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 km³ (139 mi³) 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 (Mc-Claughry 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
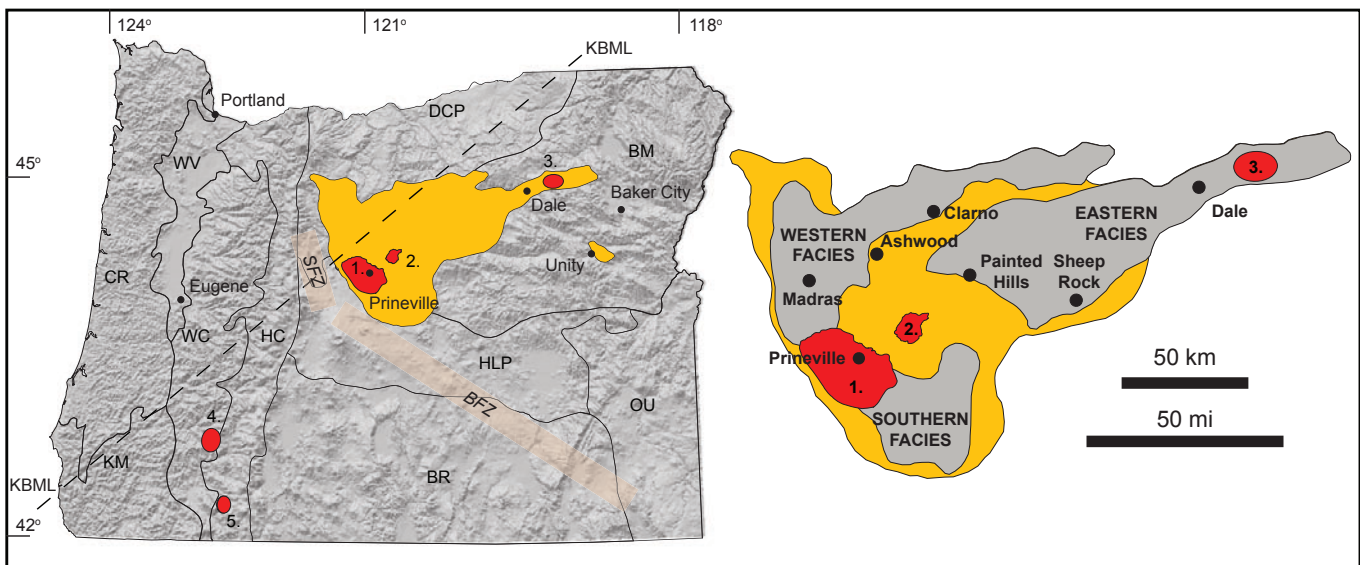

Figure 1. (left) Location of Paleogene age calderas in Oregon. Red-filled polygons are calderas: (1) Crooked River caldera; (2) Wildcat Mountain caldera; (3) Tower Mountain caldera; (4, 5) unnamed, suggested calderas. Orange shade represents the approximate distribution of ash-flow tuffs in the late 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)
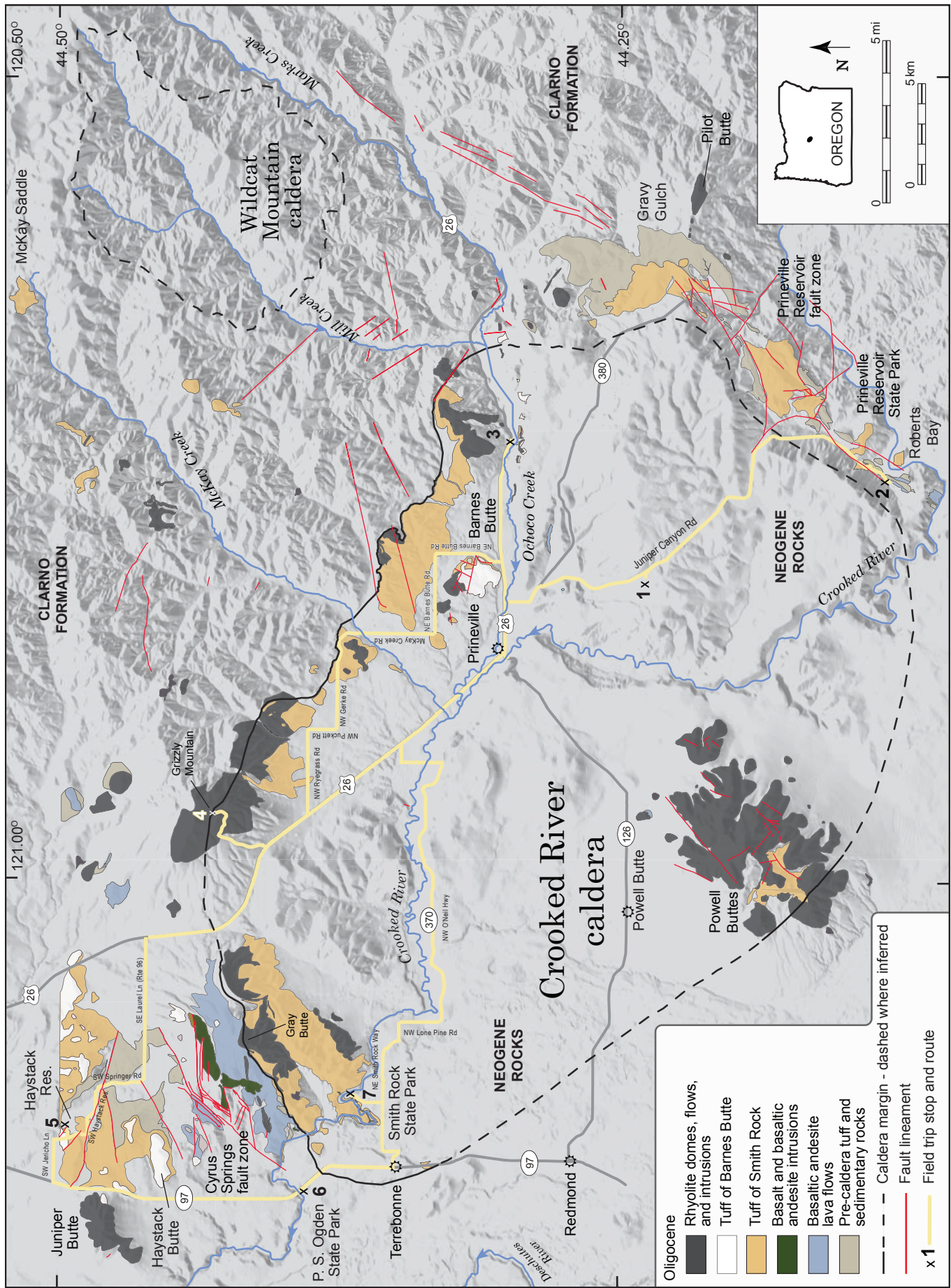
Figure 2. Simplified geologic map of the Crooked River caldera labeled with field trip route and associated stops 1 through 7. See facing page for additional description.

Oligocene

- Rhyolite domes, flows, and intrusions
- Tuff of Barnes Butte
- Tuff of Smith Rock
- Basalt and basaltic andesite intrusions
- Basaltic andesite lava flows
- Pre-caldera tuff and sedimentary rocks

— — Caldera margin - dashed where inferred
— Fault lineament
—x 1 Field trip stop and route

CLARNO FORMATION

Wildcat Mountain caldera

Crooked River caldera

NEOGENE ROCKS

Prineville Reservoir fault zone

Prineville Reservoir State Park

Cyrus Springs fault zone

McKay Saddle

Barnes Butte

Grizzly Mountain

Gray Butte

Powell Buttes

Pilot Butte

Gravy Gulch

Haystack Res.

Juniper Butte

Haystack Butte

P. S. Ogden State Park

Smith Rock State Park

Terrebonne

Redmond

Prineville

Powell Butte

Roberts Bay

OREGON

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.*

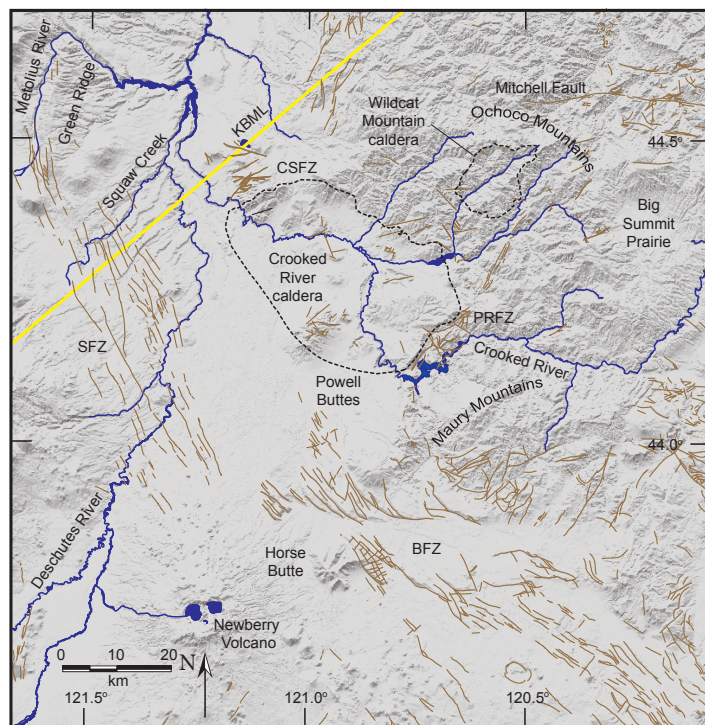**2.3** *Right turn (south) onto Juniper Canyon Road.*

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).

Smith Rock

Ring fracture zone

Gray Butte
28.82 Ma

Ring fracture zone

Grizzly Mountain

Ochoco Mts.

Ring fracture zone

Barnes Butte

Intracaldera-fill tuff

Grass Butte

Meyers Butte

Ochoco Wayside
Overlook

Prineville
X

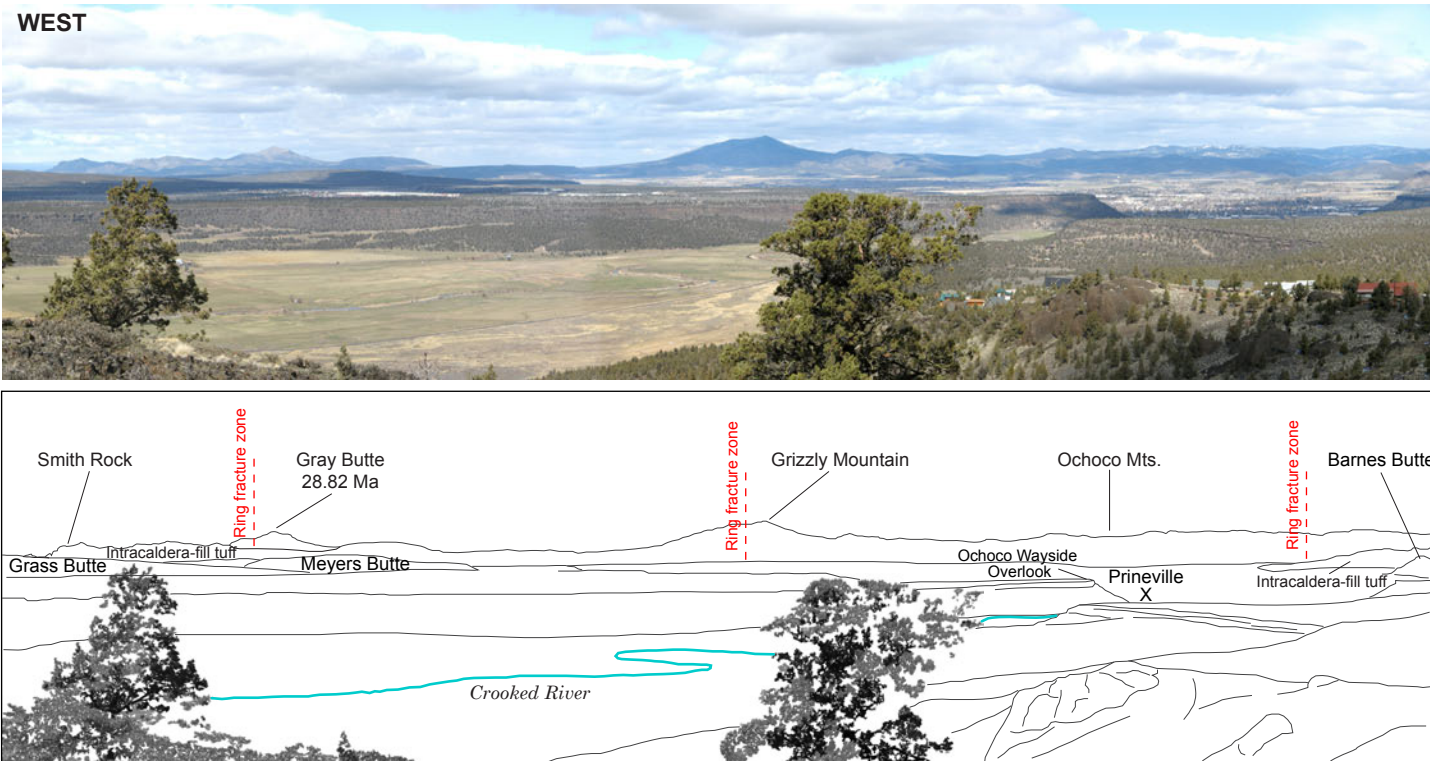Intracaldera-fill tuff

Crooked River

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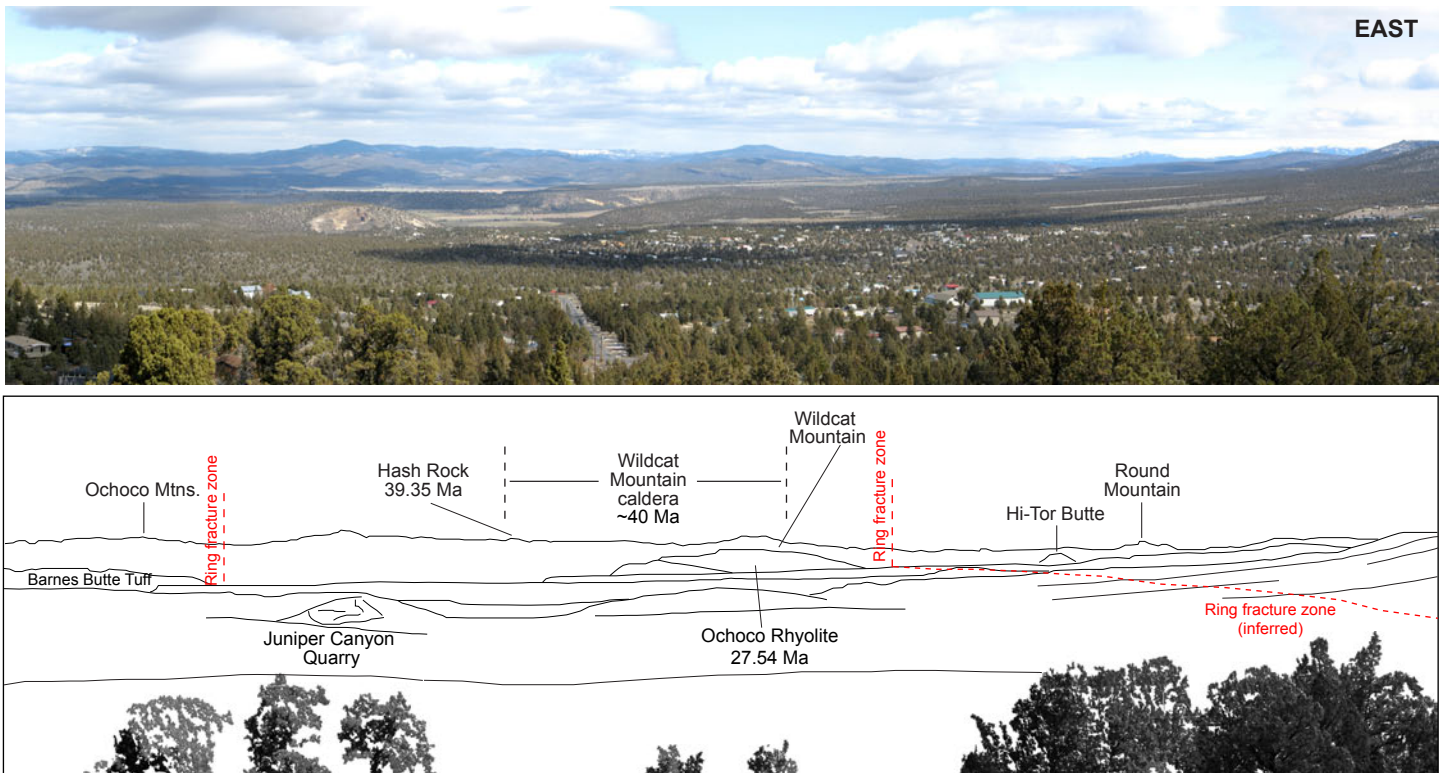
Figure 4, continued. View looking north from stop 1.

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.*

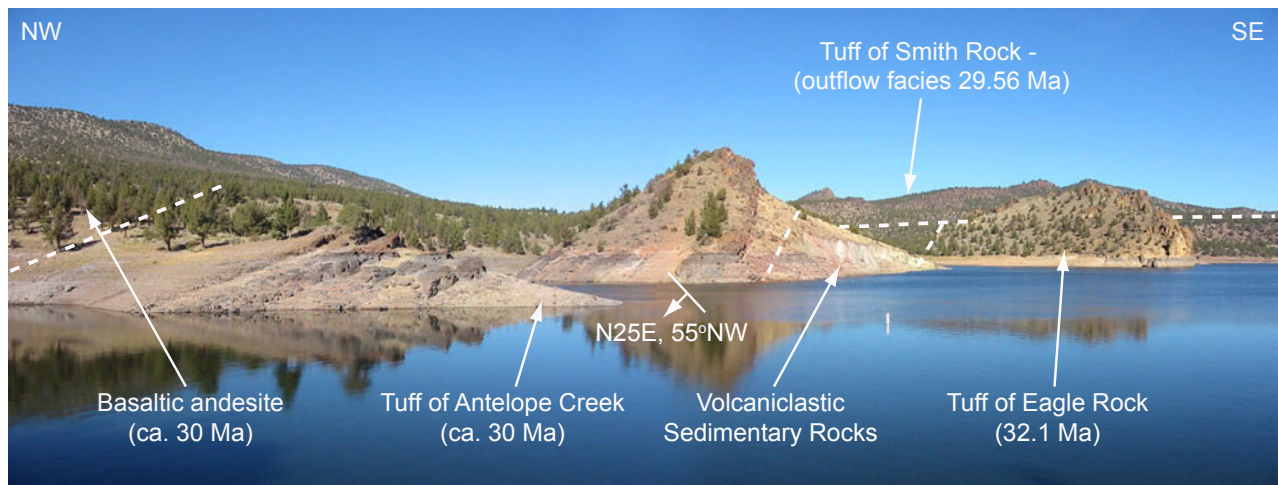Figure 5. **Northwest-dipping early Oligocene strata exposed near the Prineville Reservoir county boat ramp at stop 2. The exposed section includes two thick rhyolite tuffs interbedded with Fe- and Ti-rich basaltic andesite and volcaniclastic sedimentary rocks. Dashed white lines are approximate contacts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

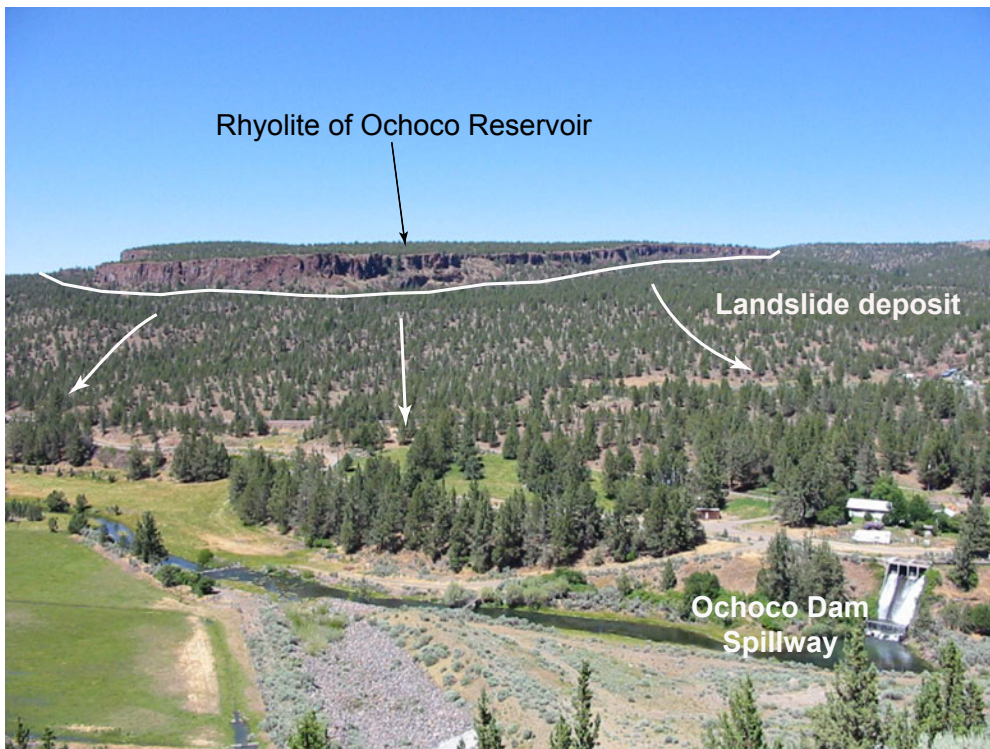**Figure 6. View north across Ochoco Creek to large, south-dipping, cliff-forming outcrops of the rhyolite of Ochoco Reservoir. The right abutment of the dam and spillway visible in the photo is founded upon a flanking, large active landslide complex that is sourced in the rhyolite. White arrows indicate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

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 km² [8 to 31 mi²]) 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 mud-pot 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

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.

(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).

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
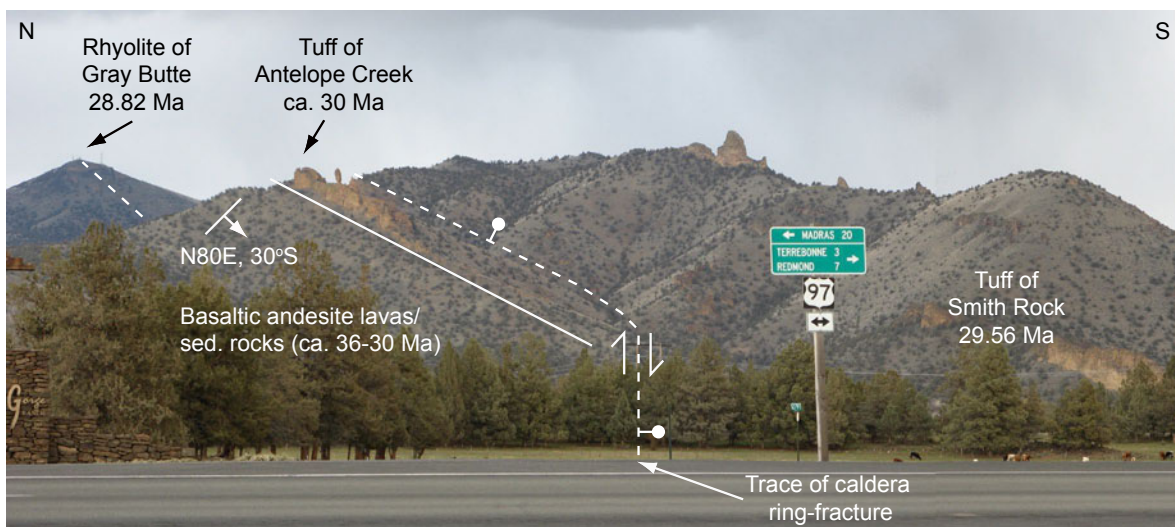
Figure 10. View east to southeast dipping section of early Oligocene strata from the old U.S 97 bridge at Peter Skene Ogden State Park at Stop 6. Intracaldera facies of the 29.56 Ma Tuff of Smith Rock are inset into and onlap the older deformed strata. Gray Butte in the distance is a 28.82 Ma rhyolite 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 pro-

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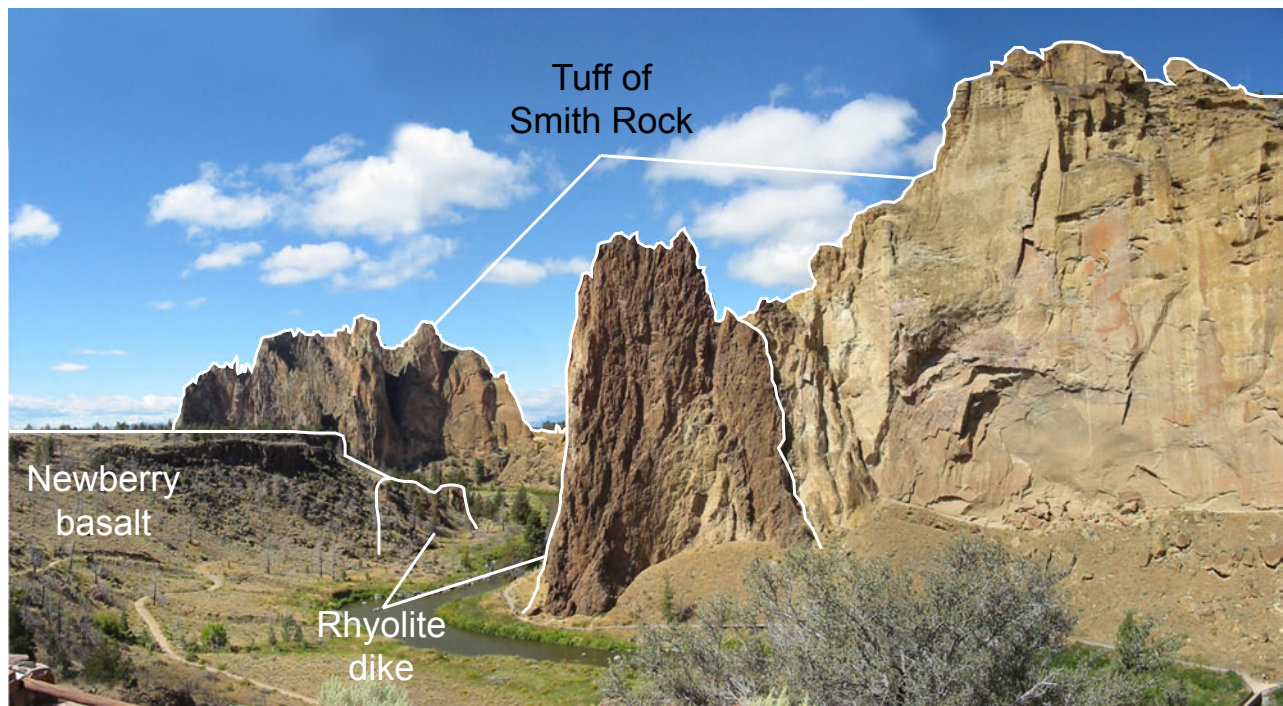**93.9** *Stop 7, at Smith Rock State Park.*

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
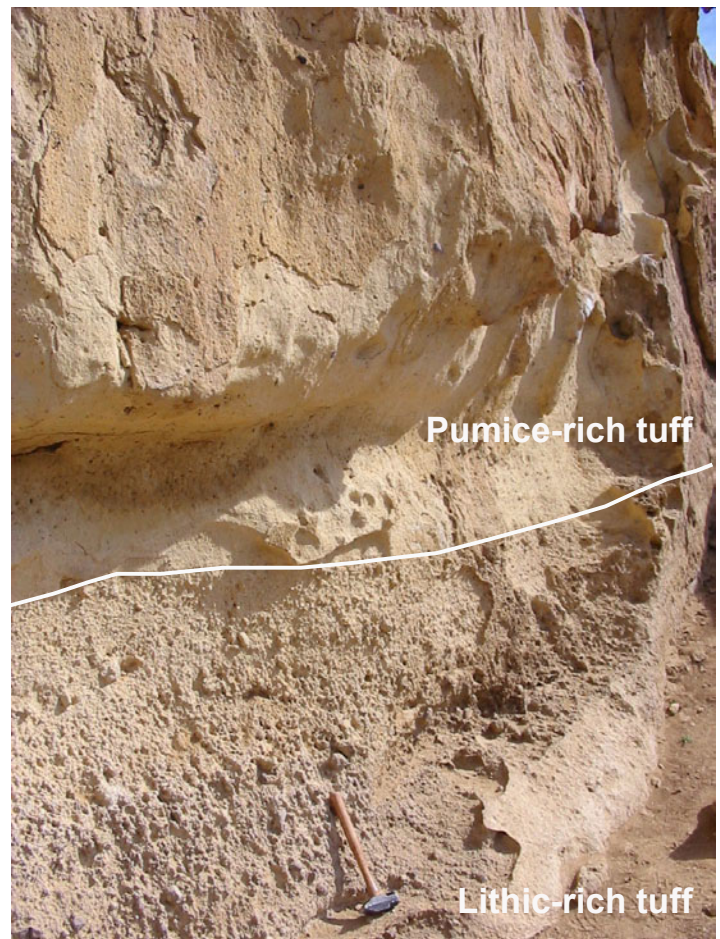
Figure 12. Close-up outcrop view of the intracaldera facies of the Tuff of Smith Rock at Smith Rock State Park. The tuff is greater than 0.5 km thick and consists of a monotonous section of pumice-lithic tuff intercalated with lithic-rich lenses and fine-ash.
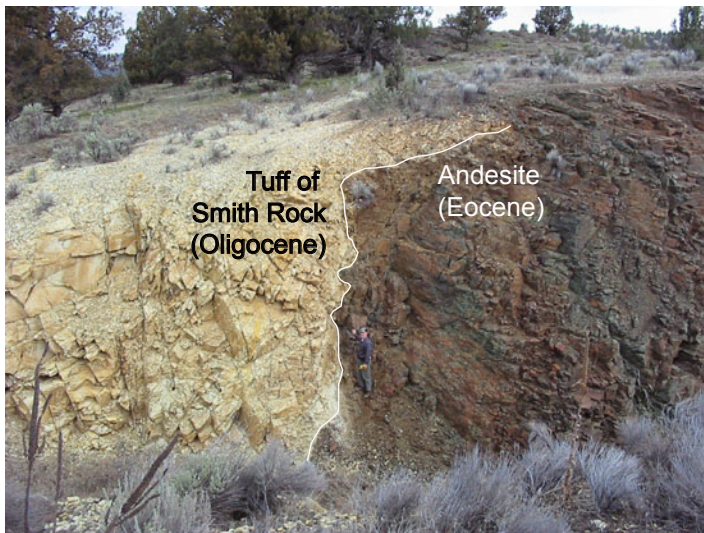
Figure 13. Caldera ring-fault exposed on the northeast caldera margin where pumice-lithic intracaldera facies of the Oligocene Tuff of Smith Rock is separated from older Eocene andesite country rock by a complex, unfaulted, high-angle contact. The tuff is not faulted and onlaps the country rock surface. 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 km³ (139 mi³) 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.**

REFERENCES

Aguirre-Diaz, G. J., and Labarthe-Hernandez, G. L., 2003, Fissure ignimbrites: Fissure-source for voluminous ignimbrites of the Sierra Madre Occidental and its relationship with Basin and Range faulting: Geology, v. 31, p. 773-776.

Ashwill, M. S., 1983, Seven fossil floras in the rain shadow of the Cascade Mountains, Oregon: Oregon Geology, v. 45, p. 107–111.

Bacon, C., and Lanphere, M. A., 2006, Eruptive history and geochronology of Mount Mazama and the Crater Lake region, Oregon: Geological Society of America Bulletin, v. 118, p. 1,331–1,359.

Bailey, R. A., 1976, Volcanism, structure, and geochronology of Long Valley caldera, Mono County, California: Journal of Geophysical Research, v. 81, p. 725–744.

Bestland, E. A., and Retallack, G. J., 1994a, Geology and paleoenvironments of the Clarno Unit, John Day Fossil Beds National Monument, Oregon: U.S. National Park Service Open-File Report, 160 p.

Bestland, E. A., and Retallack, G. J., 1994b, Geology and paleoenvironments of the Painted Hills Unit, John Day Fossil Beds National Monument, Oregon: U.S. National Park Service Open-File Report, 211 p.

Bestland, E. A., Hammond, P. E., Blackwell, D. L. S., Kays, M. A., Retallack, G. J., and Stimac, J., 2002, Geologic framework of the Clarno Unit, John Day Fossil Beds National Monument, Central Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-02-03, 39 p.

Brooks, H. C., 1963, Quicksilver in Oregon: Oregon Department of Geology and Mineral Industries Bulletin 55, 223 p.

Brown, D. E., Black, G. L., McLean, G. D., and Petros, J. R., 1980, Preliminary geology and geothermal resource potential of the Powell Buttes area, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-80-8, 117 p.

Carter, B. H., 1998, Safety of dams modifications to Ochoco Dam Crooked River Project, Oregon, in Schultz, R. A., and Siddharthan, R., eds., Proceedings of the 33rd Symposium of Engineering Geology and Geotechnical Engineering, University of Nevada, Reno.

Castor, S. B., and Henry, C. D., 2000, Geology, geochemistry, and origin of volcanic rock-hosted uranium deposits in northwestern Nevada and southeastern Oregon, USA: Ore Geology Reviews, v. 16, p. 1–40.

Castor, S. B., Boden, D. R., Henry, C. D., Cline, J. S., Hofstra, A. H., McIntosh, W. C., Tosdal, R. M., and Wooden, J. P., 2003, The Tuscarora Au-Ag district: Eocene volcanic-hosted epithermal deposits in the Carlin Gold Region, Nevada: Economic Geology, v. 98, p. 339–366.

Christiansen, R. L., 1984, Yellowstone magmatic evolution: its bearing on understanding large-volume explosive volcanism, in Boyd F. R., ed., Explosive volcanism: inception, evolution, and hazards. National Research Council Studies in Geophysics, National Academy Press, Washington D.C., p. 84–95.

Christiansen, R. L., 2001, The Quaternary and Pliocene Yellowstone Plateau volcanic field of Wyoming, Idaho, and Montana: U.S. Geological Survey Professional Paper 729-G, 145 p.

Coleman, R.G., 1949, The John Day Formation in the Picture Gorge Quadrangle, Oregon [M.S. thesis]: Corvallis, Oregon State University, 211 p.

Evans, S. H., and Brown, F. H., 1981, Summary of potassium/argon dating —1981: U.S. Department of Energy, Division of Geothermal Energy DE-AC07-80-ID-12079-45, 29 p.

Ferns, M. L., and McClaughry, J. D., 2006, Preliminary geologic map of the Powell Buttes 7.5' quadrangle, Crook County, Oregon: Oregon Department of Geology and Mineral Industries Open-File Report O-06-24, scale 1:24,000.

Ferns, M. L., Madin, I. P, and Taubeneck, W. H., 2001, Reconnaissance Geologic Map of the La Grande 30' x 60' quadrangle, Baker, Grant, Umatilla, and Union Counties, Oregon: Oregon Department of Geology and Mineral Industries Reconnaissance Map Series, RMS-1, 52 p., scale 1:100,000.

Fiebelkorn, R. B., Walker, G. W., MacLeod, N. S., McKee, E. H., and Smith, J. G., 1983, Index to K/Ar age determinations for the state of Oregon: Isochron/West, no. 37, p. 3–60.

Fisher, R.V., 1966, Geology of a Miocene ignimbrite layer, John Day Formation, Eastern Oregon: University of California Publications in Geological Sciences, v. 67, 58 p.

Fisher, R. V., and Rensberger, J. M., 1972, Physical stratigraphy of the John Day Formation, central Oregon: California University Publications in Geological Sciences, v. 101, p. 1-45.

Gannett, M.W., and Lite, K.E., Jr., 2004, Simulation of regional groundwater flow in the upper Deschutes Basin, Oregon: U.S. Geological Survey Water Resources Investigation Report 03-4195, 84 p.

Gannett, M.W., Lite, K.E., Jr., Morgan, D.S., and Collins, C.A., 2001, Ground-water hydrology of the upper Deschutes Basin, Oregon: U.S. Geological Survey Water Resources Investigation Report 00-4162, 77 p.

Gray, J. J., and Baxter, G., 1986, A reinterpretation of the Gray Butte limestone and arenite exposure as a hydrothermally-derived calcite vein and pebble dike: Oregon Geology, v. 48, no. 4, p. 45–46.

Hardyman, R. F., 1981, Twin Peaks caldera of central Idaho: in Montana Geological Society 1981 field conference on southwest Montana, Montana Geological Society, Billings, p. 317–322.

Hladkey, F. R., 1996, Geology and Mineral Resource map of the Grizzly Peak quadrangle, Jackson County, Oregon: Oregon Department of Geology and Mineral Industries Geological Map Series GMS-106, scale 1:24,000.

Hladkey, F. R. and Wiley, T. J., 1993, Ancient caldera complex revealed: Oregon Geology, v. 55, no. 3, p. 70.

Johnson, D. M., Hooper, P.R., and Conrey, R. M., 1999, XRF analysis of rocks and minerals for major and trace elements on a single low dilution Li-tetraborate fused bead: Advances in X-ray Analysis, v. 41, p. 843-867.

Kunzer, A. S., 1998, Spillway Modifications: Ochoco Dam, Crooked River Project, Oregon: in Schultz, R. A., and Siddharthan, R., eds., Proceedings of the 33rd Symposium of Engineering Geology and Geotechnical Engineering, University of Nevada, Reno.

Linneman, S., 1990, The petrologic evolution of the Holocene magmatic system of Newberry Volcano, central Oregon [Ph.D. dissertation]: Laramie, University of Wyoming, 293 p.

Lipman, P. W., 1976, Caldera collapse breccias in the western San Juan Mountains, Colorado: Geological Society of America Bulletin, v. 87, p. 1,397–1,410.

Lipman, P. W., 1984, Roots of ash-flow calderas in western North America: Windows into the tops of granitic batholiths: Journal of Geophysical Research, v. 89, p. 8,801–8,841.

Lipman, P. W., 1997, Subsidence of ash-flow calderas: Relation to caldera size and chamber geometry: Bulletin of Volcanology, v. 59, p. 198–218.

Lite, K.E., Jr., and Gannett, M.W., 2002, Geologic framework of the regional ground-water flow system in the upper Deschutes Basin, Oregon: U.S. Geological Survey Water Resources Investigation Report 02-4015, 44 p.

MacLeod, N. S., Sherrod, D. R., Chitwood, L. A., and Jensen, R. A., 1995, Geologic map of Newberry Volcano, Deschutes, Klamath, and Lake Counties, Oregon: U.S. Geological Survey Miscellaneous Investigation Series I 2455.

Mason, B. G., Pyle, D. M., and Oppenheimer, C., 2004, The size and frequency of the largest explosive eruptions on Earth: Bulletin of Volcanology, v. 66, p. 735–748.

McArthur, L. A., 1992, Oregon Geographic Names: Oregon Historical Society Press, sixth edition, 957 p.

McClaughry, J. D., and Ferns, M. L., 2006a, Preliminary geologic map of the Prineville 7.5' quadrangle, Crook County, Oregon. Oregon Department of Geology and Mineral Industries Open-File Report O-06-22, scale 1:24,000.

McClaughry, J. D., and Ferns, M. L., 2006b, Preliminary geologic map of the Ochoco Reservoir 7.5' quadrangle, Crook County, Oregon. Oregon Department of Geology and Mineral Industries Open-File Report O-06-23, scale 1:24,000.

McClaughry, J. D., and Ferns, M. L., 2007, The Crooked River Caldera: Identification of an early Oligocene eruptive center in the John Day Formation of central Oregon: Geological Society of America Abstracts with Programs, v. 39, no. 4, p. 10.

McClaughry, J. D., Gordon, C. L., and Ferns, M. L., 2009, Field trip guide to the middle Eocene Wildcat Mountain Caldera, Ochoco National Forest, Crook County, Oregon: Oregon Geology, v. 69, no. 1, p. 5–24. [this issue]

Moran-Zenteno, D. J., Alba-Aldave, L. A., Sole, J., and Iriondo, A., 2004, A major resurgent caldera in southern Mexico: the source of the late Eocene Tilzapotla ignimbrite: Journal of Volcanology and Geothermal Research, v. 136, p. 97–119.

Morgan, L. A., Doherty, D. J., and Leeman, W. P., 1984, Ignimbrites of the eastern Snake River Plain: evidence for major caldera forming eruptions: Journal of Geophysical Research, v. 89, p. 8,665–8,678.

Obermiller, W. A., 1987, Geologic, structural, and geochemical features of basaltic and rhyolitic volcanic rocks of the Smith Rock–Gray Butte area, central Oregon [M.S. thesis]: Eugene, University of Oregon, 169 p.

Peck, D. L., 1964, Geologic reconnaissance of the Antelope-Ashwood area of north-central Oregon, with emphasis on the John Day Formation of late Oligocene and early Miocene age: U.S. Geological Survey Bulletin 1161-D, 26 p.

Retallack, G.J., Bestland, E.A., and Fremd, T.J., 2000, Eocene and Oligocene paleosols of Central Oregon: Geological Society of America Special Paper 344, 192 p.

Riddihough, R., Finn, C., and Couch, R., 1986, Klamath–Blue Mountain lineament, Oregon: Geology, v. 14, p. 528–531.

Robinson, P. T., 1969, High-titania alkali-olivine basalt of north-central Oregon: Contributions to Mineralogy and Petrology, v. 22, p. 349–360.

Robinson, P. T., 1975, Reconnaissance geologic map of the John Day Formation in the southwestern part of the Blue Mountains and adjacent areas, north-central Oregon: U.S. Geological Survey Miscellaneous Investigations Map I-872, scale 1:125,000.

Robinson, P. T., and Brem, G. F., 1981, Guide to a geologic field trip between Kimberly and Bend, Oregon with emphasis on the John Day Formation: in Johnston, D. A., and Donnelly-Nolan, J., eds., Guides to some volcanic terranes in Washington, Idaho, Oregon, and northern California: U.S. Geological Survey Circular 838, p. 41–58.

Robinson, P. T., and Stensland, D., 1979, Geologic map of the Smith Rock area, Oregon: U.S. Geological Survey Miscellaneous Investigations Map I-1142, scale 1:48 000.

Robinson, P. T., Brem, G. F., and McKee, E. H., 1984, John Day Formation of Oregon: a distal record of early Cascade volcanism: Geology, v. 12, p. 229–232.

Robinson, P. T., Walker, G. W., and McKee. E. H., 1990, Eocene(?), Oligocene and lower Miocene rocks of the Blue Mountains region: in Walker, G. W., ed., Geology of the Blue Mountains region of Oregon, Idaho, and Washington: U.S. Geological Survey Professional Paper 1437, p. 29–62.

Rose, W. I., and Chesner, C. A., 1987, Dispersal of ash in the great Toba eruption, 75 ka.: Geology, v. 15, p. 913–917.

Rytuba, J. J., and McKee, E. H., 1984, Peralkaline ash-flow tuffs and calderas of the McDermitt Volcanic Field, southeast Oregon and north-central Nevada: Journal of Geophysical Research, v. 89, p. 8,616–8,628.

Self, S., Goff, G., Gardner, J. N., Wright, J. V., and Kite, W. M., 1986, Explosive rhyolitic volcanism in the Jemez Mountains: vent locations, caldera development, and relation to regional structure: Journal of Geophysical Res., v. 91B, p. 1,779–1,798.

Sherrod, D.R., Gannett, M.W., and Lite, K.E., Jr., 2002, Hydrogeology of the upper Deschutes Basin, central Oregon: A young basin adjacent to the Cascade volcanic arc: in Moore, G.W., Field Guide to geologic processes in Cascadia: Oregon Department of Geology and Mineral Industries Special Paper 36, p. 109-144.

Sherrod, D. R., Taylor, E. M., Ferns, M. L., Scott, W. E., Conrey, R. M., and Smith, G. A., 2004, Geologic map of the Bend 30 x 60 minute quadrangle, central Oregon: U.S. Geological Survey Geologic Investigations Series I-2683, 48 p., scale 1:100,000.

Smith, G. A., 1986a, Stratigraphy, sedimentology, and petrology of Neogene rocks in the Deschutes Basin, central Oregon: a record of continental margin volcanism: Corvallis, Oregon State University, Ph.D. dissertation, 467 p.

Smith, G. A., 1986b, Stratigraphy, sedimentology, and the petrology of Neogene rocks in the Deschutes Basin, Central, Oregon: A record of continental-margin volcanism and its influence on fluvial sedimentation in an arc-adjacent basin: U.S Department of Energy Basalt Waste Isolation Project, RHO-BW-SA-555 P.

Smith, G. A., Sherrod, D. R., Ferns, M. L., and Lite, K., 1996, Geology of the Opal City 7.5' quadrangle, Deschutes and Jefferson Counties, Oregon: Oregon Department of Geology and Mineral Industries unpublished map, scale 1:24,000.

Smith, G. A., Manchester, S. R., Ashwill, M., McIntosh, W. C., and Conrey, R. M., 1998, Late Eocene-early Oligocene tectonism, volcanism, and floristic change near Gray Butte, central Oregon: Geological Society of America Bulletin, v. 110, p. 759–778.

Smith, R. L., 1960, Ash flows: Geological Society of America Bulletin, v. 71, p. 795–842.

Smith, R. L., and Bailey, R. A., 1968, Resurgent cauldrons: Geological Society of America Memoir 116, p. 83–104.

Stearns, H. T., 1931, Geology and water resources of the middle Deschutes River Basin, Oregon: U.S. Geological Survey Water-Supply Paper 637-D, 220 p.

Streck, M. J., and Grunder A. L., 1995, Crystallization and welding variations in a widespread ignimbrite sheet: The Rattlesnake Tuff, eastern Oregon: Bulletin of Volcanology, v. 57, p. 151-169.

Swanson, D. A., 1969, Reconnaissance geologic map of the east half of the Bend quadrangle, Crook, Wheeler, Jefferson, Wasco, and Deschutes Counties, Oregon: U.S. Geological Survey Miscellaneous Investigations Map I-568, scale 1:250,000.

Thompson, M.L., and Wheeler, H.E., 1942, Permian fusulinids from British Columbia, Washington, and Oregon: Journal of Paleontology, v. 16, p. 700-711.

Thormahlen, D., 1984, Geology of the northwest quarter of the Prineville quadrangle [M.S. thesis]: Corvallis, Oregon State University, 116 p.

Vander Meulen, D. B., 1989, Intracaldera tuffs and central vent intrusion of the Mahogany Mountain caldera, eastern Oregon: U.S. Geological Survey Open-File Report 89-77, 69 p.

Walker, G. W., 1977, Geologic map of Oregon east of the 121st meridian: U.S. Geological Survey Map I-902, scale 1:500,000.

Waters, A. C., and Vaughan, R. H., 1968, Reconnaissance geologic map of the Ochoco Reservoir quadrangle, Crook County, Oregon: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-541, scale 1;62,500.

Williams, H., 1941, Calderas and their origin: California University Publications, Department of Geological Sciences Bulletin, v. 25, p. 239–346.

Williams, H., 1957, A geologic map of the Bend quadrangle and a reconnaissance geologic map of the central portion of the High Cascade Mountains: Oregon Department of Geology and Mineral Industries map (unnumbered series), scale 1:250,000.

Further reading: Achenbach, J., When Yellowstone explodes, National Geographic website, http://ngm.nationalgeographic.com

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
	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
		4B.12VII.05	rhyolite intrusion at Barnes Butte	4909935	674019	whole rock	$^{40}Ar/^{39}Ar$	27.97 ± 0.32	2
		648-623Bb	sanidine-phyric rhyolite, summit of Powell Buttes	4895300	661690	Sanidine	K/Ar	25.8 ± 0.2	3
		PB-5/AH-34	aphyric rhyolite northeast of Powell Buttes summit	4895610	662480	anorthoclase	K/Ar	28.3 ± 1.0	4
		GSO95-41	rhyolite vitrophyre at Gray Butte	4918390	650260	alkali feldspar	$^{40}Ar/^{39}Ar$	28.82 ± 0.23	6
	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
		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
		GSO95-132	Tuff of Smith Rock at Haystack Reservoir, upper tuff	4928570	646560	alkali feldspar	$^{40}Ar/^{39}Ar$	29.57 ± 0.17	6
		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
		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
	Intra-Caldera Tuff	—	Tuff of Smith Rock at Smith Rock State Park?	—	—	zircon	fission-track	29 ± 3.0	6
	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
		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
		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	Antelope	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$_2$O$_3$	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$_2$O	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$_2$O	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$_2$O$_5$	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.	2	18	3	5	2	1	5	3	4	5
Co	1	0	31	**N.D.	0	0	0	0	0	7	**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).