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

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

INTRODUCTION

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

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

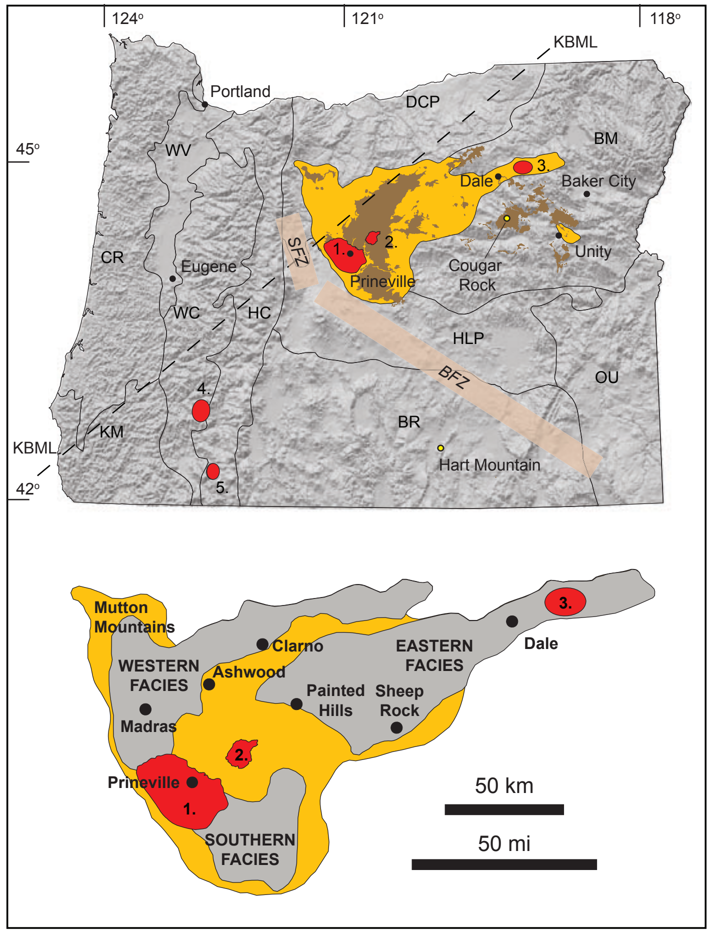

Figure 1. (top) Location of known Paleogene calderas in Oregon. Red-filled polygons are calderas: 1, Crooked River caldera; 2, Wildcat Mountain caldera; 3, Tower Mountain caldera; 4 and 5, unnamed, suggested calderas. Locations of known Paleogene volcanic centers at Cougar Rock and Hart Mountain are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

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

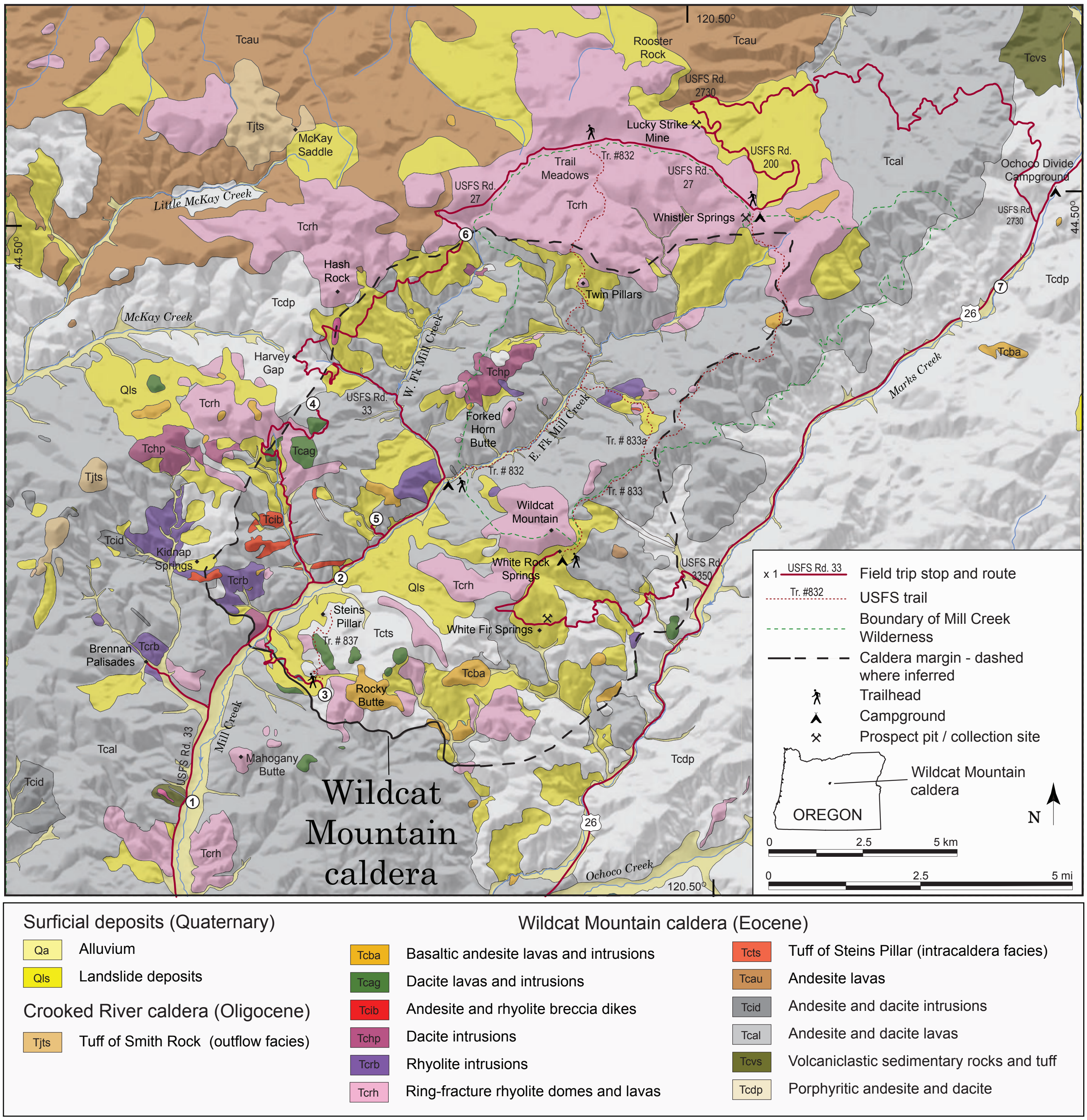

Figure 2. Geologic map of the Wildcat Mountain caldera and vicinity labeled with field trip route and associated stops 1 through 7.

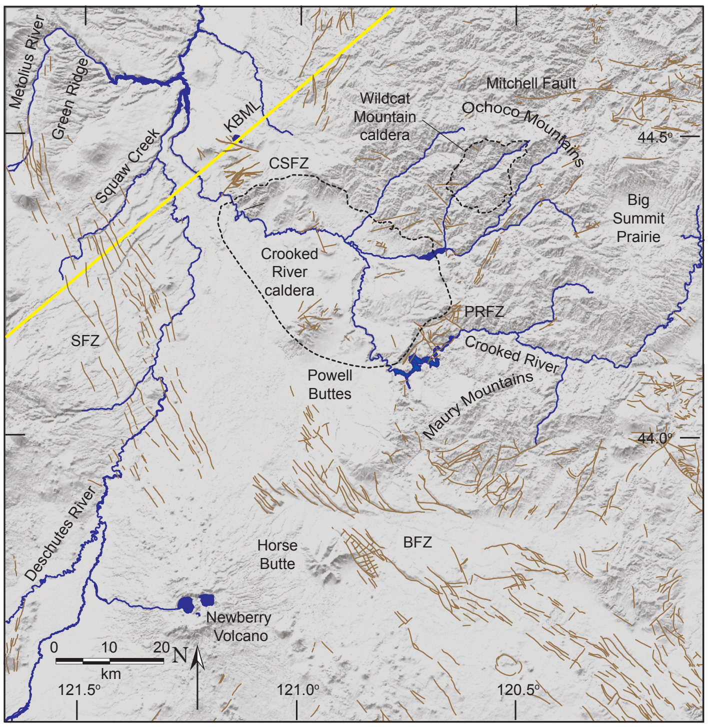

Figure 3. Fault lineament map of central Oregon with caldera structures delineated in the Lower Crooked Basin. The Wildcat Mountain caldera is coincident with a relatively stable tectonic area near the junction of the northwest trending Brothers fault zone (BFZ) and the north-northwest trending Sisters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

Location and geologic setting

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

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

Regional Paleogene stratigraphy

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

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

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

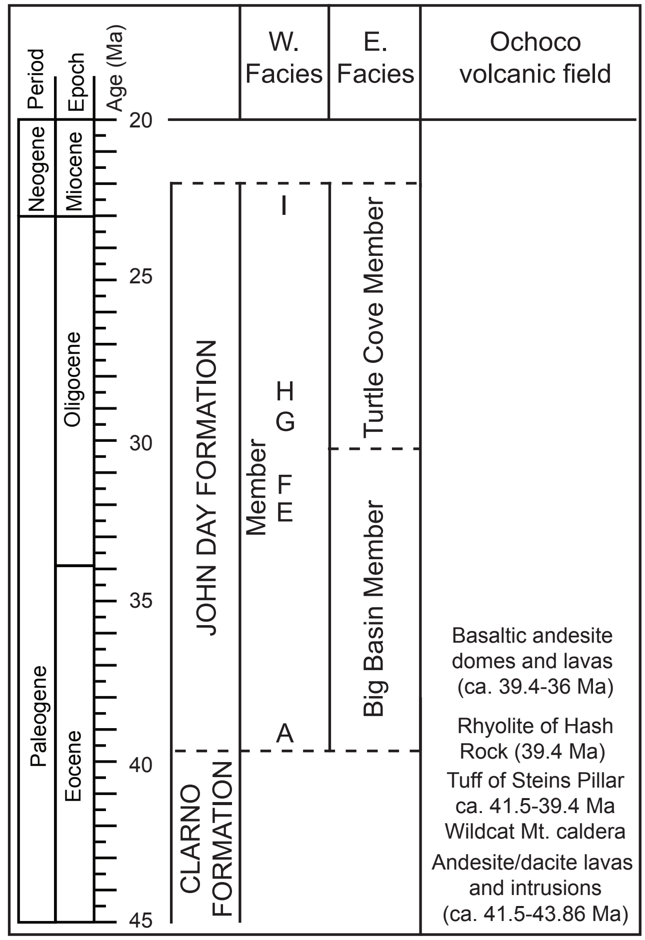

Figure 4. Generalized stratigraphic section for the John Day and Clarno Formations in central Oregon and correlative major units of the Eocene Ochoco volcanic field.

Wildcat Mountain caldera overview

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

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

FIELD TRIP GUIDE

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

Objectives of this field trip

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

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 1

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

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

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

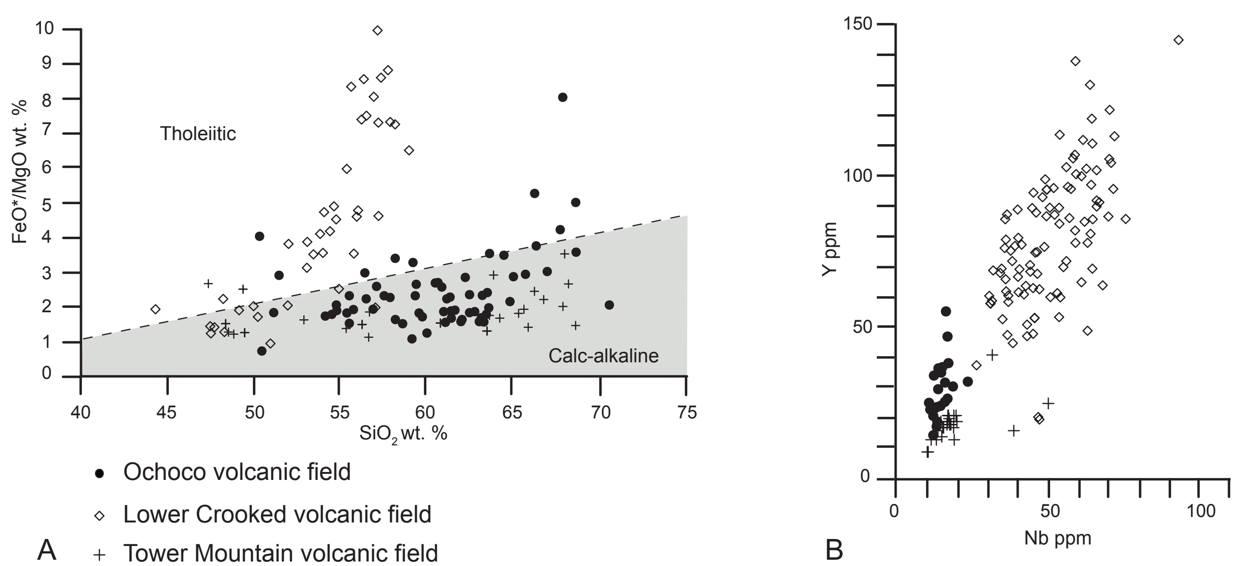

Figure 5. Variation diagrams for whole-rock geochemical analyses from the Ochoco, Lower Crooked, and Tower Mountain volcanic fields. (a) FeO*/MgO versus SiO_2 diagram showing differences between mafic to intermediate rocks within the three volcanic systems. Tholeiitic and calc-alkaline fields are from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

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

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

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

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

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

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

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

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

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

STOP 1. PRE-CALDERA DACITE INTRUSION

GPS coordinates -120.6653, 44.3694

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

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

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 2

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

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

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

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

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

STOP 2. STEINS PILLAR VIEWPOINT

GPS coordinates -120.6176, 44.4173

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

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

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

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

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

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

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

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

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

GPS coordinates -120.6216, 44.3932

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

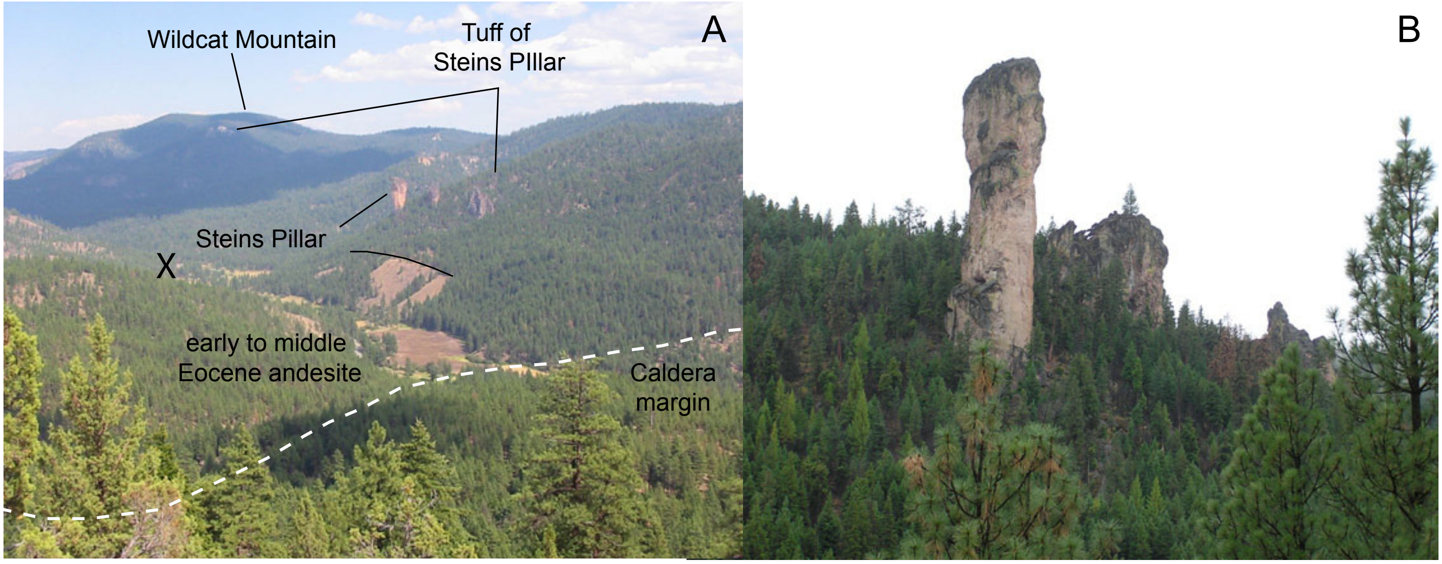

Figure 7. (a) View of the southwest margin of the Wildcat Mountain caldera, showing the location of Wildcat Mountain and Steins Pillar. Dashed white line shows the approximate location of the caldera margin. The X in the center-left of the photograph shows the location of Stop 2 (b) Steins Pillar as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

OPTIONAL HIKE 1 – STEINS PILLAR TRAIL #837

GPS coordinates -120.6228, 44.3948

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

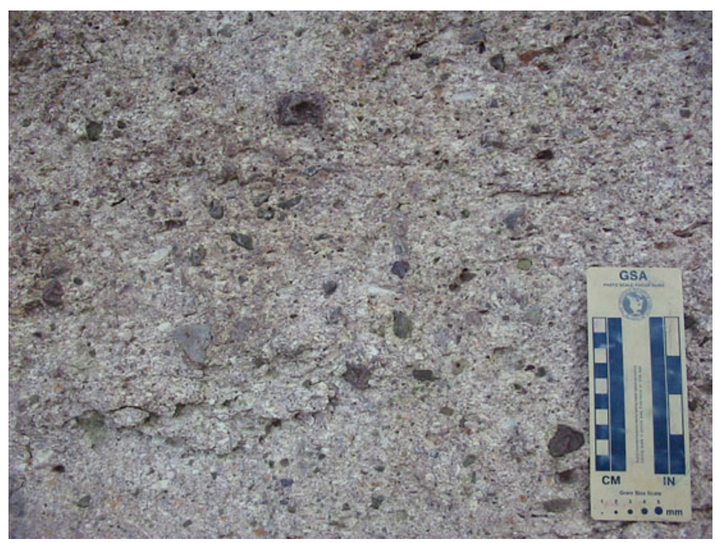

Figure 8. Pumice- and lithic-rich intracaldera tuff exposed at stop 3.

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

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 4 AND 5

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

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

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

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

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

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

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

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

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

25.9 Propylitically altered outcrop of silicified rhyolite.

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

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

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

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

STOP 4. PANORAMIC OVERVIEW OF THE WILDCAT MOUNTAIN CALDERA

GPS coordinates -120.6207, 44.4562

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

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

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

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

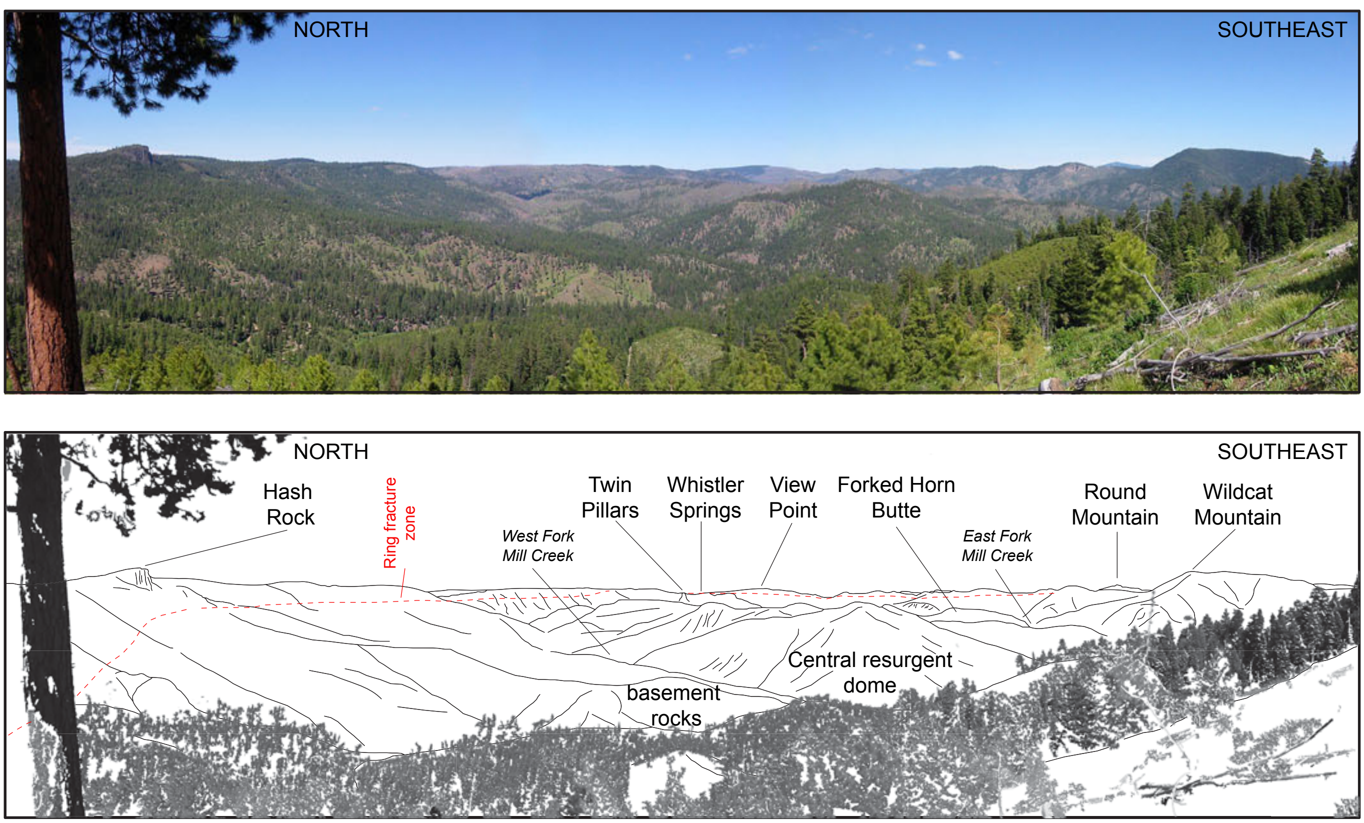

Figure 9. Panoramic view across the Wildcat Mountain caldera from stop 4. Line drawing highlights geologic features and locations discussed in the text.

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

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

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

33.9 Stop 5. Doe Creek landslide.

STOP 5. DOE CREEK LANDSLIDE

GPS coordinates -120.6042, 44.4299

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

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

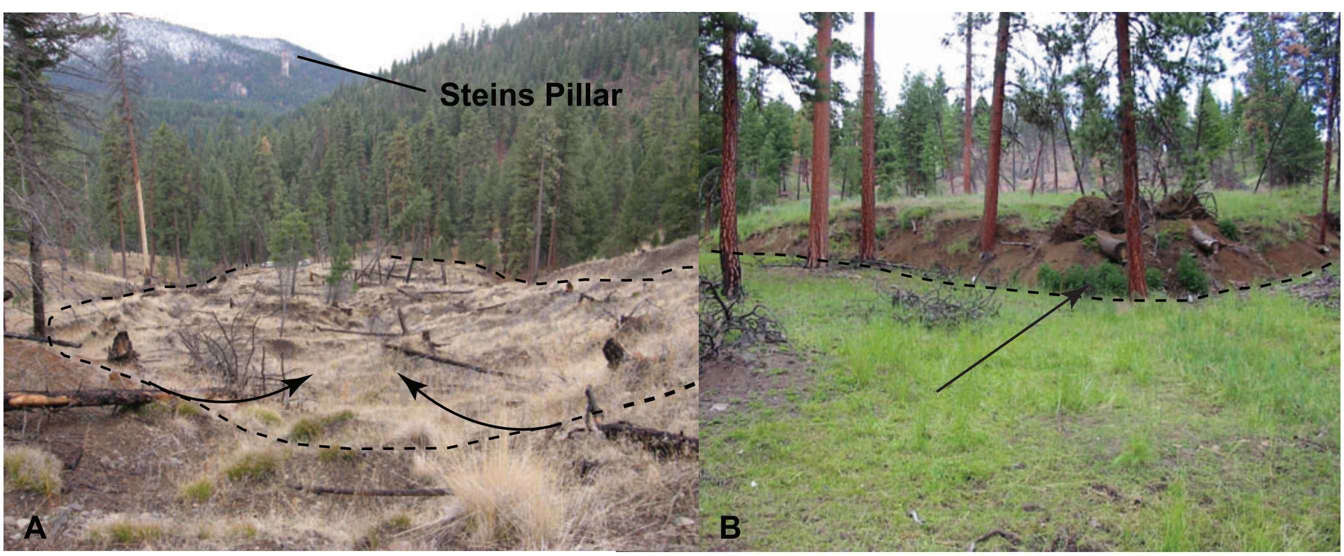

Figure 10. The Doe Creek earthflow exposed on the north side of Doe Creek at stop 5. (a) Photo looking southeast from the landslide headscarp. Arrows show the direction of slide movement. Dashed black line denotes the boundary of the slide mass. Note the irregular, hummocky topography and subvertical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

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

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

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

GEOLOGIC HIGHLIGHTS EN ROUTE TO STOP 6

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

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

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

37.1 The road crosses the west fork of Mill Creek.

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

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

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

44.2 Stop 6. The Rhyolite of Hash Rock.

STOP 6. THE RHYOLITE OF HASH ROCK

GPS coordinates -120.5723, 44.4955

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

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

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

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

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

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

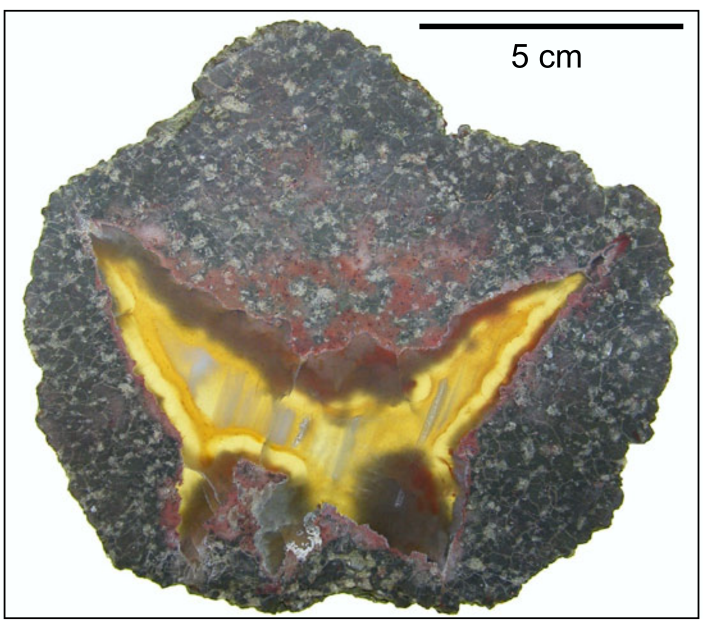

Figure 12. Butterfly wing, agate-filled geode (thunderegg) from the Lucky Strike Mine.

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

GPS coordinates -120.5323, 44.5149

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

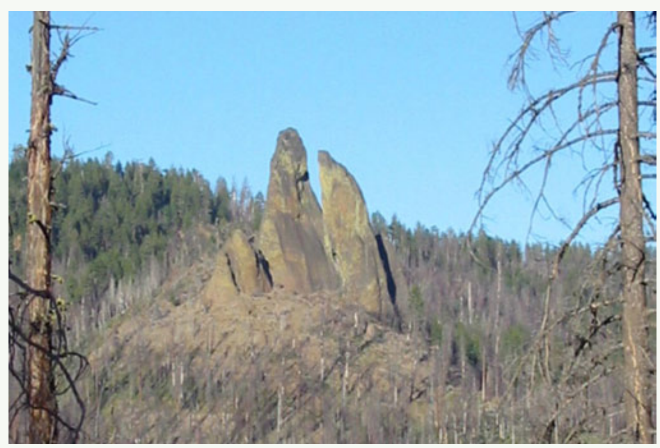

Figure 13. View north toward Twin Pillars from the interior of the Wildcat Mountain caldera. Twin Pillars is a composite dike, composed of several east-west (90°) oriented planar sheets of blue-gray, plagioclase-phyric rhyolite.

OPTIONAL HIKE 3 – WILDCAT MOUNTAIN TRAIL #833

GPS coordinates -120.4816, 44.4974

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

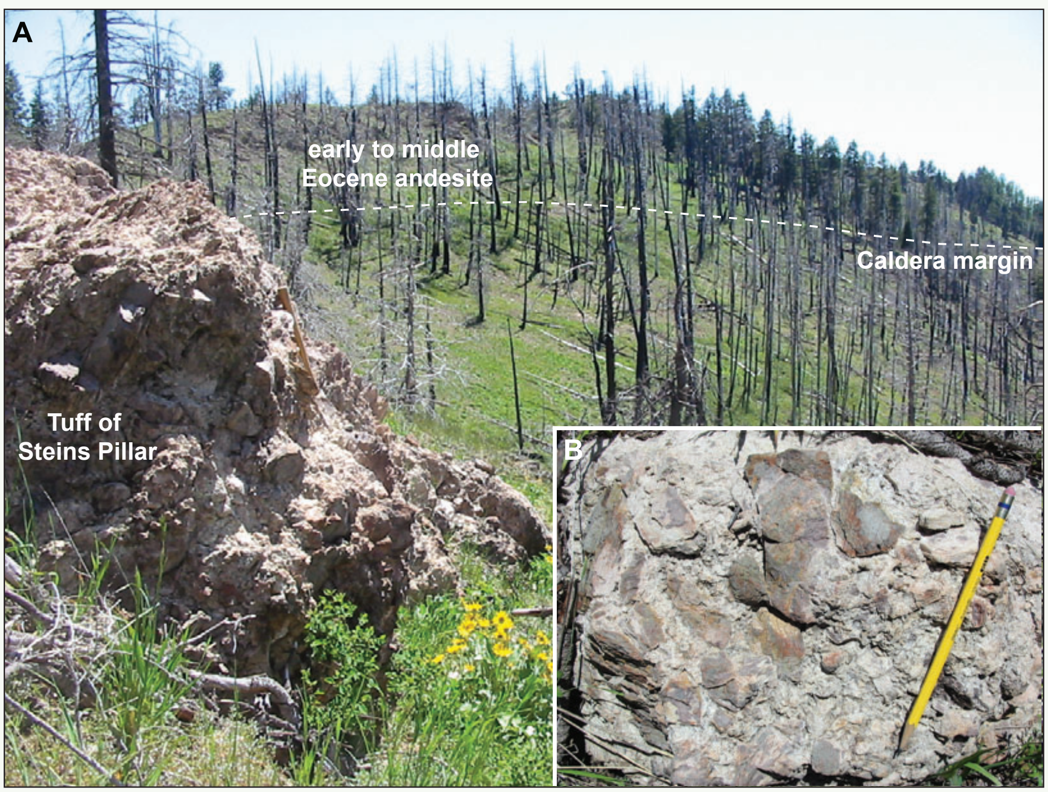

Figure 14. Lithic-rich intracaldera tuff exposed along Wildcat Mountain Trail #833. (a) Tuff is directly juxtaposed against early to middle Eocene andesite that forms the wall of the Wildcat Mountain caldera. (b) Close-up view of the lithic-rich tuff. Pencil for scale at the right of photograph is 15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

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

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

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

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

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

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

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

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

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

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

STOP 7. MIDDLE EOCENE PORPHYRITIC ANDESITE

GPS coordinates -120.4029, 44.4809

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

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

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

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

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

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John Day Fossil Beds National Monument

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

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

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

(photo credits: Jason McClaughry, DOGAMI)