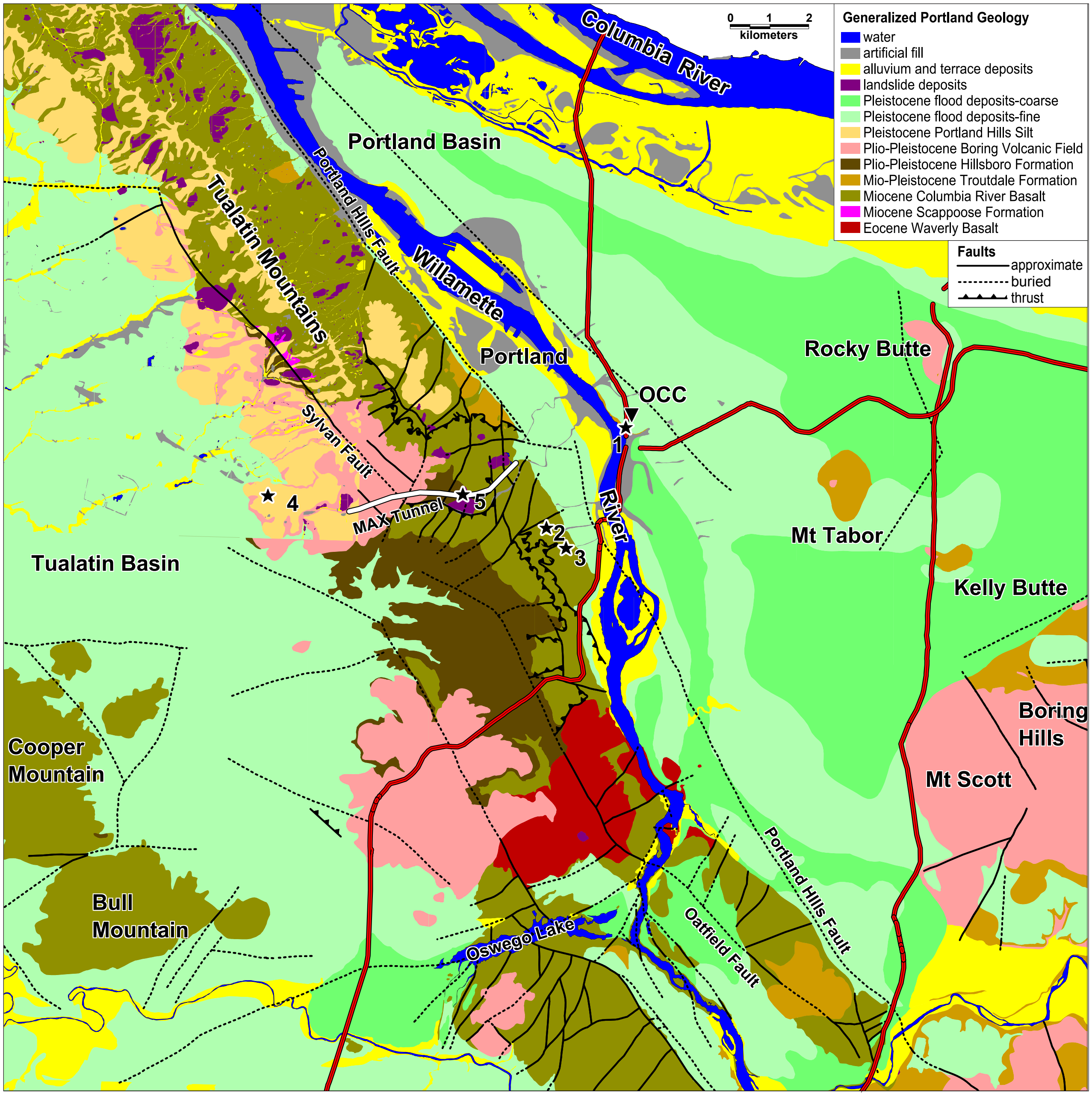

Figure 3. Generalized geologic map of Portland, Oregon. Map area is identical to Figure 2. Data from Oregon Geologic Data Compilation, release 5.

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-

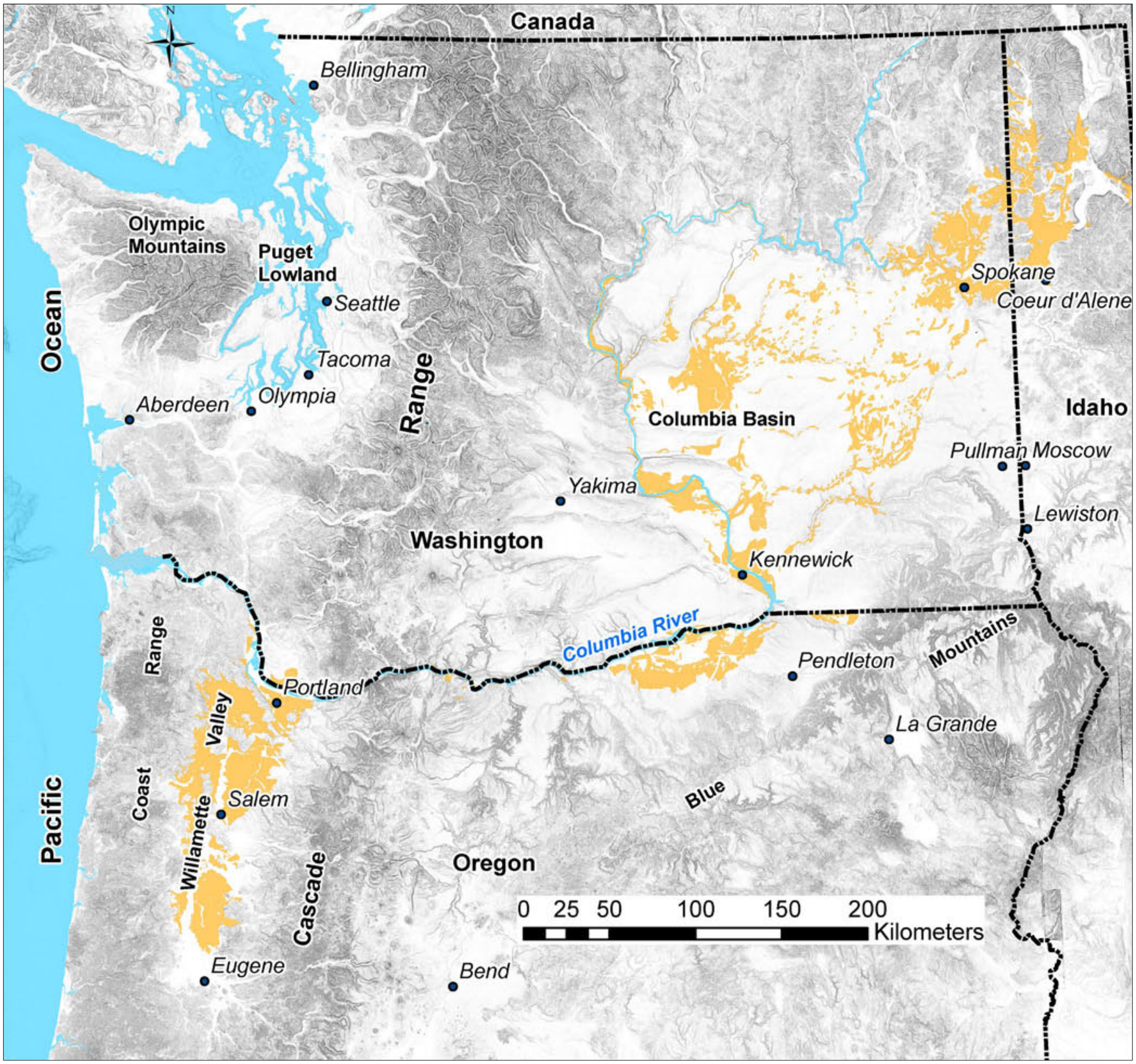

Figure 1-2. Mapped Bretz/Missoula flood deposits in the Pacific Northwest. Data from Oregon, Washington, and Idaho state digital geologic maps.

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.

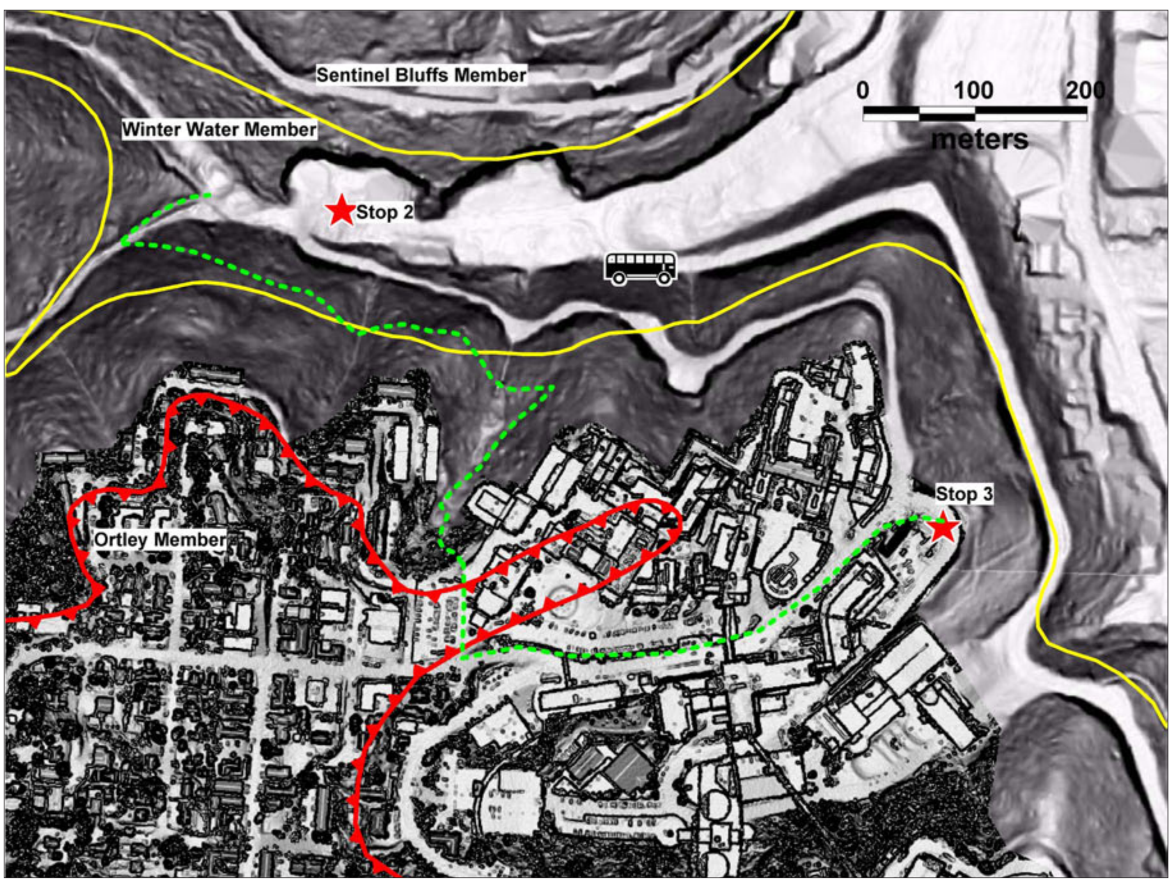

Figure 2-1, Locations for Stops 2 and 3 (starred). Short dashed line (green) is route from Stop 2 to Stop 3; solid lines (yellow) are geologic contacts; toothed line (red) is thrust fault. Composite bare-earth and highest-hit lidar slope map as base. Bus icon denotes Sam Jackson Parkway bus stop (#5804).

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.

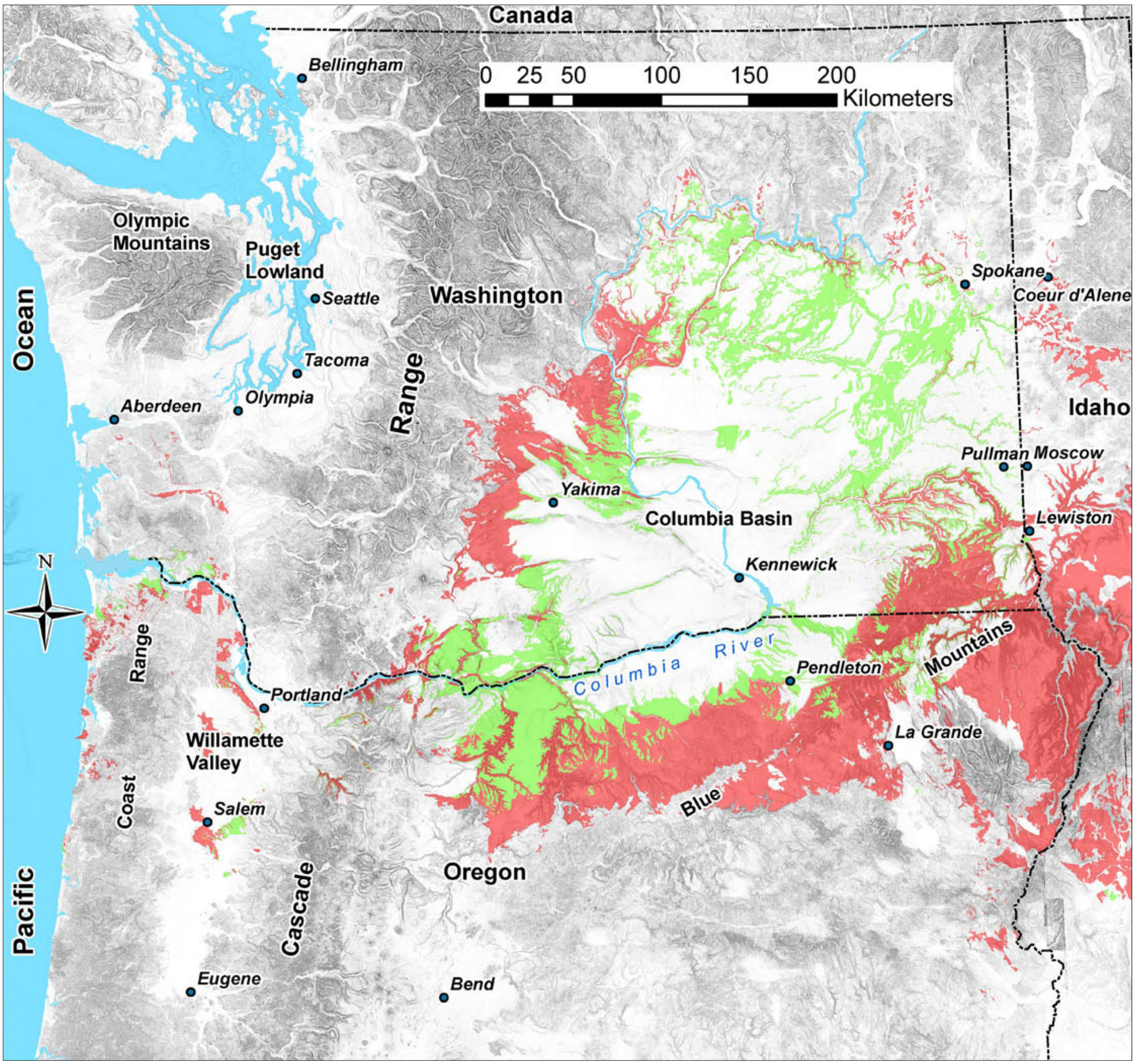

Figure 2-2. Mapped distribution of the Wanapum (green) and Grande Ronde (pink) formations of the Columbia River Basalt Group. Many individual flows span much of the mapped range. Data from Oregon, Washington, and Idaho state digital geologic maps.

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.

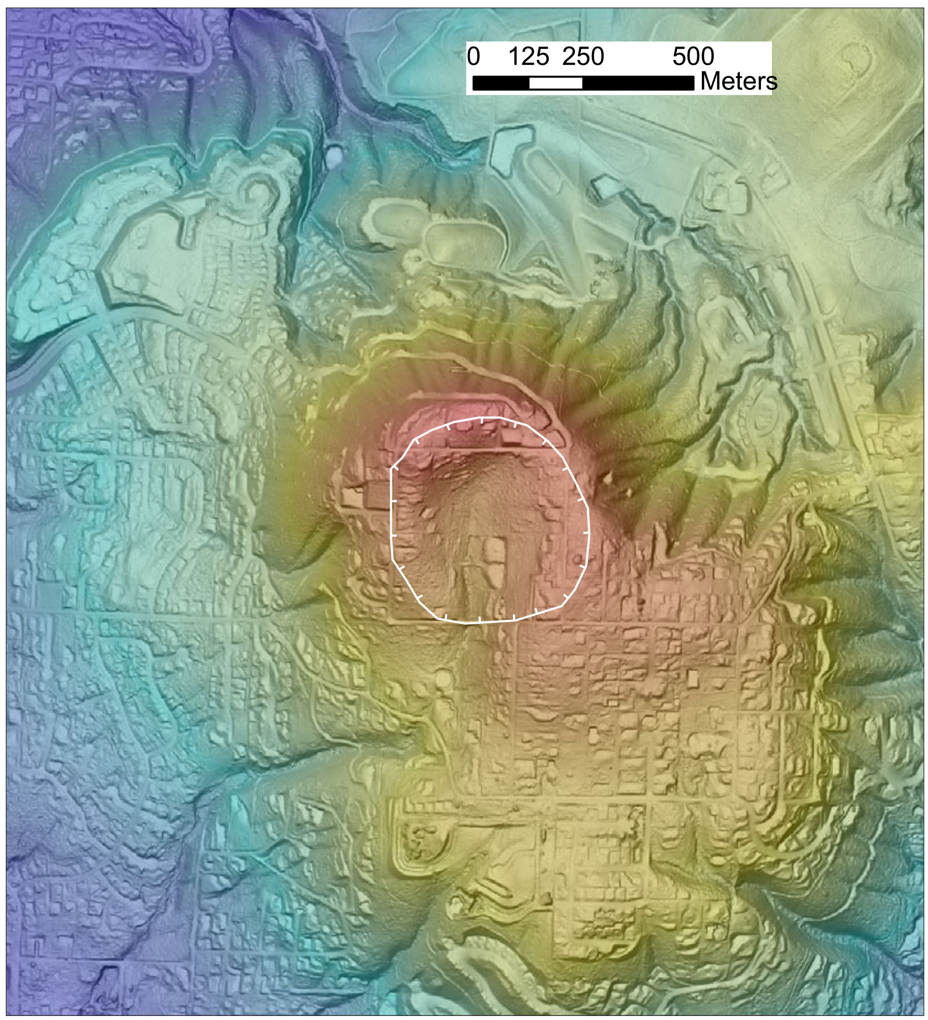

Figure 3-2. Lidar slopeshade image of Mt. Scott, showing the 500-m-wide central crater of this 1.6-Ma Boring volcanic field vent, now covered with subdivisions.

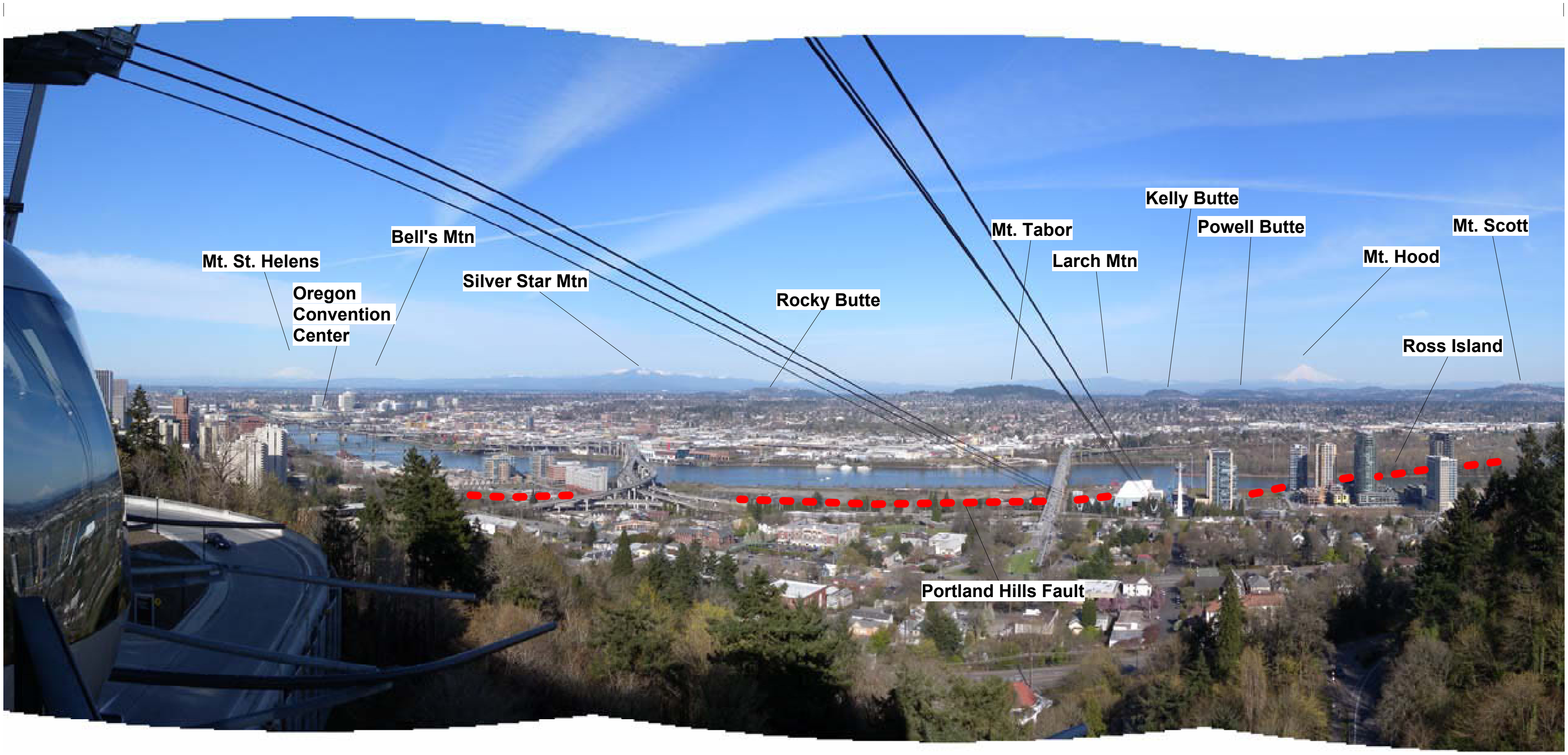

Figure 3-1. Panorama from Oregon Health and Sciences University tram terminal, Stop 3. Features include:

- **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.

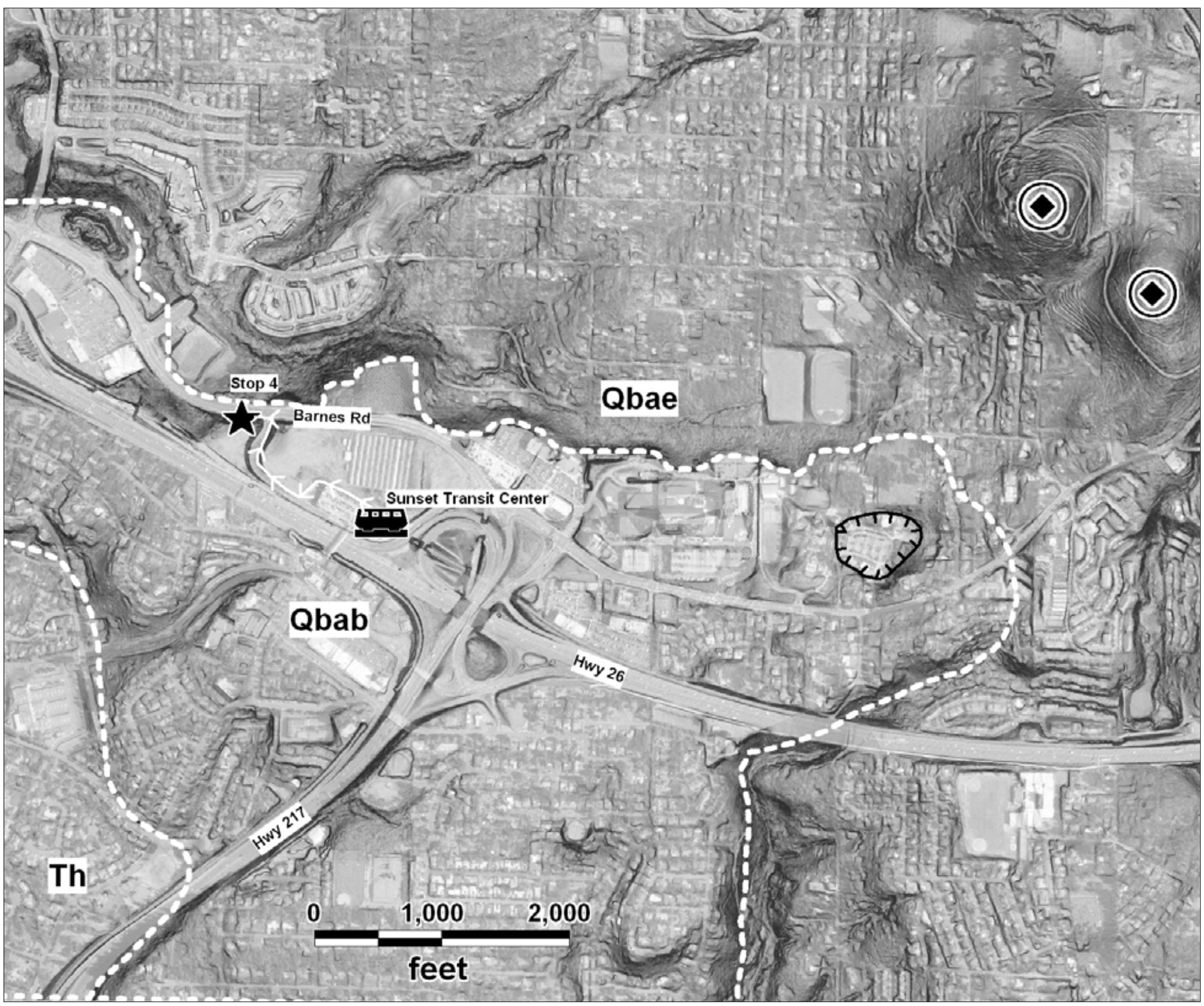

Figure 4-1. Stop 4 location (starred) and geologic map (from Madin and others, 2008). White dashed lines are bedrock geology contacts. Hachured polygon is inferred basaltic andesite of Barnes Road (Qbab) vent. Circled diamond symbols mark inferred basaltic andesite of Elk Point (Qbae) vents. Train icon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

Acknowledgments. Thanks to Russ Evarts and Terrence Conlon of the U.S. Geological Survey and Vicki S. McConnell, Oregon State Geologist, for their thoughtful and helpful reviews.

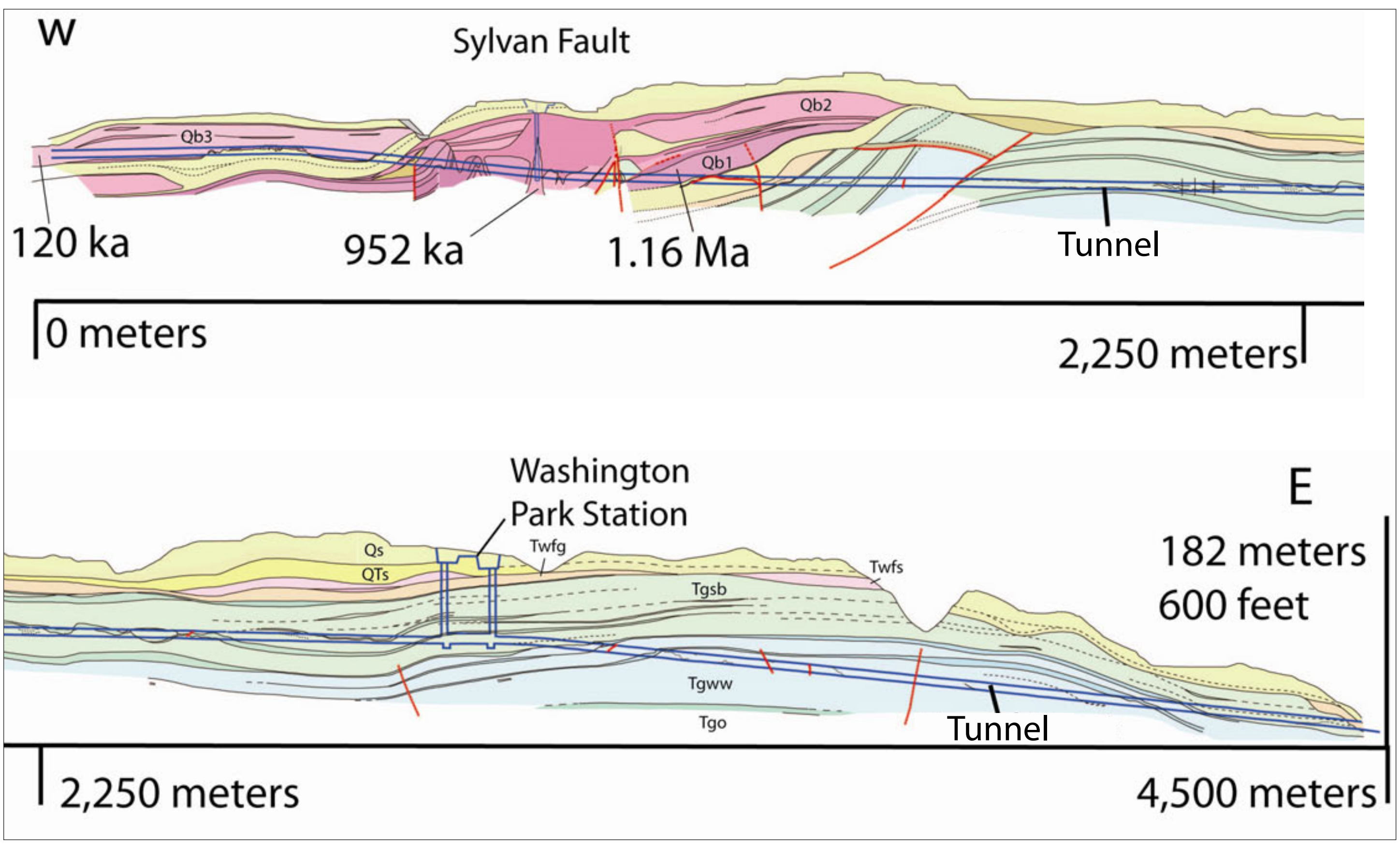

Figure 5-2. Simplified version of the geologic section through the Tualatin Mountains along the MAX light rail tunnel. Qb1, Qb2, and Qb3 are Pleistocene Boring Volcanic Field lavas and tephra. Qs is Pleistocene loess. QTs is Pliocene or early Pleistocene loess. Twfg is basalt of Ginkgo, Frenchman Springs 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.)

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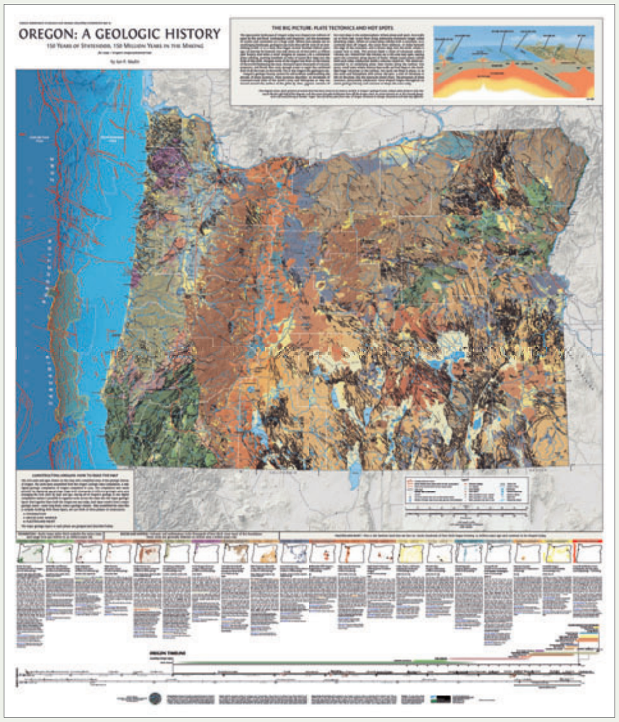
Series		Group	Formation	Member	Isotopic Age (m. y.)	Magnetic Polarity
Miocene	Upper	Columbia River Basalt Group	Saddle Mountains Basalt	**Lower Monumental Member**	6	N
				Ice Harbor Member	8.5	
				Basalt of Goose Island		N
				Basalt of Martindale		R
				Basalt of Basin City		N
				Buford Member		R
	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		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		
			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)

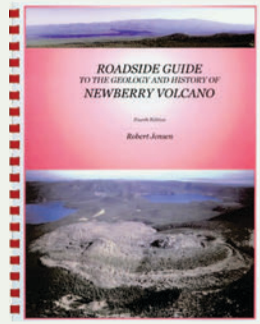
Highlighting Publications

Available from The Nature of the Northwest Information Center



Oregon: A Geologic History (IMS-28), by Ian P. Madin. Oregon Department of Geology and Mineral Industries. 50- × 58-inch full-color wall poster, 2009. $15.

IMS-28 was released as part of the State of Oregon's sesquicentennial anniversary. Geologic units shown in the map are derived from the recently completed Oregon Geologic Data Compilation (OGDC-5; $30).



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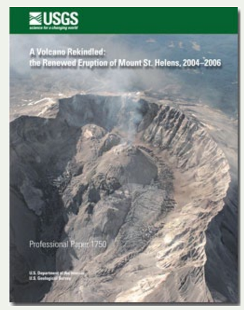
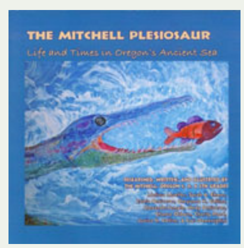


A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006, Professional Paper 1750, edited by David R. Sherrod, William E. Scott, and Peter H. Stauffer, U.S. Geological Survey. Hardcover, 856 p., 2008. $30.



The Mitchell Plesiosaur: Life and Times in Oregon's Ancient Sea, written and illustrated by the Mitchell, Oregon 3rd, 4th, and 5th grades. Mitchell, Oregon, School District and Oregon Paleo Lands Institute. Paperback, 40 p., 2009. $18.

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Publication of *Oregon Geology*

Budget cutbacks and changing technology require that we make changes to the magazine. We will predominantly compile rather than extensively edit material submitted. Consequently, we ask that material be submitted to us in production-ready quality. For details and the new publication schedule, see "Information for Contributors" below.

We believe *Oregon Geology* is an important publication, offering a unique and suitable place to share information about Oregon that is useful for the geoscience community and ultimately for all Oregonians. Please help us by continuing to read the journal *Oregon Geology* and submit articles.

Information for contributors

Oregon Geology is designed to reach a wide spectrum of readers in the geoscience community who are interested in all aspects of the geology of Oregon and its applications. Informative papers and notes, particularly research results, are welcome, as are letters or notes in response to materials published in the journal.

Two copies of the manuscript should be submitted, one paper copy and one digital copy. While the paper copy should document the author's intent as to unified layout and appearance, all digital elements of the manuscript, such as text, figures, and tables should be submitted as separate files. Hard-copy graphics should be camera ready; photographs should be glossies. Figure captions should be placed together at the end of the text.

Style is generally that of U.S. Geological Survey publications. (See USGS *Suggestions to Authors*, 7th ed., 1991, or recent issues of *Oregon Geology*.) References are limited to those cited. We accept only those articles that have at least one acknowledged outside review. We maintain the authority to request a copy of the reviewer's comments. Pre-submission reviewers should be included in the acknowledgments. In view of increasing restrictions on editing time, adherence to such style will be required more strictly than in the past.

Conclusions and opinions presented in articles are those of the authors and are not necessarily endorsed by the Oregon Department of Geology and Mineral Industries.

Authors will receive a complimentary CD with a PDF version of the issue containing their contribution.

Manuscripts, letters, notices, and photographs should be sent to Deb Schueller, Editor, *Oregon Geology*, 800 NE Oregon Street #28, Suite 965, Portland, OR 97232-2162, e-mail contact deb.schueller@dogami.state.or.us.

Send us your photos

Since we have started printing color pictures in *Oregon Geology*, we are finding ourselves woefully short of good color photographs showing geologic motifs in Oregon. That is why we invite your contributions.

Good glossy prints or transparencies will be the best "hard copy," while digital versions are best in TIFF or EPS format.

If you have photos you would like to share with other readers, please send them to us (Editor, *Oregon Geology*, 800 NE Oregon Street #28, Suite 965, Portland, OR 97232-2162; e-mail deb.schueller@dogami.state.or.us) with information for a caption. If they are used, publication and credit to you is all the compensation we can offer. If you wish to have us return your materials, please include a self-addressed envelope.

(DOGAMI Publications, continued from page 72)

Published in 2008

Digital Data Series, **SLIDO-1, Statewide Landslide Information Database for Oregon**, by William J. Burns, Ian P. Madin, and Lina Ma, $10.

Geologic Map GMS-118, **Geologic map of the Klamath Falls area, Klamath County**, Oregon, by George R. Priest, Frank R. Hladky, and Robert B. Murray, 53 p., 1:24,000, 1 pl., $10.

Interpretive Map, IMS-25, **Tsunami hazard map of the Florence-Siuslaw River area, Lane County**, Oregon, by George R. Priest, Arun Chawla, and Jonathan C. Allan, 42 p., 1:20,000, 1 pl., $10.

Interpretive Map IMS-24, **Geologic hazards, earthquake and landslide hazard maps, and future earthquake damage estimates for six counties in the Mid/Southern Willamette Valley including Yamhill, Marion, Polk, Benton, Linn, and Lane Counties, and the City of Albany**, Oregon, by William J. Burns, R. Jon Hofmeister, and Yumei Wang, 121 p., 1:422,400, 1 pl., 11 appendices, GIS data, $25.

Open-File Report O-08-15, **Oregon Beach and Shoreline Mapping and Analysis Program: 2007-2008 beach monitoring report,** by Jonathan C. Allan and Roger Hart, 54 p., $10.

Open-File Report O-08-14, **Preliminary geologic maps of the Corvallis, Wren, and Marys Peak 7.5' quadrangles, Benton, Lincoln, and Linn counties**, Oregon, by Thomas J. Wiley, 10 p., 3 pl., $10.

Open-File Report O-08-13, **Preliminary digital geologic compilation map of part of western Oregon** [map plate of West portion of OGDC project], by Ray E. Wells, Alan R. Niem, George R. Priest, Lina Ma, Clark A. Niewendorp, and Ian P. Madin, 1:175,000, 1 pl., $10.

Open-File Report O-08-12, **Prehistoric Cascadia tsunami inundation and runup at Cannon Beach, Clatsop County**, Oregon, by Robert C. Witter, 36 p. and 3 app., $10.

Open-File Report O-08-11, **Preliminary geologic map of the Lebanon and Onehorse Slough 7.5' quadrangles, Linn County**, Oregon, by Mark L. Ferns and Jason D. McClaughry, report text on map plate, 1:24,000, 1 pl., $10.

Open-File Report 0-08-10, **Oregon Public Utilities Commission—Oregon Department of Geology and Mineral Industries Leadership Forum and Seismic Critical Energy Infrastructures Workshop, April 2, 2008**, by Yumei Wang and Jose R. Gonzalez, 13 p., $10.

Open-File Report O-08-09, **Regional Landslide Hazard Maps of the Southwest Quarter the Beaverton Quadrangle, West Bull Mountain Planning Area, Washington County**, Oregon, by William J. Burns, 17 p., 1:8,000, 3 pl., $10.

Open-File Report O-08-08 published in 2009.

Open-File Report O-08-07, **Preliminary geologic map of the Dixie Mountain 7.5' quadrangle, Washington, Multnomah, and Columbia counties**, by Ian P. Madin and Clark A. Niewendorp, 43 p., 1:24,000, 1 pl., $10.

Open-File Report O-08-06, **Preliminary geologic map of the Linnton 7.5' quadrangle, Multnomah and Washington counties**, Oregon, by Ian P. Madin, Lina Ma, and Clark A. Niewendorp, 35 p., 1:24,000, 1 pl., $10.

Open-File Report O-08-05, **Geomorphic and hydrologic assessment of historical water level changes at Cleawox Lake, Jessie M. Honeyman Memorial State Park, Lane County**, Oregon, by Robert C. Witter, Gerald H. Grondin, and Jonathan C. Allan, 46 p., Plate 1, 1:15,840; Plate 2, 1:32,354, 2 pl., $10.

Open-File Report O-08-04, **Preliminary geologic map of the Little Chinquapin Mountain 7.5 minute quadrangle, Jackson and Klamath Counties**, Oregon, by Stanley A. Mertzman, Stephen Crabtree, Amy Lunt, and Isaac Weaver, 31 p., 1:24,000, 1 pl., $10.

Open-File Report O-08-03, **Preliminary geologic map of the Surveyor Mountain 7.5 minute quadrangle, Klamath County**, Oregon, by Stanley A. Mertzman, Matthew Reuer, and Benjamin Schiffer, 18 p., 1:24,000, 1 pl., $10.

Open-File Report O-08-02, **Beach and shoreline response due to dune lowering on the Elk River Spit, Curry County**, Oregon, by Jonathan C. Allan, and Roger Hart, 17 p., $10.

Open-File Report O-08-01, **Preliminary geologic map of the Spencer Creek 7.5 minute quadrangle, Klamath County**, Oregon, by Stanley A. Mertzman, 18 p., 1:24,000, $10.

Special Paper SP-40, **Johnson Creek landslide research project, Lincoln County**, Oregon: Final report to the Oregon Department of Transportation, by George R. Priest, Jonathan A. Allan, Alan R. Niem, Wendy A. Niem and Stephen E. Dickenson, 76 p. plus 14 appendices, $10.

Look online (http://www.oregongeology.org) for:

Interactive maps:

- **Lidar Data Viewer–** http://www.oregongeology.org/sub/lidardataviewer/index.htm
- **SLIDO - Statewide Landslide Information Layer for Oregon–** http://www.oregongeology.org/sub/slido/
- **GTILO - Geothermal Information Layer for Oregon–** http://www.oregongeology.org/sub/gtilo/
- **Oregon Geologic Data Compilation (OGDC-3) interactive map–** http://www.oregongeology.org/sub/ogdc/index.htm
- **Pilot Lidar Project - Portland Metro Area–** http://www.oregongeology.org/sub/lidar/

Other publications:

- **Statewide Seismic Needs Assessment Using Rapid Visual Screening (RVS)–** http://www.oregongeology.org/sub/projects/rvs/
  Individual seismic needs assessment site reports: http://www.oregongeology.org/sub/projects/rvs/county/county-sites.htm
- **All *Ore Bin* and *Oregon Geology* past issues–** http://www.oregongeology.org/sub/quarpub/OrGeo.htm
- **All Geologic Map Series (GMS) maps–** http://www.oregongeology.org/sub/publications/GMS/gms.htm

Also:

- **Tsunami evacuation brochure for Cannon Beach/Arch Cape**
- **¡Tsunami! Cómo sobreviver en la coasta de Oregon**
- **Geothermal energy in Oregon**, *Cascadia*, Spring 2007 (vol. 5, no. 1), 12 p.
- **FEMA Flood Map Modernization**, fact sheet, 2 p.
- **Lidar data acquisition, uses, and partners**, fact sheet, 2 p.
- **Tsunami hazards in Oregon**, fact sheet, 4 p.
- **Liquefied natural gas (LNG)**, fact sheet, 4 p.

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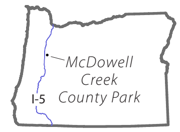
Places to see—Recommended by the Oregon Department of Geology and Mineral Industries



Royal Terrace Falls on Fall Creek ▲
Beds of lithic breccia, pebbly sandstone, and sandstone of Oligocene to early Miocene Little Butte Volcanics make up the terraces of 119-foot-tall Royal Terrace Falls on Fall Creek near Lebanon, Oregon.

Majestic Falls on McDowell Creek ▶
Majestic Falls is 39 feet tall and is composed of a very coarse-grained anorthositic diabase that is early Miocene in age and has a K/Ar radiometric age of 22.8 million years.

Getting there: From Lebanon, Oregon, travel 4 miles east on U.S. Highway 20 to Fairview Road, where signs direct you to McDowell Creek County Park. Turn left onto Fairview Road. In 1 mile turn left onto McDowell Creek Drive. Travel 7.5 miles on McDowell Creek Drive to McDowell Creek County Park. A parking area with restrooms and picnic facilities is on the right side of the road. A well-developed 3-mile loop trail system starts from this parking area. A short 1/2-mile hike reaches a viewing deck overlooking Royal Terrace Falls. Continue on the hiking loop to Majestic Falls on the main branch of McDowell Creek.

Majestic Falls can also be reached from an additional parking area 0.5 miles farther east on McDowell Creek Road. From the parking area a short descent down a developed stairway leads to a viewing deck beneath the falls.

(Photos: Jason McClaughry, DOGAMI)