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

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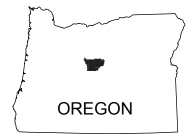
Overview: This field trip along the wild and scenic Crooked River between Ochoco Wayside State Park and Bowman Dam provides an overview of the Neogene basalt stratigraphy in the Lower Crooked Basin. Emphasis is placed on the interaction between basalt lavas and the development of the ancestral Crooked 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

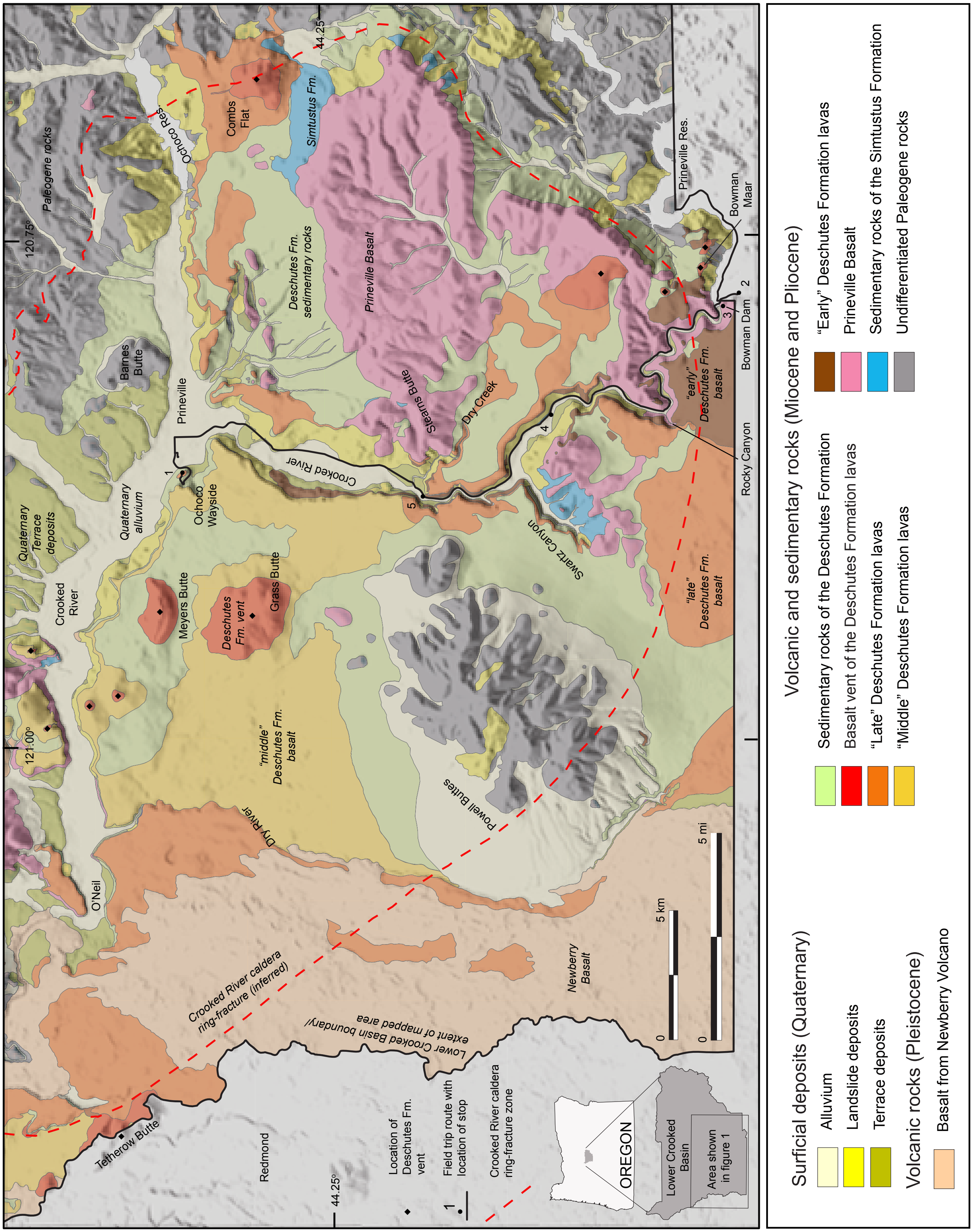


Figure 1. Simplified overview geologic map of the Crooked River between Bowman Dam and Prineville, Oregon. Numbers indicate stops described in this field guide.

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

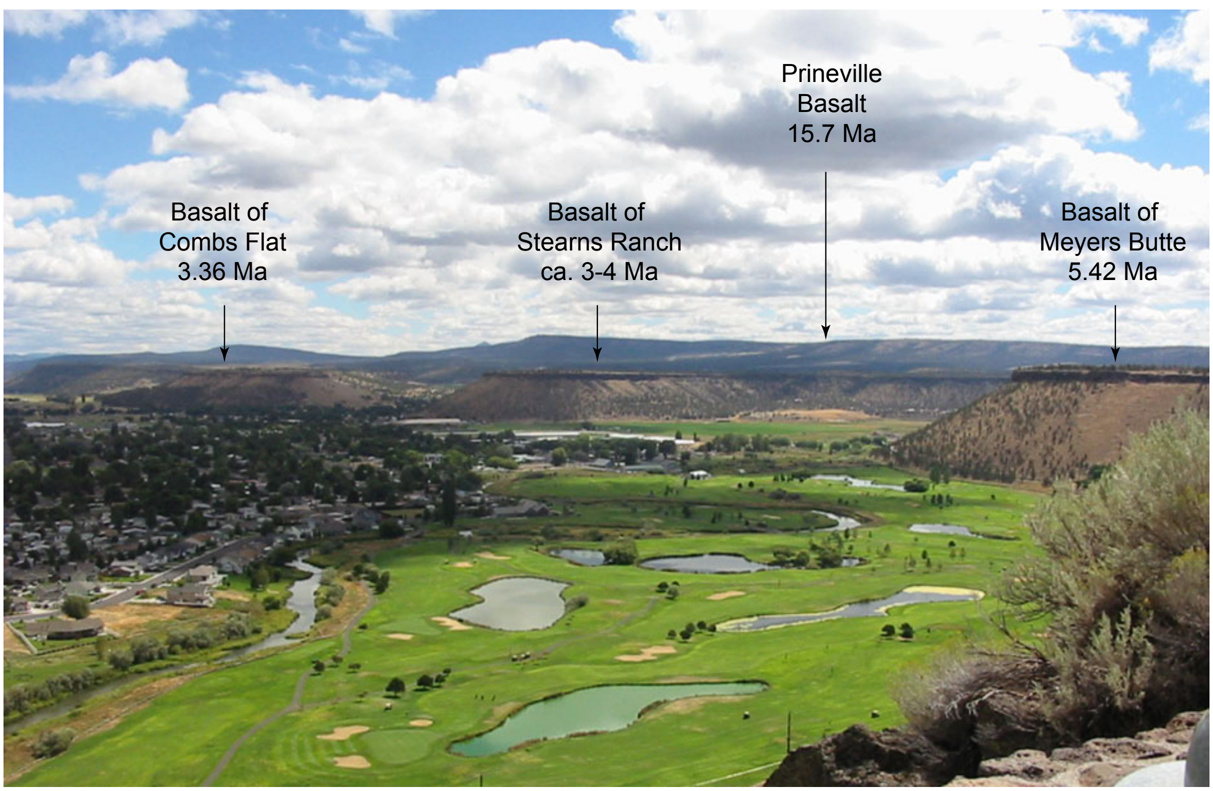


Figure 2. View east across the city of Prineville from Ochoco Wayside State Park. Topographically inverted basalt lavas of the Deschutes Formation trace the course of ancestral channels of the Crooked River. The high skyline on the east is composed of the Prineville Basalt.

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.

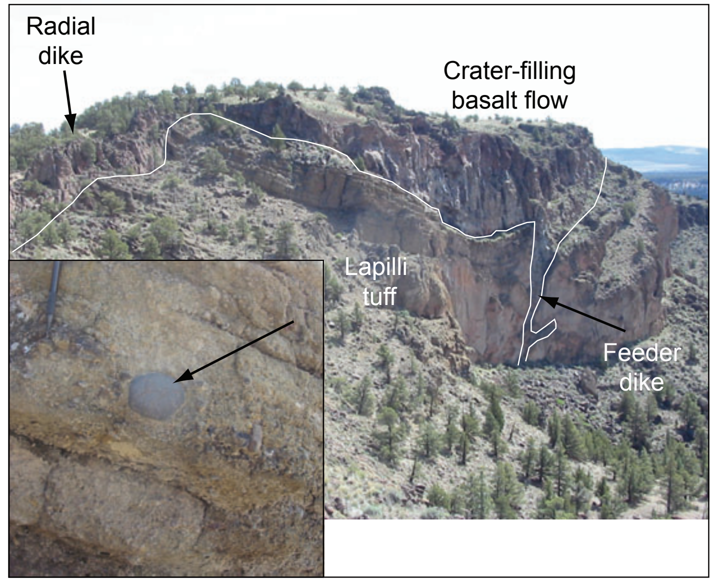


Figure 4. Bowman Maar is filled by a thick section of internally dipping lapilli tuff and an overlying crater-filling basalt lava. Inset photograph shows one of many well-rounded stream cobbles that were incorporated in primary lapilli tuff deposits inside the crater. The lithology of the cobble (approximately 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.

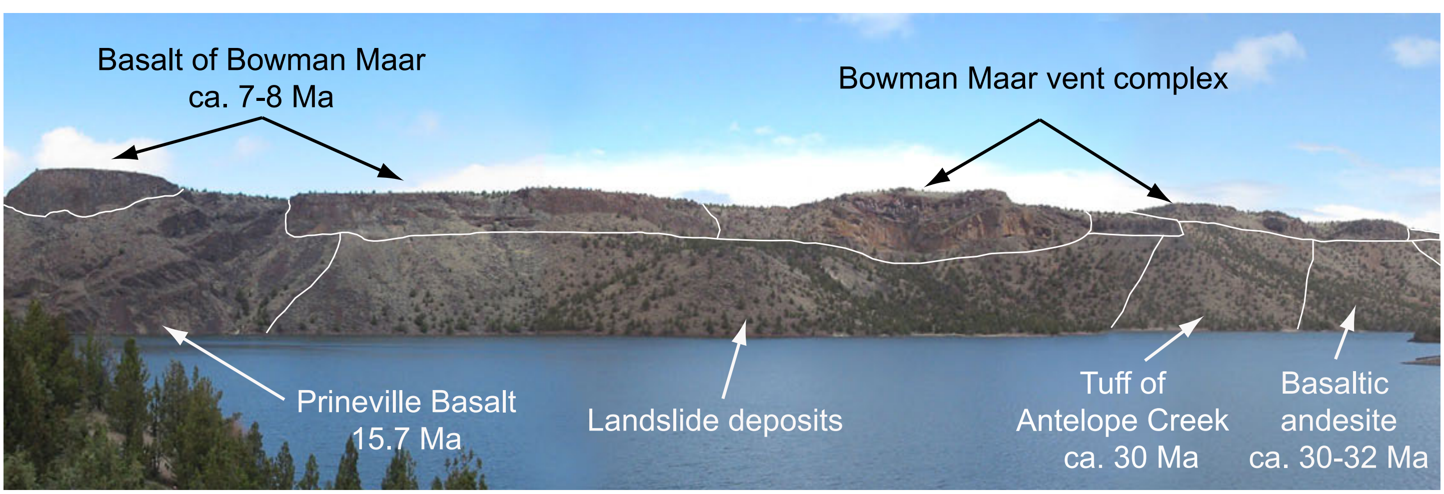


Figure 3. View northeast across Prineville reservoir toward Bowman Maar. Bowman Maar is a late Miocene hydrovolcanic eruptive center that formed above structurally deformed Oligocene rocks that predate eruption of the Crooked River caldera and the middle Miocene Prineville Basalt. Lavas erupted from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

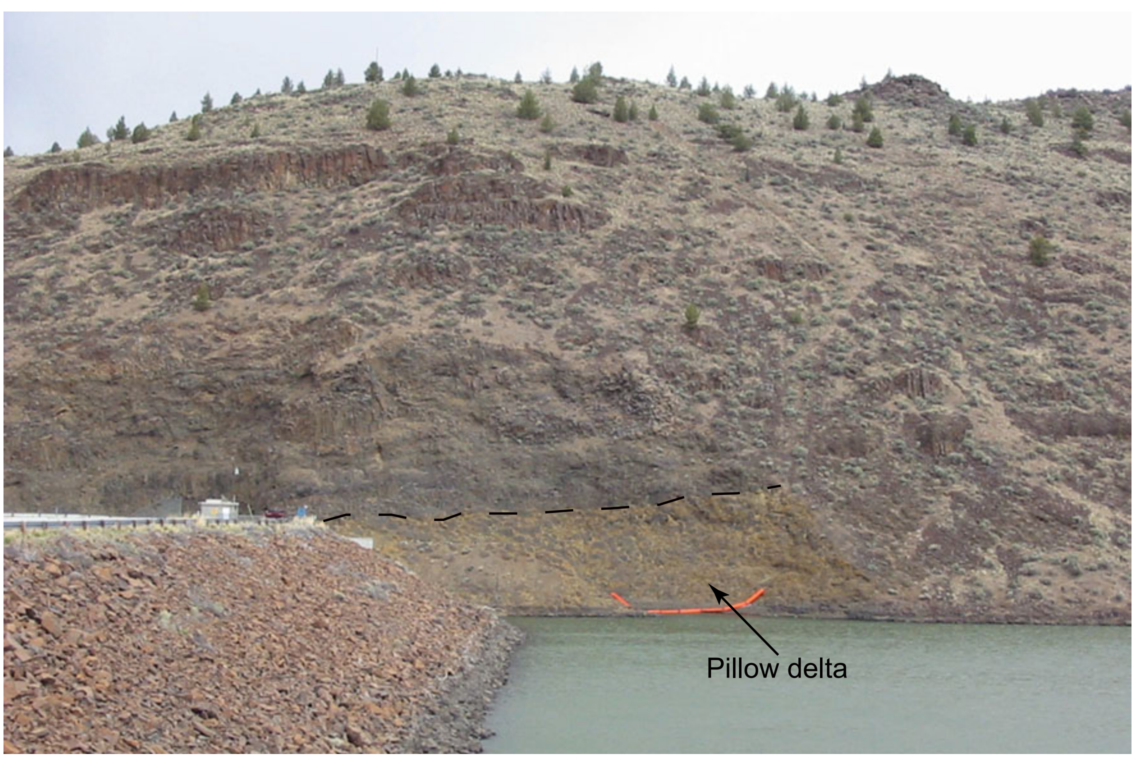


Figure 5. Pillow delta exposed at the base of a thick section of Prineville Basalt along the right abutment of Bowman Dam near stop 3.

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.

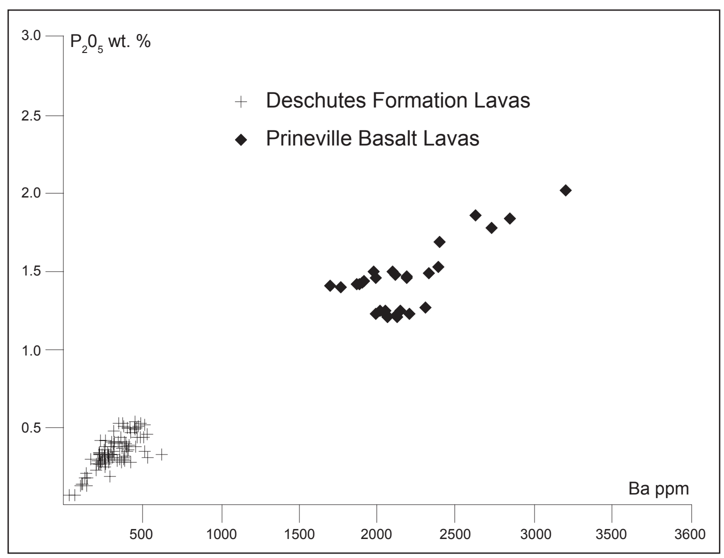


Figure 6. Variation plot of phosphorous (weight percent P_2O_5) versus barium (parts per million Ba) for Deschutes Formation Basalt lavas and the Prineville Basalt in the Lower Crooked Basin. The Prineville Basalt is distinguished from overlying lavas of the Deschutes Formation by its unusually high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

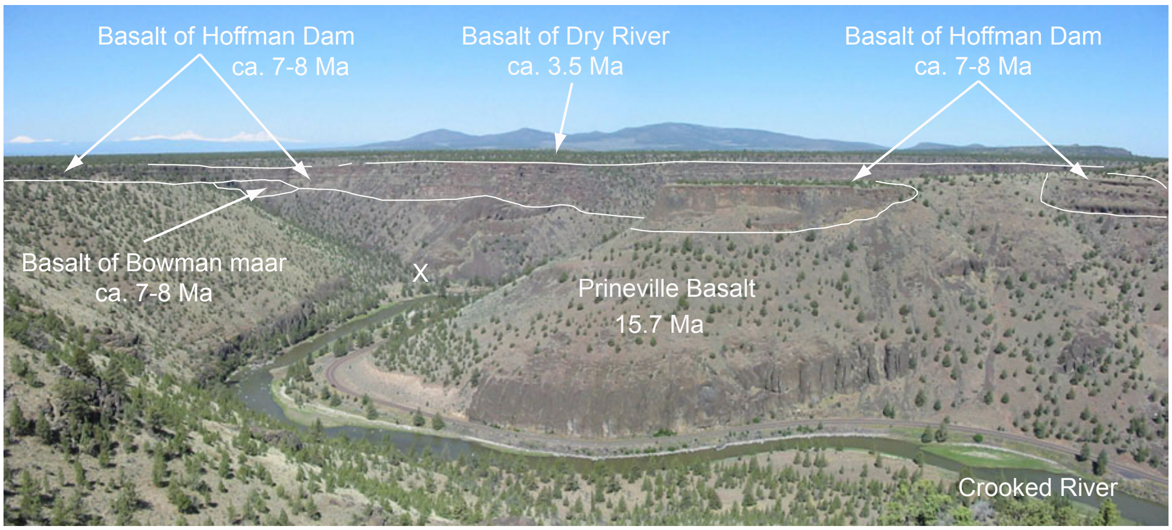


Figure 7. Well-exposed lavas of the Prineville Basalt and overlying intracanyon, olivine-phyric lavas of the Deschutes Formation that line the Crooked River Canyon. Lavas of the Prineville Basalt reach a maximum composite thickness of 210 m (690 ft) at this locality and thin abruptly to the north and 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.

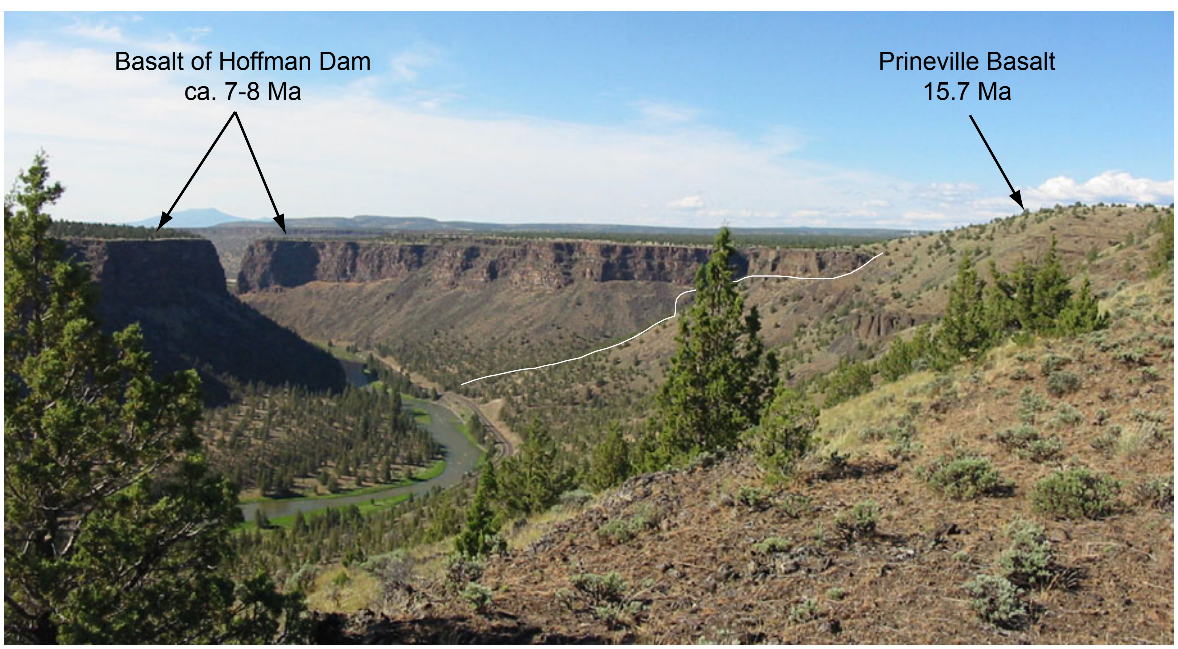


Figure 8. Thick, intracanyon lavas of the Basalt of Hoffman Dam juxtaposed against paleocanyon walls composed of Prineville Basalt.

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

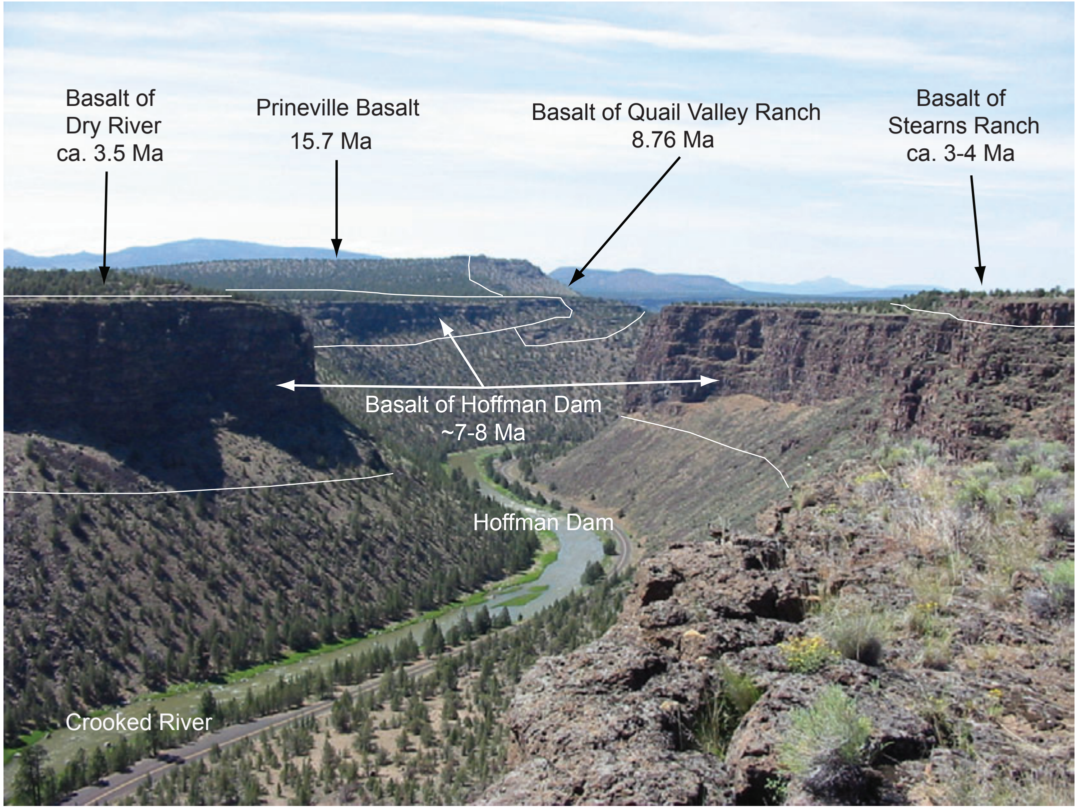


Figure 9. Thick, intracanyon Deschutes Formation lavas exposed near Hoffman Dam and stop 4. View is to the north-northwest. The 8.76 Ma Basalt of Quail Valley Ranch is the oldest Deschutes lava recognized in the Lower Crooked Basin and is here juxtaposed against a Prineville Basalt paleocanyon wall.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

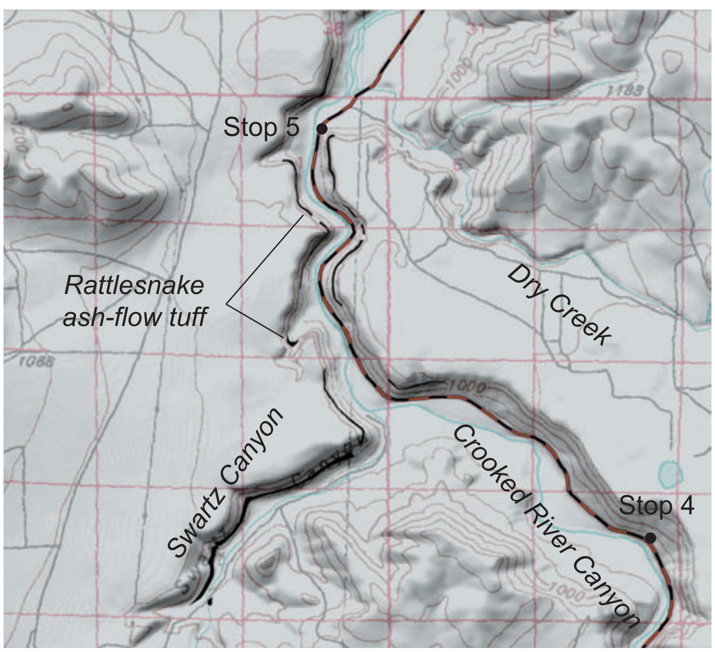


Figure 11. The 7.05 Ma Rattlesnake Ash-Flow Tuff interbedded with a section of Deschutes Formation lavas in the Crooked River Canyon at stop 5. The Rattlesnake Ash-Flow Tuff was erupted from a vent to the southeast in the Harney Basin and became partially channelized by the ancestral Crooked River south 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

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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. 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.