SOTA Field Trip Guide

State of the Cascade Arc: stratocone persistence, mafic lava shields, and pyroclastic volcanism associated with intra-arc rift propagation

by

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Introduction to the geology of the north-central Oregon Cascade Range

Along arc rift propagation

The Cascade Range is a classic continental margin arc built atop Cenozoic, Mesozoic, and Paleozoic accreted terranes due to subduction of the young Juan de Fuca plate (Fig. 1). The portion of the arc between Mt. Hood and the Three Sisters, the area dealt with in this guide, occupies the so-called Columbia embayment, underlain by the youngest, chiefly Cenozoic accreted crust, as indicated by regional geologic and isotopic data (Fig. 1). The complex history of the Cascade arc, beginning around 40 Ma (Lux, 1982; Phillips et al., 1986), includes a major episode of intra-arc rifting spanning the past 8 Ma (Smith et al., 1987; Conrey et al., 2002; Sherrod et al., in press). A synthesis of new map, age, and chemical data from northern Oregon suggests the High Cascade intra-arc graben is structurally segmented and time-transgressive (Fig. 2), and thus resembles a propagating rift.
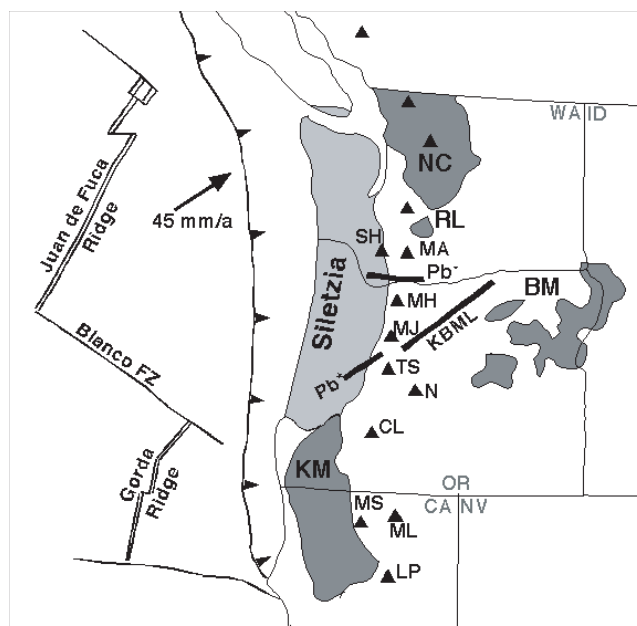
Figure 1. Tectonic setting and basement terranes of the Cascade arc. Dark pattern = Mesozoic-Paleozoic accreted crust (NC = North Cascades; RL = Rimrock Lake inlier; BM = Blue Mountains; KM = Klamath Mountains). KBML = Klamath-Blue Mtn. lineament, likely the NW margin of accreted Mesozoic terranes in Oregon (Riddihough et al., 1986). Pb* = boundaries of Mesozoic accreted terranes defined by Pb isotopes (Church et al., 1986). Light pattern = extent of Cenozoic accreted block "Siletzia" (Trehu et al., 1994; Wells et al., 1998). Cascade volcanoes indicated are Mt. St. Helens (SH), Mt. Adams (MA), Mt. Hood, MH), Mt. Jefferson (MJ), Three Sisters (TS), Newberry (N), Crater Lake (CL), Mt. Shasta (MS), Medicine Lake (ML), and Lassen Peak (LP).

Rift segment boundaries coincide with stratocones or with the Columbia River (Fig. 2). The northern segment along the Hood River is a down-east half graben with a broken (western) hinge zone. Faulting appears to offset rocks as young as ~1.2 Ma but not rocks younger than ~0.9 Ma. The central segment along the upper Clackamas River is a full graben with a complex pattern of faulting that appears to have propagated northward with time as rocks ~4 Ma are cut on the southern end, whilst rocks ~2 Ma are cut on the northern end. The southernmost segment, defined on the east in large part by Green Ridge, is a Quaternary graben within a Pliocene (as old as ~5.5 Ma) graben. The change in structural style, and the fact that the rift basins become both wider and deeper southward along the arc, is consistent with increasing amounts of extension southward.

The primary magmatic indication of rifting in each segment of the arc was the eruption of voluminous lavas of mid-ocean ridge (MORB)-like low-K basalt (0.1-0.5 wt% K_2O; Fig. 2). Along with these low-K basalts, abundant basaltic andesites and large-volume pumiceous silicic ash-flow tuffs were erupted. Aphyric Fe-rich intermediate rocks are also common in these sequences, especially along the southern segment. Andesites are also common and often show spectacular evidence of magma mixing. Amphibole is nearly absent. Eruption rates were dramatically higher during the accumulation of these volcanic piles compared with the preceding Miocene rocks. Typically the high eruption rates would last for some 2-3 million years, and as they declined structural foundering of the arc axis commenced. There was so much volcanic material erupted prior to the foundering that much of the older arc was buried. During or after foundering the rift-related rock package was uplifted along the rift flanks (especially the western side), and thus is now found capping ridges on both sides of the Cascade graben (Fig. 2).

Record of rifting in three eastside basins

Voluminous eruptions prior to arc rifting are recorded both east and west of the present High Cascades (Fig. 2). The westside record is forest-covered and deeply weathered and eroded due to glaciation and high rainfall. In contrast, the eastside record is better preserved in a much drier climate, and much less effaced by glacial stripping. Each structural segment of the arc is associated with a correlative eastside basin, which contain records of volcanism immediately prior to rift formation. The Deschutes, Shitike ("sshhh-dike"; informal name), and Tygh Valley Formations, from south to north, respectively (Figs. 2 and 3), are the remnants of these voluminous rift-related eruptions (Farooqui et al., 1981; Taylor, 1981; Smith et al., 1987; R.M. Conrey, unpub.). This trip will provide an overview of the Shitike and Deschutes Formations.

The fundamental character of the three eastside formations is similar in that each contains interbedded low-K basalt, often voluminous silicic and intermediate ash-flow tuffs, abundant mafic and K-rich intermediate lava, and large volumes of volcaniclastic sediment. Facies relationships in all of the formations are identical, with proximal records dominated by lava flows, and distal records dominated by sediment and sparse far-traveled basalt and tuff. Mapping indicates that paleodrainages were eastward or northeastward from the arc high, and thus the lava dominated sections are closer to the modern arc axis.

The Deschutes Fm. is the best known of these deposits due to extensive thesis work by the students of Ed Taylor at OSU in the early to mid-1980's, which built on prior work by Peter Hales and the late Don Stensland (Stensland, 1970, and extensive unpub. mapping; Hales, 1975; Jay, 1982; Hayman, 1983; Cannon, 1985; Conrey, 1985; Smith, 1986; Yogodzinski, 1986; Wendland, 1988; McDannel, 1989; Dill, 1992). The Shitike Fm. was mapped on the Fort Butte 15 minute quadrangle (Fig. 5) by R.M. Conrey in 1993-1995. The Tygh Valley Fm. is mostly known only in reconnaissance (Farooqui et al., 1981; Sherrod and Scott, 1995), with some local detailed mapping by R.M Conrey to explore paleodrainage and structural relationships.

Compositional changes associated with rifting

The formation of the High Cascade graben postdates a long history of arc volcanism in northern Oregon. The predominant volcanic rock prior to the development of the rift was middle to late Miocene (to early Pliocene in northern Oregon) andesite, which accumulated at apparently rather low rates from 15 to 8 or as young as 5 Ma along the arc in northern Oregon. Basalt and rhyolite rarely erupted during the Miocene; andesite, often amphibole-bearing, was by far the most common rock produced. In contrast, volcanism associated with rifting was compositionally diverse, including voluminous basalt as well as rhyolite, and many varieties of intermediate rock, especially including Fe-rich. The rift-related intermediate and silicic rocks are invariably richer in K and other incompatible elements (e.g., Zr, Y, Nb, Ba) than the Miocene andesites. In the Mt. Hood area, volcanism has returned to its restricted Miocene pattern following Pliocene-early Quaternary rifting, but farther south along the rift the rift type pattern is increasingly prevalent with increasing extension.

The Cascade mantle wedge or lithosphere must include both subduction- and rift-related domains because the chemical character of voluminous MORB-like mafic lavas erupted during the early stages of rifting does not display subduction-related signatures (Conrey et al., 1997). In
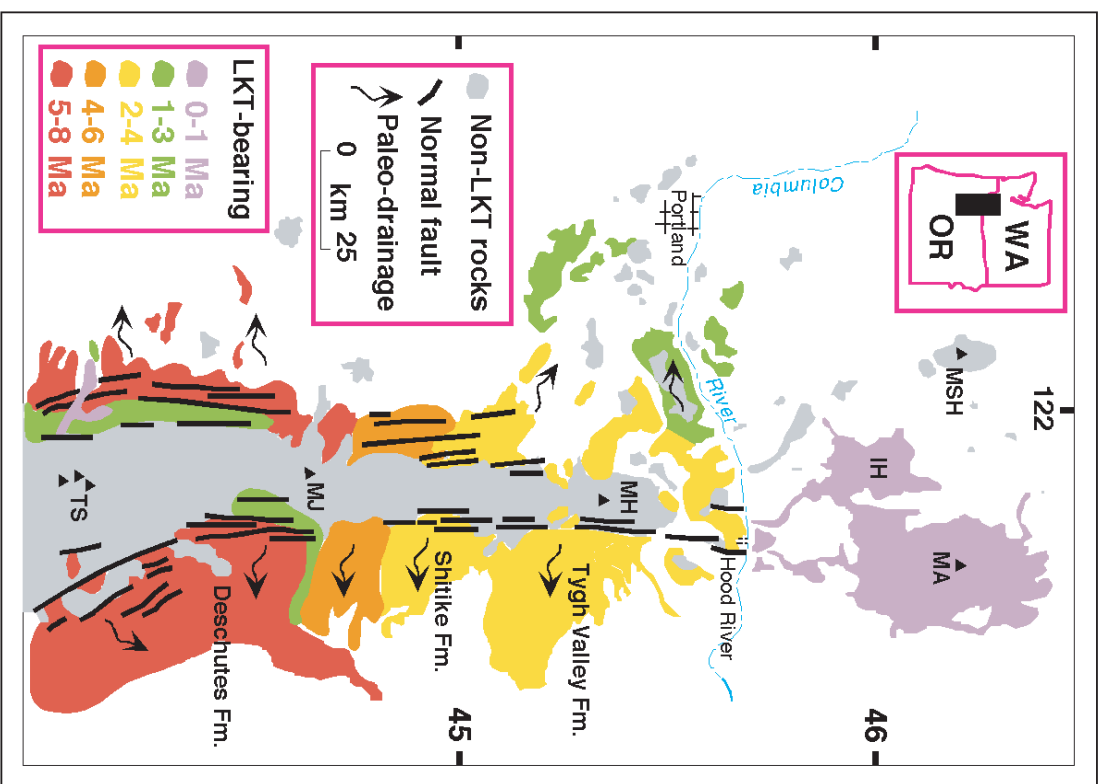
Figure 2. Distribution of low-K tholeiite-bearing, chiefly ridgecapping formations along the intra-arc rift in northern OR and southern WA. Formations containing LKT also contain abundant mafic lavas and a variety of intermediate rocks, including many with high Fe/Mg, especially on the southern end of the rift. Northward propagation of LKT volcanism is evident - with a westward excursion toward the Portland Basin and a hiatus at the Columbia River. Note the persistence of LKT volcanism at Foley Ridge on the southern end of the rift into the early Brunhes.
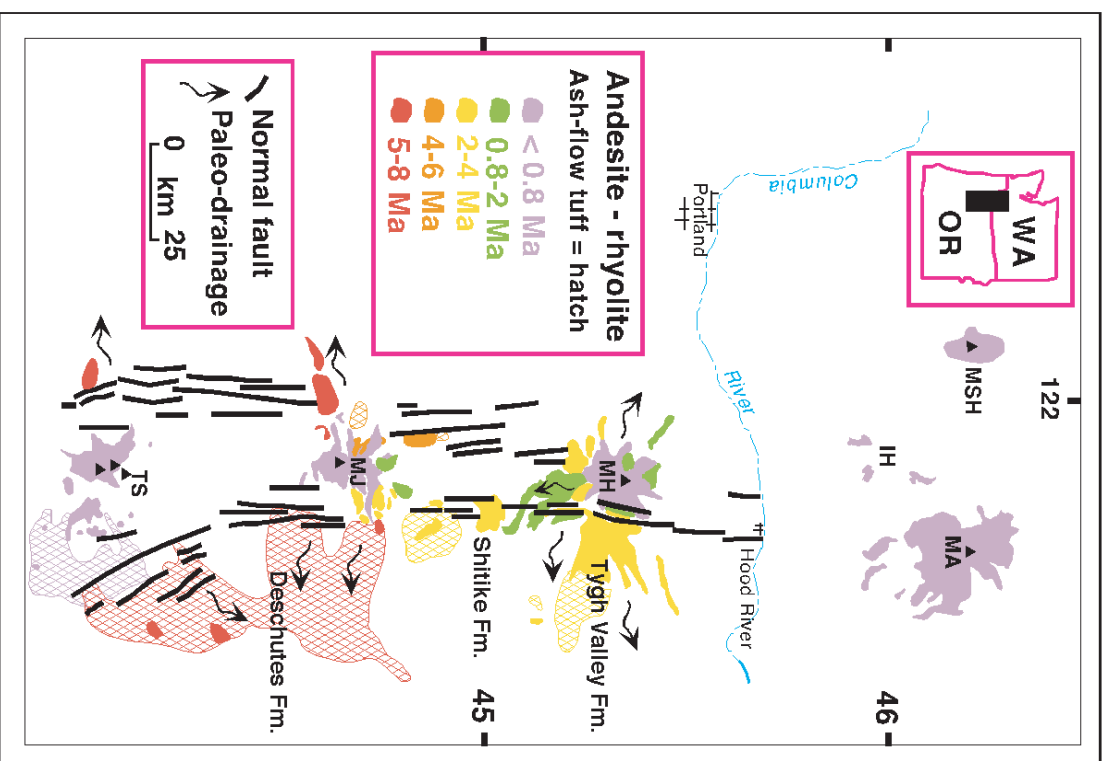
Figure 3. Distribution of intermediate and silicic rocks in the northern OR and southern WA Cascade Range. Brunhes age centers are regularly spaced approx. 70 km apart. Mt. Hood and Mt. Jefferson have been foci of intermediate-silicic volcanism at least since the late Miocene. Three Sisters-Bend Highland may have similar longevity but more extension and eruption on the southern end of the rift has buried the intervening age deposits. Note that large scale Brunhes age silicic volcanism occurs only along the southern rift segment where extension still persists.

contrast, lesser volumes of mafic lavas erupted during Brunhes time in the latter stages of rifting comprise a diverse assemblage of both subduction- and rift-related rocks, the latter similar to within-plate basalts (Leeman et al., 1990; Conrey et al., 1997; Bacon et al., 1997).

Persistence and spacing of stratocones

Compilation of new map and age data indicate that the present stratocones in north-central Oregon mark the loci of long-lived centers of intermediate and silicic volcanism (Fig. 3). The consistent 60-70 km spacing between stratocones suggests some fundamental control by processes either in the mantle wedge or the arc lithosphere or both. The geologic relations suggest the ultimate longevity of these centers is on the order of 8 m.y.

The Mt. Hood center may extend back as old as ~8 Ma, as plutons of that age are present SW of the modern cone, and equivalent age lavas and volcaniclastics on the east side of the volcano (the Dalles Fm.) can be traced back up eastward paleodrainages toward the modern cone (not shown on Fig. 3; Taylor, 1990; Sherrod and Scott, 1995 and references therein). The Tygh Valley Fm. contains most of the Pliocene record of intermediate and silicic volcanism from the Mt. Hood center, along with ridges to the SW and SE of the modern cone (Fig. 4) that are capped by K-rich Pliocene andesite (Wise, 1969; Sherrod and Scott, 1995; R.M. Conrey, unpub. data). During Matuyama time, andesite was erupted coincident with the modern cone (Sandy Glacier volcano) and andesite flowed south from the site of Mt. Hood southward along an ancestral White River (andesite of Wapinitia Pass - see below).

The Mt. Jefferson center appears to be similarly long-lived, as the eastside record of silicic ash-flow volcanism in the 5-8 Ma Deschutes Fm. points to a source near the modern cone (Fig. 3). Abundant silicic volcanism from 4-6 Ma occurred immediately to the NW, and a Gauss age center to the NE, of Mt. Jefferson. The Shitike Fm. does not contain an extensive record of silicic and intermediate volcanism, presumably due to its position between Mts. Hood and Jefferson.

The Three Sisters/Bend Highland center is the likely source for much of the late Miocene ash-flow volcanism in the southern Deschutes basin, thus suggesting a long-lived center in that location as well (Fig. 3). But the intervening record from ~2-5 Ma is buried and thus cannot be directly evaluated. Two geothermal coreholes in the vicinity of the Three Sisters encountered abundant intermediate and silicic rocks, likely of Matuyama age, at depth (500-1000 m; Conrey et al., 2000), consistent with the interpretation that this area was similarly a long-lived intermediate center.

Along arc changes in the character of the rift

The decline in extension northward along the arc is associated with systematic changes in the character and style of volcanism. The southern graben-in-graben is probably still under extension, which may reach northward into the graben along the Clackamas River. The Mt. Hood area lacks evidence for extension post-~0.9 Ma. The increasing, and apparently active extension southward is accompanied by increases in eruption rate, such that the volumes of Brunhes age volcanic rocks increase southward and so do the volumes of the older rift-related sequences (e.g., the Deschutes Fm. is far more voluminous than the Tygh Valley). Brunhes age volcanism picks up ~1/2 way between Mts. Hood and Jefferson (Fig. 5), and forms a continuous and increasingly thicker plateau southward to the Three Sisters (Fig. 10).

The more active Brunhes volcanism south of ~lat 45°N is expressed by dozens of mafic shield volcanoes and cinder cone fields between the major stratocone centers (Fig. 15). Over a longer time span, this volcanism has produced what has been termed the High Cascade "mafic platform" (Taylor, 1981). One of the purposes of this trip is to examine the distribution of these mafic shields and cinder cone fields, and to discuss the potential relationships between this mafic volcanism and the persistent stratocone centers.

The lower eruption rates on the north end of the graben result in very complex geology that demands a great deal of sampling and dating because the older rocks are not buried. This fact is best illustrated by comparing the Mt. Hood area with the Three Sisters (Fig. 3). The higher eruption rates around the latter have buried the record of Pliocene and early Quaternary volcanism.

Another change evident along arc is the decline of large-scale ash-flow volcanism northward. This is expressed in the older record east of the graben, where the Deschutes Fm. contains ~100 ignimbrites, whereas the Tygh Valley Fm. has but a handful. And during Brunhes time, large-scale ash-flow volcanism persists only in the southernmost portion of the graben, in the vicinity of the Bend Highland (Figs 3 and 17). In addition, mafic to intermediate rocks with high Fe/Mg ratios also increase in abundance southward, and Fe-, Ti-, and V-rich basalt occurs only along the southern rift segment (see below).

Main themes of this trip

This trip provides an overview of the Cascade Range between Mt. Hood and Bend, OR. The three stratocone centers of northern Oregon, and their systematic along arc spacing, is one theme of the trip. Another is the change in the character of the arc south from Mt. Hood, as increasing extension is associated with an increasing volume of mafic lava between stratocones. The presence of dozens of short-lived mafic shield volcanoes invites comparison with the long-lived stratocones. Along arc changes in the volume and extent of rift-related pyroclastic volcanism form a final theme for the trip. A one day trip cannot focus on lithology or compositional detail, but instead emphasis is placed on fundamental geologic features and relations including paleodrainage and structure.

Outline of the guide

This field guide was prepared for the State of the Arc conference held at Timberline Lodge on August 17-21, 2003. The one-day guide covers the geology visible from the main roads between Mt. Hood and Bend, OR. The majority of stops are viewpoints where large portions of the Cascade arc can be seen and their geology conveniently summarized. Reference is made to existing field guides which provide for more detailed examination of lithology and volcanology. Short synopses are provided of the geology encountered for each of the 10 legs of the route. Roadlog mileages are included for directions and, in some cases, locations of particularly interesting and/or analyzed outcrops. Analytical data for all samples referred to in text (sample numbers in parentheses) can be found in the Appendix.

Roadlog and field trip guide

The trip begins at Timberline Lodge, with **Stop 1** at a large roadside quarry (~2.4 miles below the lodge) in inclusion-bearing Mt. Hood andesite on the Timberline Road. Carefully pull off road to left.

Stop 1. Overview of the "sleepy" arc south of Mt. Hood

This stop provides a vantage of the geology south of Mt. Hood, where only rare eruptions have occurred during Brunhes time (Fig. 5), thus the term "sleepy". The visible geographic features are all underlain by older rocks (Fig. 4; thumbnail descriptions provided below). The width of the intra-arc graben between Mts. Hood and Jefferson, as well as its termination at the latitude of Mt. Hood (Fig. 2), can be gauged from here. Mt. Jefferson on the far skyline is ~70 km away, illustrating the typical spacing between stratocones.

The following descriptions are derived from the work of Wise (1969), Keith and others (1985), Sherrod and Scott (1995), Conrey and others (1996), and Gray and others (1996), as well as unpublished analyses by R. M. Conrey.

Bonney Butte: a fault block at the northern termination of the central graben segment. The block appears to be tilted (ramped) a few degrees southward. Faulting occurred ~ 2 Ma: Grasshopper Point, the next fault block east of Bonney Butte, is capped by 2.2 Ma lavas that flowed eastward, whereas Bonney Butte is capped on its northern end by tilted 1.7 Ma andesite that flowed southward. The change in paleodrainage is ascribed to the development of N-S fault scarps.

Barlow Ridge: underlain by altered Miocene andesite capped by fresher, more potassic Pliocene andesite.

Frog Lake Buttes: a large R-polarity dome complex likely of Matuyama age, but undated.

Unnamed ridge: probably a downdropped block of Pliocene lava as it includes both basalt and K-rich andesite, but is undated.
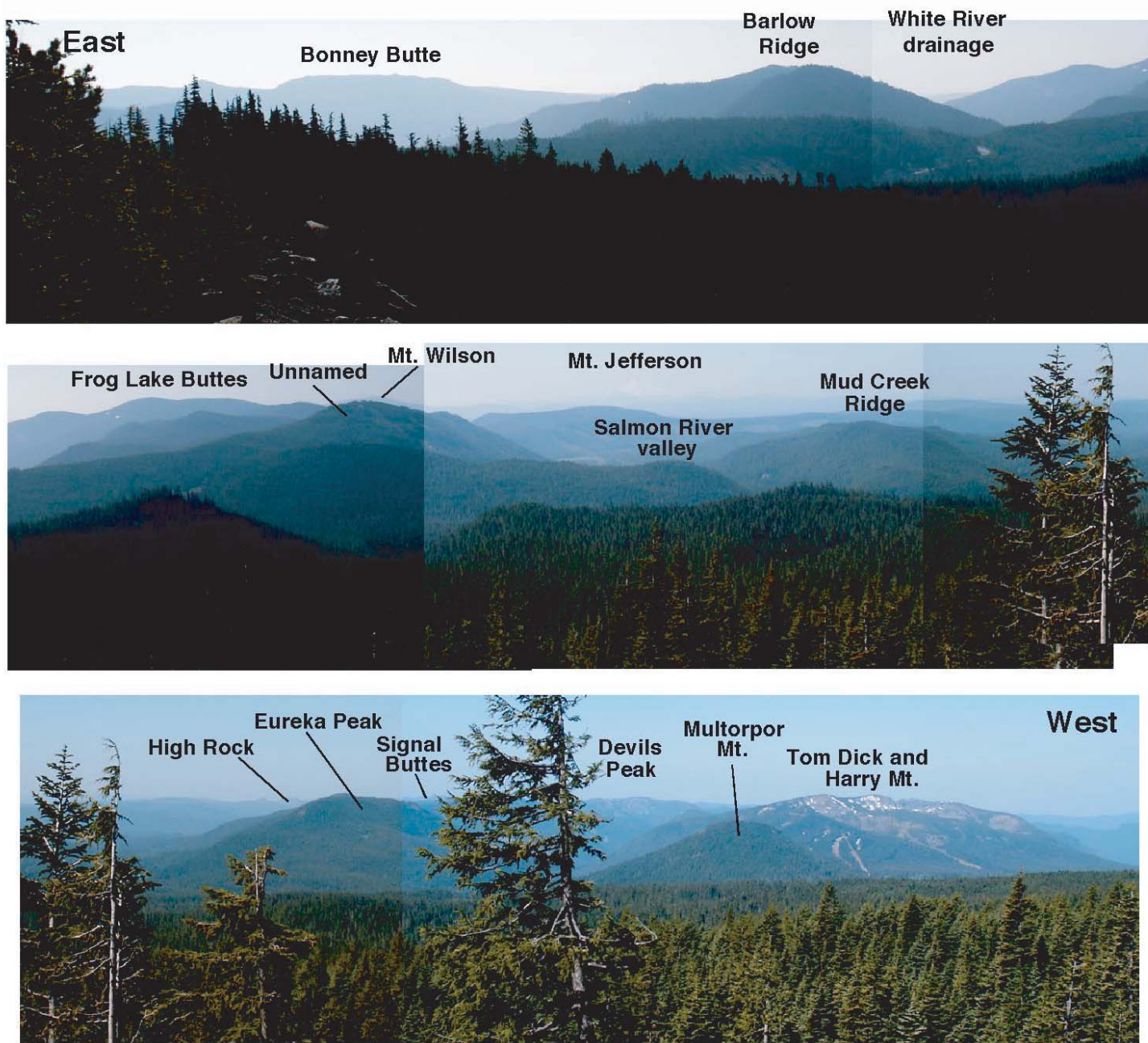
Figure 4. South-facing panorama from the Timberline Road quarry. The visible terrain is chiefly underlain by rocks >0.8 Ma, thus we apply the moniker "sleepy" to this portion of the arc. Brunhes age rocks reappear in abundance approximately half way between Mts. Hood and Jefferson. The long distance (~70 km) between stratocones is evident from this vantage. The termination of the intra-arc graben segment just south of Mt. Hood is also evident from here. The graben spans from west of Signal Buttes on the west to Bonney Butte and the upper White River drainage south to east of Mt. Wilson on the east between Mts. Hood and Jefferson. In contrast, just south of Mt. Hood the graben-bounding faults die away and the graben is constricted between older (mid-Miocene) rocks underlying Devils Peak, Multorpor, and Tom Dick and Harry Mts (the latter two capped with K-rich, likely Pliocene andesite) and Barlow and the unnamed ridge east of the Salmon River (again both capped with K-rich, likely Pliocene andesite). Mud Creek Ridge may be underlain by a tongue of Matuyama age andesite intracanyon to the Salmon River valley, but dates are lacking.
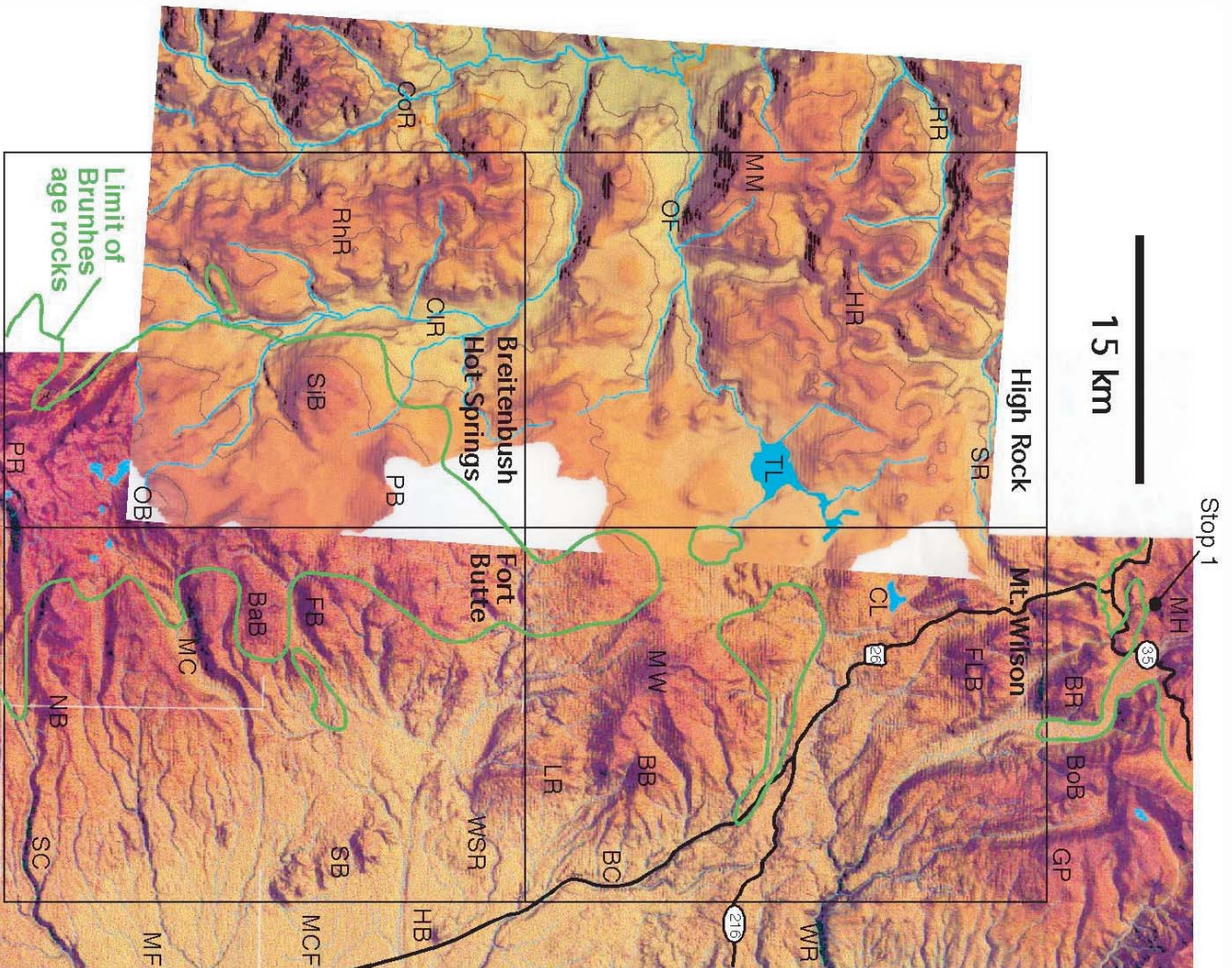
Figure 5. 30 m DEM image of the north-central Oregon Cascade Range (courtesy of Karl Wozniak). Geographic features indicated are: BaB = Badger Butte; BoB = Bonney Butte; BR = Barlow Ridge; CL = Clear Lake; CIR = Clackamas River; CoR = Collowash River; FB = Fort Butte; FLB = Frog Lake Buttes; GP = Grasshopper Point; HB = Hehe Butte; HR = High Rock; LR = Long Ridge; MC = Mill Creek; MCF = Mill Creek Flat; MF = Miller Flat; MH = Mt. Hood; MM = Mt. Mitchell; MW = Mt. Wilson; NB = North Butte; OB = Olallie Butte; OF = Oak Grove Fork of the Clackamas River; PB = Pinhead Buttes; PR = Park Ridge; RhR = Rhododendron Ridge; RR = Roaring River; SB = Sidwalter Buttes; SC = Shitike Creek; SiB = Sisi Butte; SR = Salmon River; TL = Timothy Lake; WR = White River; WSR = Warm Springs River. Rectangular pattern delineates boundaries of the four labeled 15 minute quadrangles. Outer limits of Brunhes age (N polarity; <0.8 Ma) rocks are shown by green lines.

Mud Creek Ridge: either a Matuyama age intracanyon remnant or possibly a downdropped block of Pliocene lava.

Eureka Peak: underlain by Pliocene mafic lava, including basalt that has within-plate chemistry. K-Ar ages suggest the section is 4.2 - 2.9 Ma.

Devils Peak: Underlain by middle Miocene andesite, with a thin cap of Pliocene mafic lava emplaced along a NW-flowing drainage.

Multorpor Mountain: Underlain by middle Miocene andesite intruded by the ~8 Ma Laurel Hill pluton, overlain by a thin cap of K-rich Pliocene andesite.

Tom Dick and Harry Mountain: Similar to Multorpor Mtn with middle Miocene andesite intruded by the Laurel Hill pluton, but the Pliocene capping section is thicker and includes a basal mafic unit similar to that found on Eureka Peak, overlain by K-rich andesite.

Mt. Wilson (distant skyline): a R-polarized basaltic andesite shield, likely Matuyama age, banked up against a small silicic dome complex of Gauss normal age at Beaver Butte.

High Rock (distant skyline): basaltic andesite plug, the remnant of a Pliocene mafic shield volcano.

Signal Buttes (distant skyline): also a small mafic plug, surrounded by Pliocene mafic lava, dated at 2.9 Ma.

0.0   Mileage log begins at junction of Hwy 26 and Timberline Road - head E (left) on Hwy 26.

Leg 1 synopsis: Mt. Hood to Mill Creek canyon

The route quickly drops off the Brunhes apron of Mt. Hood lava and enters the "sleepy" part of the arc along the upper Salmon River valley. There appears to be some structural foundering in a narrow zone here because Pliocene rocks are found downdropped on both sides of the valley. Mud Creek Ridge (west of the road) may be part of a Matuyama intracanyon tongue (or part of the downdropped Pliocene block). The road climbs out of the Salmon drainage onto R-polarized 1.3 ma andesites; mapping suggests these were emplaced along south-flowing drainages. Near the end of the long SE-trending tongue of this andesite, Brunhes age lava derived from a vent west of the road is encountered. The remainder of the route is entirely in Pliocene rocks, and the escarpment east of the highway along Beaver Creek appears to be the southern extension of the fault zone coming south from Bonney Butte that cuts these rocks. The forest ends after crossing the Warm Springs River and the road traverses Mill Creek Flat. The flat is underlain by Pliocene basalt with interbedded and overlying fluvial sediment. Hehe Butte and the Sidwalter Buttes west of the highway are Pliocene rhyolite domes. East of the highway the high ground is underlain by much older rhyolite domes and deposits of the John Day Formation (~20-40 Ma) in the Mutton Mountains, a major anticline.

1.9   Junction with Hwy 35 - keep left on Hwy 26 toward Madras and Bend.
2.1   Stay right on Hwy 26.
4.5   Gas station (CJ's)
5.0   Roadcut on left in within-plate-like basalt with Ba/Nb = 10 (RCS5-45). Similar basalt across the White River ~2 miles to the NW is dated at 4.21 ± 0.12 Ma (K-Ar; Conrey et al., 1996).
5.2   Roadcut on left at corner in andesite (RC98-2) likely of Pliocene age (map unit Ttla1 of Sherrod and Scott, 1995).
5.6   Just past Ghost Creek is an outcrop of more typical calc-alkaline basalt (RC93-MW10), which here underlies the dacite of Frog Lake Buttes.
6.0   Roadcut in dacite (RC98-1) mapped as the andesite of Wapinitia Pass by Sherrod and Scott (1995). May be a Pliocene dacite and not early Pleistocene as mapped.
6.7   Wapinitia Pass
7.4   Roadcut on right in andesite (RC98-3) mapped as part of the Frog Lake Buttes dacite by Sherrod and Scott (1995).
7.9   Blue Box Pass
8.3   Roadcut on left in andesite of Wapinitia Pass (RC98-5).
9.0   Clear Lake turnoff
10.8   Skyline Road junction. **Recommended side trip to Clear Lake Butte lookout.** An overview of this portion of the Cascades may be had by turning right onto the Skyline Rd (USFS Road 42). Proceed ~1.7 miles along the paved road and turn right onto a gravel road that climbs the east side of Clear Lake Butte. Drive as far as you can and walk the remaining distance (~0.3 mi) to the summit and climb the lookout (ask permission). The view includes the fault scarps of Bonney Butte and Grasshopper Point to the NE, and several N-trending scarps to the west of the lookout and

north of Timothy Lake. Clear Lake Butte is a small evolved basaltic andesite shield volcano (RC99-79) of reversed paleomagnetic polarity, and thus older than ~0.8 Ma. The first corner on the Skyline Rd. ~0.25 mi from the highway has a roadcut in the andesite of Wapinitia Pass (RC98-8) compositionally similar to RC98-5 at mileage 8.3. This similarity is some of the evidence which suggests that paleodrainage during Wapinitia Pass time flowed from north to south.

12.5 Old quarry on left in andesite of Wapinitia Pass (RCS5-44), here dated by K-Ar at 1.37 ± 0.04 Ma (Gray et al., 1996).

12.6 Junction with USFS Rd 43.

14.4 Prominent roadcut on right is still in andesite of Wapinitia Pass (RC98-211).

15.0 Boundary of Warm Springs Indian Reservation

15.6 Junction of Hwy 26 with Hwy 216 - stay on Hwy 26.

18.5 Roadcuts along here are in normally polarized basaltic andesite (RC93-MW23) from North Mt. Wilson, a small shield volcano ~5 miles west of the highway (Sherrod and Scott, 1995). The youthful North Wilson vent is one of the few in this "sleepy" part of the arc that has been active during Brunhes time.

21.9 Quarry on right in normally polarized, likely Gauss age, dacite (RC93-MW20) mapped as andesite of Rocky Point (Sherrod and Scott, 1995). Rocky Point is a vent complex ~4 miles SW of the quarry.

27.2 Prominent roadcut with two mafic lavas separated by a reddened soil horizon. The lower flow comprises several flow units of low-K tholeiitic basalt (RC93-38). This flow underlies a large bench termed "The Island" that extends SE from here for ~10 miles. The upper flow is a distal basaltic andesite (RC93-39) from the faulted Long Ridge shield volcano ~5 miles west of the highway.

27.7 Fluvial sediment including conglomerate overlies the mafic lavas exposed at mileage 27.2, and are a significant part of the informally named Pliocene Shitike Formation on the north end of the Warm Springs Indian Reservation.

29.0 Simnasho and Kahneeta Hot Springs (largest in Oregon) turnoff

29.9 Cross Warm Springs River. The low-K basalt noted at mileage 27.2 is exposed in roadcuts on both sides of the crossing.

30.5 Roadcuts in fluvial conglomerate and sandstone are common for the next mile. Typically the sediments are preserved as mounds or ridges on top of the sheet-like basalts that underlie Mill Creek Flat.

33.5 Junction with Sidwalter Buttes Road (B160).

33.7 Exposures of basalt which underlies Mill Creek Flat are common for the next mile or so.

35.1 Slight rise over a ridge of exposed conglomerate

35.8 **Stop 2** at junction with Mill Creek Road. Pull off road to right.

Stop 2. Overview of geology on the Warm Springs Indian Reservation

This stop provides a vantage point from which to view the two northern Oregon stratocones, the longevity of the Mt. Jefferson system, as well as overview the informally named Pliocene Shitike Fm and the surrounding geology (Fig. 6). The northern limit of continuous Brunhes age mafic cover is just south of Mt. Wilson (Fig. 5). The structural segmentation of the graben may in part be seen here as well; major faulting cannot be present where Gauss age Lionshead rocks are so close to the Cascade crest. To the east are the anticlinal Mutton Mountains and several domes of the John Day Fm (~20-40 Ma).

A comparison of the Mt. Hood and Mt. Jefferson stratocones

The view from here invites a comparison of the northern Oregon stratovolcanoes. Mt. Hood is the highest summit in Oregon, and the cone has a ~3X larger volume than that of Mt. Jefferson, the second highest summit (Sherrod and Smith, 1990). Mt. Hood has been much more active during the past 20 ka (the age of the youngest Jefferson eruptions; M.A. Lanphere, unpub. data), but that activity is not the primary reason for the volume difference. The reason lies with the style of eruptive activity at the Mt. Jefferson center, which is actually a widespread intermediate and silicic dome and lava field with a small stratocone constructed on its southern perimeter (Conrey, 1991). So at Mt. Jefferson, magma is spread out by eruption from a broad vent field. In contrast, the near-summit region of Mt. Hood has served as the central conduit for a large proportion of the Brunhes-age volcanism in northernmost Oregon. This focusing has resulted in growth of a large cone. Similar focusing is responsible for the growth of large cones in Washington, e.g., Mt. Rainier. The difference in style is probably related to the degree of extension, with little or none at Mt. Hood, and slight extension at Mt. Jefferson. Modest

South — Green Ridge, Twin Buttes, Bald Peter, Shitike Butte, Lionshead, Mt. Jefferson, North Butte

Park Ridge, Unnamed, Lookout Butte, Mill Creek canyon, Olallie Butte, Sawmill Butte, Badger Butte

Fort Butte, Sidwalter, Buttes

North — Long Ridge, Mt. Wilson, Beaver Butte, Hehe Butte, Mt. Hood
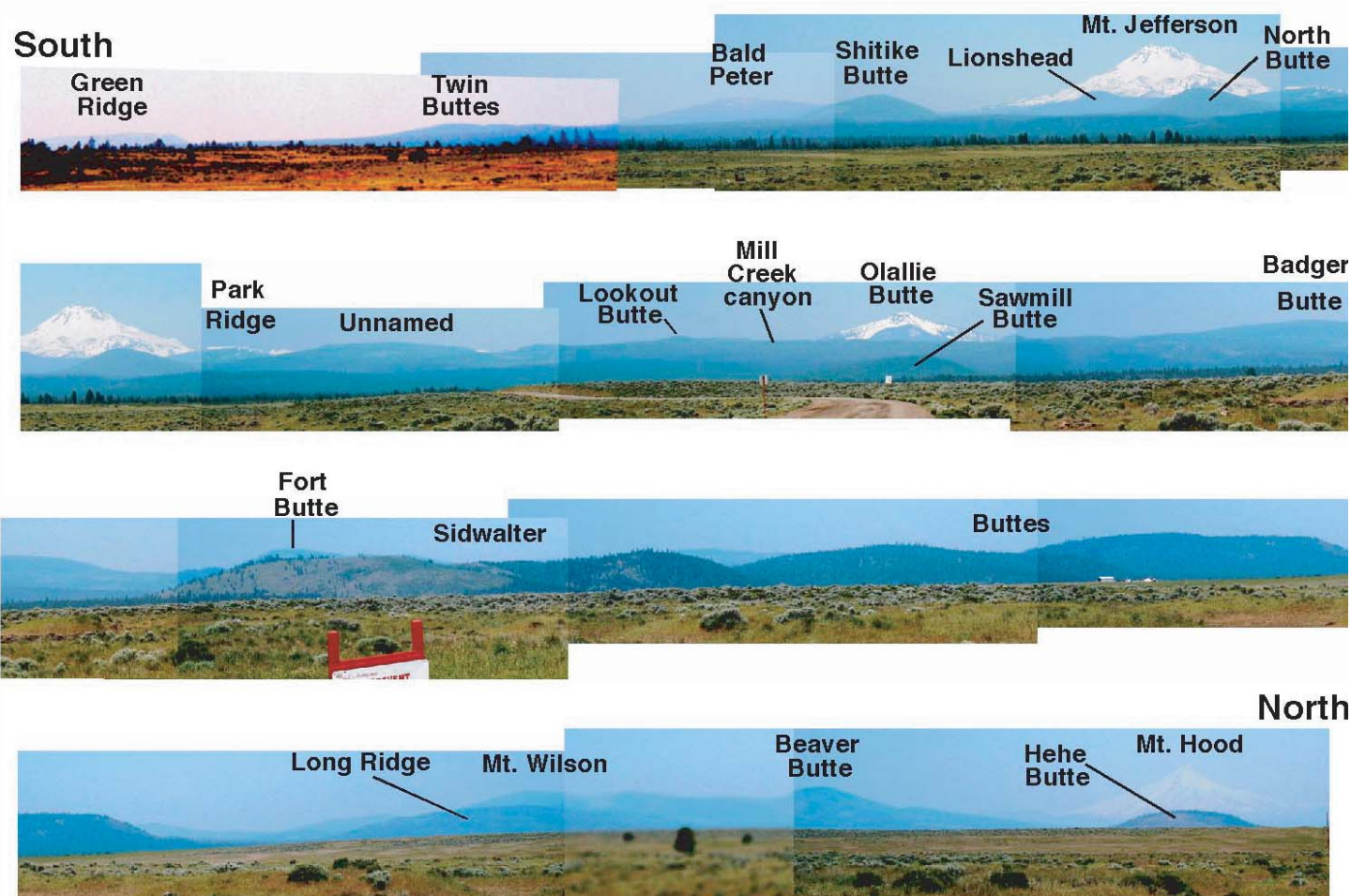
Figure 6. Panorama looking west from Mill Creek Flat (junction of Hwy 26 with Mill Creek Rd.) Green Ridge marks the eastern boundary of the intra-arc graben south of the latitude of Mt. Jefferson. Termination of that segment of the graben northward is shown by the presence of the Gauss age Bald Peter shield and Lionshead eruptive center (including Shitike, North and unnamed Buttes) considerably west of the strike extension of the Green Ridge fault zone. In addition, the relatively unfaulted ~4 Ma basalts underlying Metolius Bench and Miller and Mill Creek Flats can be traced to beneath the Lionshead center at Shitike Butte. Long Ridge is a fault block that marks the eastern boundary of the intra-arc graben at this latitude. Faults on strike with Long Ridge extend to south of Mill Creek, where they lose expression. Graben-bounding faults north of Long Ridge step eastward of Beaver Butte and extend northwards past Bonney Butte (Figs. 4 and 5). Hehe, Sawmill, and the Sidwalter Buttes are all rhyolite domes, except for the southernmost Sidwalter Butte which is mostly a basalt vent. The spatial near-coincidence of the Brunhes-Matuyama age Mt. Jefferson and the Gauss age Lionshead eruptive center is evident from this vantage and argues for the longevity of that stratocone center.

extension is consistent with the onset of Brunhes age mafic volcanism between Mts. Hood and Jefferson, as well as with abundant Brunhes age mafic rocks south of Mt. Jefferson (Figs. 5 and 10). The compositional range erupted at Mt. Jefferson (Conrey et al., 2001) is much wider (50-72 wt% SiO_2) than that found at Mt. Hood (~55-65 wt % SiO_2), also consistent with more extension at the former that allows diverse magmas to percolate to the surface.

Persistence of the Mt. Jefferson center

This is a good vantage point to see evidence for the longevity of the Mt. Jefferson center. Several rhyodacite domes and flows are visible in the foreground before the mountain, including Shitike Butte, Lionshead, North Butte, and an unnamed butte right of Park Ridge. All of these rhyodacites are similar in composition and stratigraphic position (Yogodzinski, 1986; R.M. Conrey, unpub.). One of the Lionshead lavas has been dated at 2.27 ± 0.05 (Ar-Ar; Smith, 1986), thus the informally named "Lionshead eruptive center", which includes all of the above named rhyodacites and a section of underlying andesite, is chiefly of Gauss age (Yogodzinski, 1986). The close spatial coincidence with the Brunhes-Matuyama age Mt. Jefferson center suggests that the center was active during Gauss time as well. There is a slight but consistent difference in the composition and mineralogy of the Lionshead rocks compared to the younger rocks: e.g., the former have higher Zr concentrations and only traces of the amphibole phenocrysts that are ubiquitous in the younger rocks.

Geology of the Fort Butte 15' quadrangle

The Fort Butte, Oregon 15 minute quadrangle, on the western margin of the Warm Springs Indian Reservation, is underlain by volcanic rocks derived from the Cascade Range. The southeast corner of the area has poor exposures of ~5 Ma Deschutes Fm. tuffs and a likely age-equivalent dome, Twin Buttes. A newly recognized package of volcanic and sedimentary rocks, here termed the Shitike Formation, overlies the Deschutes rocks. Shitike (sshhh-dike) is an Indian place name that refers to the area around Shitike Creek. The Shitike Fm. consists of a wide variety of lava flows and domes, several pumiceous tuffs, and sedimentary rocks, mostly stream-deposited. The Shitike Fm. was derived from volcanoes mostly on the west side of the quadrangle; the volcanic and sedimentary materials flowed down eastward paleodrainages. The youngest of these rocks have ages between 2.26 ± 0.13 and 2.65 ± 0.05 Ma (unpub. Ar-Ar ages by R.A. Duncan). A few Shitike Fm. rhyolite domes, such as Sidwalter, Sawmill, and Hehe Buttes, were constructed on the east side of the quadrangle. Sidwalter Butte was emplaced at 3.8 ± 0.1 Ma (M.A. Lanphere, unpub. Ar-Ar age). A thick pile of chiefly basaltic lavas, 4.0 to 3.2 million years old, comprises the lower part of the Shitike Fm. and underlies the Mill Creek and Miller Flat benches. The basalt unconformably overlies the older Deschutes Fm. (Smith, 1986). On the south end of the quadrangle the basalts are overlain successively by sediments, basaltic andesite lavas, and finally by a sequence of andesite and rhyodacite lavas and domes, which comprise the Lionshead eruptive center (see above). The Shitike Fm. is cut by numerous north-trending, down-to-the-west normal faults from south of Mill Creek northward. Offset across this broad, newly named Long Ridge fault zone increases northward to Long Ridge but then steps eastward of Beaver Butte, where it continues north to the latitude of Mt. Hood.

Volcanic rocks younger than the Shitike Fm. occur chiefly in the northwestern portion of the quadrangle and along its southwestern edge. These rocks are mainly basaltic andesite and andesite erupted from numerous small shield volcanoes, but also include local rhyodacite domes and basalt cinder cones and lavas, for example North Pinhead Butte. Several younger volcanoes have been built atop strands of the Long Ridge fault zone. The youngest rocks have not been dated but their youthful appearance testifies to a young age, perhaps only 40 ka. Glacial deposits, including lateral moraines and outwash of two distinct ages, occur along all of the major drainages south of the Warm Springs River.

Other features visible from here and not described above include:

Beaver Butte: a small silicic dome complex likely of Gauss normal age (Sherrod and Scott, 1995).

Long Ridge: a fault block underlain by the remains of a small mafic shield volcano on its southern end, and dacite and rhyodacite on its northern end. Faults cut rocks as young as 2.3 Ma, but do not displace R-polarized, likely Matuyama age rocks that partly bury traces of the fault zone.

Fort Butte: a small andesite shield volcano, likely of Matuyama age.

Badger Butte: a small andesite shield with normal polarity of uncertain age, possibly Brunhes.

Olallie Butte: a young, slightly glaciated basaltic andesite shield volcano (Conrey, 1991), similar in composition to North Sister.

Lookout Butte: a small cinder cone that erupted a basalt lava over one trace of the Long Ridge fault zone. The lava overlies till that is probably ~150 ka.

Bald Peter: faulted and glacially eroded remnant of a reverse polarity basaltic andesite shield (the central plug is well exposed; Hales, 1975), K-Ar age 2.2 ± 0.2 Ma (Armstrong et al., 1975).

Green Ridge: a long N-S fault block that bounds the east side of the southern graben (Fig. 10). The north end of the ridge visible from here is underlain by the dissected remains of a large pyroxene- and hornblende-bearing andesite volcano centered near Castle Rocks (Wendland, 1988). K-Ar dating suggests an age of ~8 Ma (Armstrong et al., 1975). The volcano is overlain unconformably by Deschutes Fm. lava and tuff. Termination of the Green Ridge fault zone northward (Fig. 2) is indicated by the presence of 2-4 Ma rocks (the western part of Metolius bench and the Lionshead eruptive center) close to the central axis of the arc. Some faulting may be present but it cannot be of great magnitude between the north end of Green Ridge and Mill Creek.

Continue south on Hwy 26
36.8 Cross Mill Creek canyon. The stack of low-K tholeiitic basalt (RC GSPP5) exposed in the canyon walls is >200 feet thick. The lowermost flow yielded an Ar-Ar age of 3.72 ± 0.11 Ma (Smith, 1986).

Leg 2 synopsis: Mill Creek canyon to Deschutes River

Mill Creek canyon offers an excellent exposure of the basalt which underlies both Mill Creek and Miller Flats. The road traverses Miller Flat and drops through a thin basalt as it descends the grade down to Warm Springs. Beneath the basalt the highway cuts through the thin northern edge of the 5-8 Ma Deschutes Fm., the older and more voluminous cousin of the Shitike Fm. Two ash-flow tuffs interbedded with sediment are exposed in the grade. The thin Deschutes is underlain by the more monotonous tan beds of the John Day Fm., here believed to be ~20 Ma, and tilted southward. At the Warm Springs junction, the view ahead is of the angular unconformity between the south dipping basalt of Prineville (15.7 Ma; Hooper et al., 1993), and the ~flat-lying Deschutes Fm.

43.5 More low-K basalt (RC GSWS15) is exposed as the road drops over the edge of Miller Flat. Exposures for the next mile are in the thin northern edge of the Deschutes Formation.
43.9 Roadcut in pink rhyodacitic (RC93-36) ash-flow tuff of the Deschutes Fm. The tuff has abundant large pumice < ~25 cm, and is the second one down the grade.
44.7 Roadcuts from here to Warm Springs junction are in pale tuff, lapillistone, and fine-grained volcaniclastic sediment of the John Day Formation. Landsliding is common in these materials, and steeper dips represent landslide blocks.
47.2 Warm Springs/Kahneeta Hot Springs junction. View ahead of prominent angular unconformity between the south-tilted Prineville Basalt and the flat-lying Deschutes Formation.
48.0 The Museum at Warm Springs (highly recommended display of Indian life and culture).
49.1 Deschutes River bridge - reset odometers

Leg 3 synopsis: Deschutes River to Cove Palisades

Overhead after crossing the Deschutes River is the prominent columnar jointed Seekseequa basalt, ~ 6 Ma, a member of the Deschutes Fm. The basalt flowed down the ancestral north-flowing Deschutes River (Fig. 12), and is now tipped slightly southward. The canyon walls expose two flows of Prineville basalt and the underlying John Day Fm. As the road begins to climb away from the river, these older rocks are buried by landslides. At the Pelton Dam turnoff there is a view upslope of the Deschutes Fm. exposed in a cliff. The prominent pale layer is the Chinook tuff, another member of the Deschutes Fm. that flowed down the ancestral Deschutes channel (Fig. 11). After the Pelton Dam turnoff, the roadcuts are in distal sediment dominated Deschutes Fm., overlain by the Fe-rich, 5.3 Ma Tetherow Butte basalt, which again also flowed down the old Deschutes drainage (Figs. 7 and 8). The long flat of Agency Plains on the road to

Madras is underlain by this basalt; close to Madras the road drops down through more of the Deschutes Fm. From Agency Plains the small alkaline basalt shield visible to the SW is the 4.0 Ma Round Butte.

0.0 Deschutes River bridge
0.1 Rainbow Market. A rhyodacitic pyroclastic flow deposit (age probably > 100 ka) derived from Mt. Jefferson is interbedded in a small fluvial terrace ~50 m above modern river level and ~0.2 miles NE of the market (Smith, 1986; 1987; Conrey, 1991). Farther downstream along the Deschutes River a Mt. Jefferson lahar deposit (age believed to be 70-100 ka) is found in terraces ~15 m above river level discontinuously all the way to the river mouth, a river distance of nearly 200 km from its source (O'Connor et al., in press).
0.4 Look up to see vertically and radially columnar-jointed Seekseequa basalt of the Deschutes Formation, which filled and overflowed the ancestral channel of the Deschutes River ~6 Ma (Smith, 1986).
2.5 Pelton Dam turnoff. View upslope is of distal sediment-dominated facies of the Deschutes Formation. The prominent pale layer near the base of the exposure is the Chinook ignimbrite, a major silicic ash-flow tuff derived from sources west of the Deschutes basin that flowed eastward into the basin and then northward along the ancestral Deschutes River channel (Smith, 1986, 1987b; Fig. 11). For a **recommended alternate route** to the next stop turn R and reach Pelton Dam in ~2.8 miles. Prineville basalt and interbedded and overlying Simtustus Formation (Smith, 1986b) are exposed in roadcuts and at the abutment of Pelton Dam (see the field guide of Smith [1991] for a detailed description of these localities). Continue past the dam and cross Willow Creek. Jackson Buttes are opposite the mouth of Willow Creek on the Warm Springs reservation, and the Jackson Buttes tuff is exposed upslope on the north side of the creek. The road climbs away from Willow Creek through the Pelton basalt. Follow the road to a tee with Belmont lane and turn R. After ~1.5 mi turn L onto Mountain View Drive and follow it to the Stop 3 overlook in the Cove Palisades State Park.
4.5 Roadcuts for the next 0.3 mile are in the Deschutes Fm.
4.8 Highway climbs onto Agency Plains through the wildly jointed Agency Plains basalt, one of two flows comprising the basalt of Tetherow Butte (Smith, 1986; Figure 7). These basalts erupted from Tetherow Buttes, a NW-trending chain of cinder cones nearly 50 km south of here, and flowed northward down the ancestral Deschutes River channel 5.3 Ma.

FeTi basalt rich in V in the central Oregon Cascades

The basalt of Tetherow Butte is Fe- and Ti-rich, similar in many respects to differentiated FeTi basalt at mid-ocean ridges (Table 2 in Appendix). FeTi basalt is also rich in V (see Table), and poor in Ni and Cr. The composition of FeTi basalt presumably reflects extensive fractionation of dry magma at shallow pressure where plagioclase and olivine are the principal crystallizing phases. Vanadium is incompatible in a troctolite (plag-oliv) cumulate assemblage so its concentration is enhanced in the residual liquid. V- and Fe-rich basalt in the Cascades is associated with extension and intra-arc rifting, and may be derived from crystal fractionation of dry MORB-like low-K tholeiitic parents, which are common companions of Cascade rifting (e.g., Conrey et al., 1997). The distribution of such basalt along the intra-arc rift is interesting, as it is only found along the southernmost rift segment where the greatest amount of extension occurs. Even though low-K tholeiitic basalt is common all along the rift, it appears that extensive shallow fractionation of basaltic magma occurs only where extension rates are above a certain threshold, ~1 mm/a. More commonly, low-K basaltic magma is trapped at deeper crustal levels and appears to undergo a period of clinopyroxene-dominated fractionation (because V is buffered by a cpx-oliv cumulate assemblage as long as $\dagger O_2$ is not high). Thus most Cascade basalt may have been underplated rather than supplied directly to the surface or to shallow crustal levels.

11.6 The highway drops down off the Agency Plains basalt. Lava, tuff, and sediment of the Deschutes Fm. are exposed in and around Madras (see Smith, 1991).
12.1 Junction of Highways 26 and 97 in Madras - stay on 26.
12.7 Turn right (sign "Cove Palisades") onto the Culver highway.
13.5 Junction with Belmont Lane, an alternative route to the next stop (and to Pelton and Round Butte Dams). Stay straight.
19.9 Turn right toward Cove Palisades State Park (signed) on Gem Lane
20.9 Straight at junction.
21.9 Turn right toward Cove Palisades (signed).
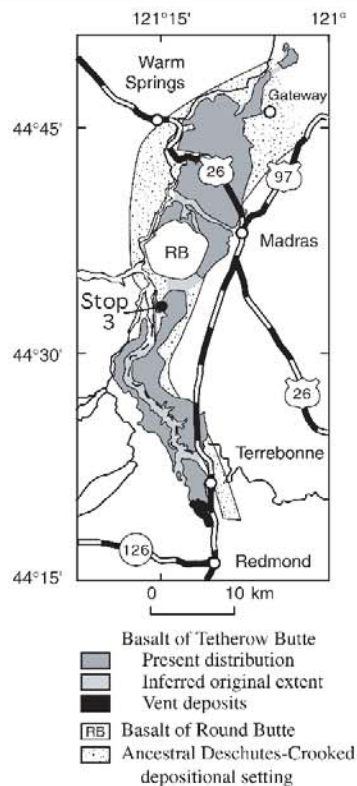
Figure 7. Distribution of the Basalt of Tetherow Butte, an intra-basinally erupted lava that flowed down the ancestral Deschutes River channel at 5.31 ± 0.05 Ma (after Smith, 1986). The composition of this lava is similar in many respects to evolved MORB (Table 1). Round Butte is a small alkaline basalt shield which postdates (3.97 ± 0.05 Ma; Smith, 1986) the Deschutes Formation and the Basalt of Tetherow Butte.
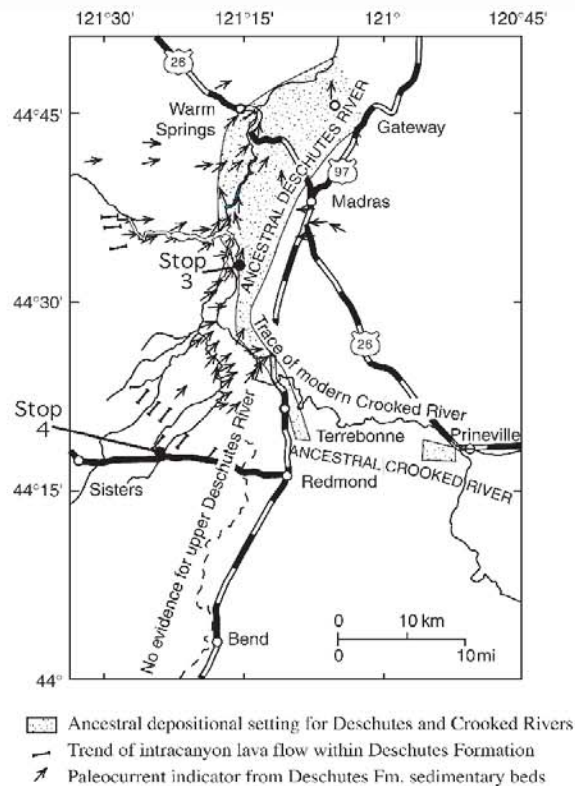
Figure 8. Paleodrainage directions and paths of the ancestral Deschutes and Crooked Rivers ~5 Ma during aggradation of the chiefly Cascade arc-derived Deschutes Formation (after Smith, 1986). Extensive paleosol development east of the ancestral Deschutes channel proves that little material was contributed to the Deschutes Formation from sources other than the Cascades (Smith, 1986).
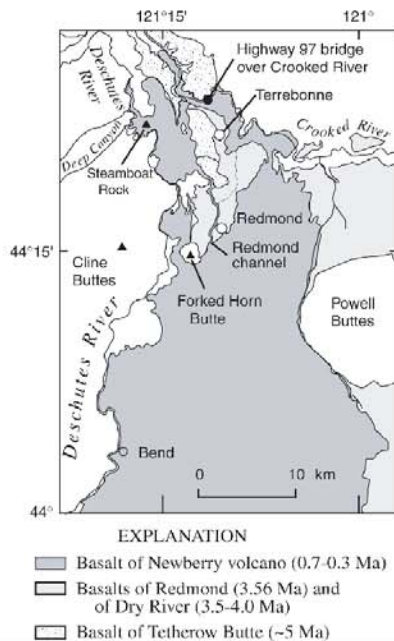
Figure 13. Distribution of the Redmond, Dry River, and Newberry basalts in the Redmond-Bend area. The basalt of Redmond has been dated at 3.56 ± 0.30 Ma (Ar-Ar; Smith, 1986); the Dry River basalt is undated but thought to be of similar age. Brunhes age Newberry basalt entered the canyons of both the Crooked and Deschutes Rivers, gaining access to the latter in part through the narrow Redmond channel. The older basalts are poorly known and reconnaissance analyses indicate diverse lavas are present at least within the Redmond basalt. Known vents for the older lavas are all north and east of Powell Buttes; the Newberry basalts were erupted from cinder cones on the northern flank of the volcano.

22.0 Quarry on right is in the basalt of Tetherow Butte (RCRB-66; Table 1). Down the grade below the basalt are exposures of the distal sediment-dominated facies of the Deschutes Fm. Two ash-flow tuffs are present in this section - the lower silicic white Cove tuff is also present at The Ship (see next stop). Air-fall pumice lapilli from an eruption (70-100 ka) of Mt. Jefferson are exposed above the road just before the switchback at the bottom of the grade (Taylor and Smith, 1987).
23.6 Turn into parking lot (restrooms available).
23.7 Retrace route back up the grade.
25.5 Turn left (signed for viewpoints and Round Butte Dam) past the Tetherow Butte basalt quarry.
26.2 Turn left onto gravel for viewpoint and **Stop 3.**

Stop 3. Overview of central Oregon Cascade geology

This stop provides an overview of much of the east-side geology of the central Oregon Cascades (Fig. 9). The same stop has been featured in several previous field guides (Taylor and Smith, 1987; Smith, 1991; Conrey et al., 2002), and those sources should be consulted for further details. The viewpoint is on Tetherow Butte basalt, and overlooks the Deschutes Fm. exposed in the Cove Palisades State Park at the junction of the Deschutes, Crooked, and Metolius Rivers. A thick, reversely-polarized, 1.3 Ma (Smith, 1986) intracanyon basalt forms benches in the Park, and comprises The Island between the Crooked and Deschutes Rivers.

The Deschutes Formation, A record of intra-arc rifting

The Deschutes Formation is a thick deposit of lava, sediment, and tuff derived from the Cascades during the onset of intra-arc rifting (Taylor, 1981; Smith et al., 1987). It covers much of north-central Oregon east of the graben. The widespread Pelton basalt near the base of the deposit has an Ar-Ar age of 7.42 ± 0.22 Ma (Smith et al., 1987). The top of the formation is ~5 Ma, based on numerous Ar-Ar and K-Ar ages (Armstrong et al., 1975; Smith, 1986). The Deschutes Fm. is the eastside equivalent of a contemporaneous uplifted ridgecapping sequence west of the graben. A prominent volcanic ridge must have lain along the axis of the arc during the emplacement of both formations because the individual lavas and tuffs in the Deschutes Fm. were emplaced in east to northeast-flowing drainages (Figs. 8, 11, 12, and 14), the mirror image of their west-flowing, westside counterparts (Conrey et al., 2002). The Deschutes Fm. is one of the best mapped arc rift-related formations anywhere; literally hundreds of individual flows and tuffs have been traced and the more prominent are illustrated in the accompanying figures (see Introduction; Figs. 11, 12, and 14). The modern Deschutes River follows the boundary between the Tetherow Butte and Canadian Bench basalts.

The Deschutes Fm. records a large pulse of volcanism and sedimentation associated with intra-arc rifting. The deposit was chiefly derived from sources to the west and southwest along the pre-graben Cascade axis. Deposition ended when the graben formed and cut the connection to the source area. Some of the Deschutes Fm. was derived from erosion of high ground to the east, and material from those sources dominates the eastern side of the Deschutes Basin. Here we are just west of the ancestral Deschutes River channel (Fig. 8), so virtually all of the deposit at the Cove Palisades is Cascade in origin. There is a systematic facies change within the Deschutes Fm. which reflects its derivation from the west. Here in the Cove Palisades the formation is predominantly volcaniclastic sediment, with interbedded ash-flow tuff and basalt. Farther west at Green Ridge, ~20 km closer to the source region, the formation becomes lava-dominated.

Age propagation of rifting

This overview provides an along arc view of nearly the entire east flank of the Cascade Range in northern Oregon. Geology similar to that found here along the southernmost graben segment, with an eastside pulse of rift-related volcanism and sedimentation, followed by foundering of the arc axis, is present all along the arc visible from here north, and is recorded in the Shitike and Tygh Valley Formations. The geology is similar but is not coeval; the eastside deposits become progressively younger farther north, and their volumes diminish considerably. The graben structures also young progressively northward; thus the graben resembles a propagating rift (Fig. 2; Conrey and Sherrod, in prep.).
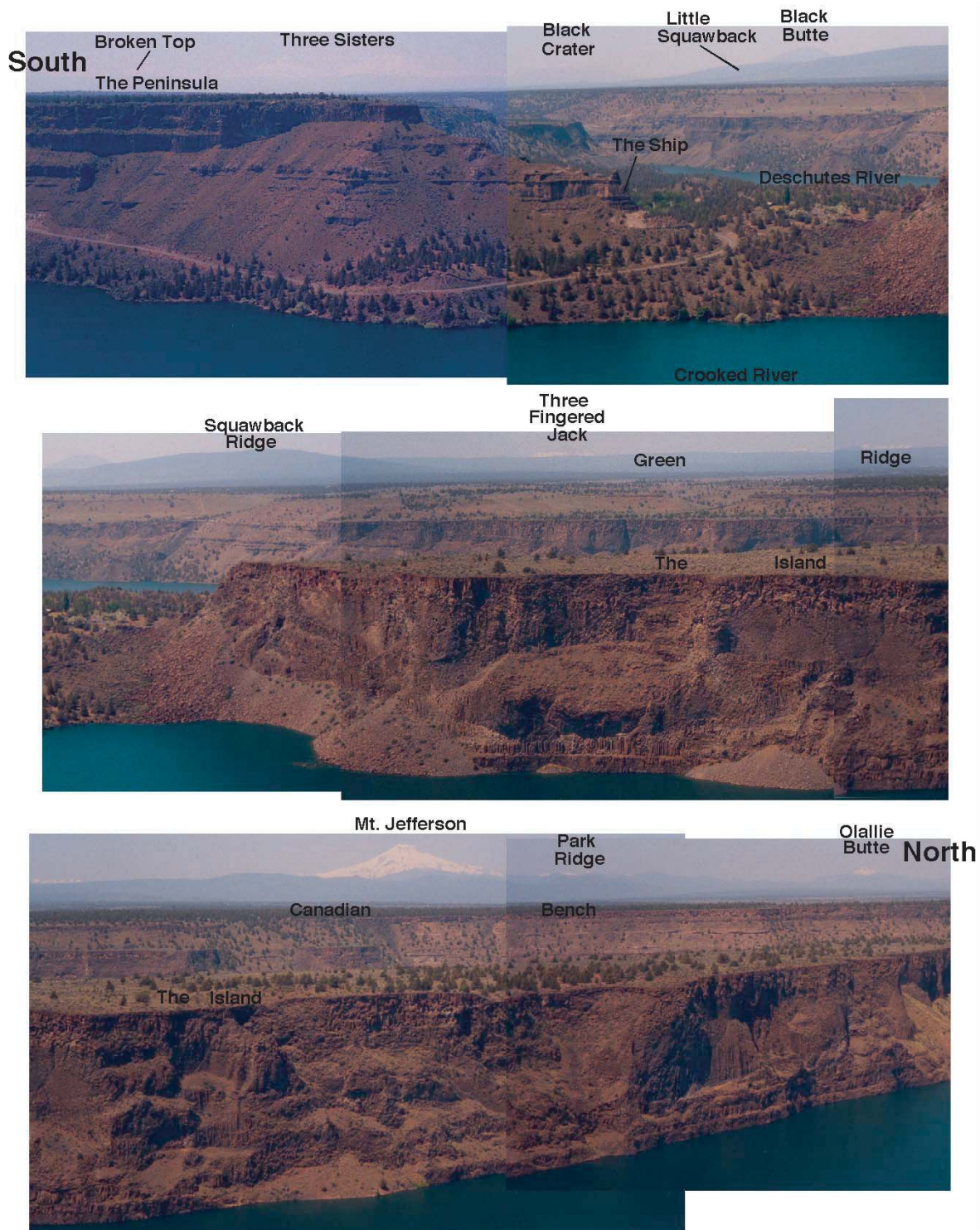
Figure 9. Panorama looking west from above the Cove Palisades State Park. The Peninsula is capped by the basalt of Canadian Bench, overlying the basalt of Tetherow Butte. Note the canyon-filling nature of their lower contact with bedded deposits of the Deschutes Fm. The lower of the two ignimbrites exposed at the The Ship is the Jackson Buttes; the upper is the Cove. The Island is underlain by R-polarity 1.2 Ma intracanyon basalt. The distant Green Ridge fault block bounds the eastern side of the intra-arc graben, and is underlain by a proximal lava-dominated section coeval with the distal sediment-dominated Deschutes Fm. section exposed here.

Persistence of the Mt. Jefferson stratovolcano

Mapping of individual units in the Deschutes Fm. has revealed the trend of ancient paleodrainage (Figs. 8, 11, 12), pointing to source areas in an ancestral Cascades prior to graben formation. The distribution of ash-flow volcanism in the Deschutes Fm. points to two sources for these deposits, one in the Mt. Jefferson region and the other to the SW in the area of the Three Sisters or Bend Highland (Figs. 3, 11, 12, 14). These records are thus consistent with the interpretation that the Mt. Jefferson stratocone marks the locus of a very long-lived silicic and intermediate volcanic center, extending back to ~8 Ma. Similar arguments apply to the Three Sisters/Bend Highland center.

Systematic spacing of stratocones in north-central Oregon

On a clear day the view from this point includes the three stratocones South Sister, Mt. Jefferson, and Mt. Hood. Evident from this view is the nearly equal spacing (60-70 km) between them. Evidence discussed above suggests that each of these centers may have been active for long periods, on the order of 7-8 Ma.

Description of the distant geology, or pertinent geographic features, arranged by azimuth:

10 **Round Butte**: a small alkaline basalt shield volcano that overlies the Deschutes Fm. Ar-Ar age is 3.97 ± 0.05 Ma (Smith, 1986).

350 **Mutton Mountains**

337 **Mt. Hood and high ground to its SE**: the high ground visible to the SE of Mt. Hood is capped chiefly by Pliocene andesite and dacite, the proximal deposits of the Tygh Valley Fm., derived from sources near the modern cone.

330 **Mt. Wilson - Beaver Butte**

315 **Fort Butte**

304 **Olallie Butte**

293 **N end of Green Ridge**

295 **Lionshead and Shitike Butte**

286 **Mt. Jefferson**

272 **South Cinder Peak**: conspicuous summit on the skyline south of Mt. Jefferson is a Holocene(?) cinder cone that fed a small basalt lava which flowed down to the SW of the cone.

290-250 **Green Ridge**: a nearly 30 km long fault escarpment that bounds the eastern margin of the High Cascade graben (Fig. 10). The ridge comprises the proximal correlative of the 5.0-7.5 Ma rocks of the Deschutes Fm. exposed in the Cove Palisades (Taylor, 1981; Smith *et al.* 1987). Much of the formation in this area was emplaced along east-trending drainages leading from Green Ridge (Figs. 8, 11, and 12).

259 **Three Fingered Jack**: a large, glacially dissected basaltic andesite shield volcano (Davie, 1980), believed, on the basis of lava-till field relations and lack of Three Fingered Jack clasts in circa 150 ka Jack Creek age moraines, to be younger than that glaciation, and clearly older than the Wisconsin glaciations (Scott et al., 1996). An age of 100-150 ka is inferred.

247 **Squawback Ridge**: a mildly alkaline Gauss age basaltic andesite shield east of Green Ridge and above the Deschutes Fm. (N polarity; K-Ar age 2.9 ± 0.2; Armstrong et al., 1975; Conrey, 1985).

239 **Black Butte**: reversely polarized basaltic andesite shield volcano at the southern end of Green Ridge; K-Ar age 1.42 ± 0.33 Ma (Hill 1992). Conical form is preserved due to the fact that the summit elevation was below the permanent snowline during glacial epochs as it was far enough to the east.

237 **Little Squawback**: cousin to Squawback Ridge and probably similar in age as it is highly weathered with virtually no outcrop.

229 **Black Crater**: a relatively uneroded and thus late Pleistocene (estimated 50 ka) basaltic andesite shield volcano with several flanking cinder cones. The crater is a shallow cirque.

223-218 **Three Sisters**: see stops 5 and 6.

213 **Broken Top and the Bend Highland**: see stop 6

208 **Mt. Bachelor**: A large basaltic andesite shield volcano at the northern end of a 25 km long, north-trending chain of late Pleistocene mafic vents (Scott and Gardner, 1992).

186 **Cline Buttes**: see stop 6

180 **Newberry Volcano**: The enormously broad mafic Newberry shield can be seen on a clear day.

Figure 10. 30 m DEM image of central Oregon Cascade Range (courtesy of Karl Wozniak). Geographic features indicated are: AB = Awbrey Butte; B = Bend; BB = Black Butte; BC = Belknap Crater; BCH = Mt. Bachelor volcanic chain; BH = Bend Highland; BIC = Black Crater; BP = Bald Peter, BT = Broken Top; CB = Canadian Bench; CIB = Cline Buttes; CM = Cache Mt.; CR = Crooked River; DC = Deep Canyon; DR = Deschutes River; GR = Green Ridge; H = Husband; JB = Juniper Butte; LS = Little Squawback; MB = Metolius Bench; McR = McKenzie River; MJ = Mt. Jefferson; MR = Metolius River; MS = Middle Sister; MW = Mt. Washington; MxB = Maxwell Butte; NS = North Sister; NSR = North Santiam River; NWB = Flank of Newberry volcano; RB = Round Butte; S = Sisters; SB = Squawback Ridge; SM = Scott Mt.; S-NC = Sand Mt.-stitute Point; SS = South Sister; TB = Tetherow Buttes; TC = Tumalo Creek; TCB = Trout Creek Butte; TF = Tumalo Fault; TFJ = Three Fingered Jack; TH = Triangle Hill; TM = Tumalo Mt.; TP = Turpentine Peak. Green lines demarcate the outer limits of High Cascade-derived Brunhes age rocks, exclusive of lavas derived from Newberry volcano.

5 ● Field trip stop

Limit of High Cascade Brunhes age rocks

10 km
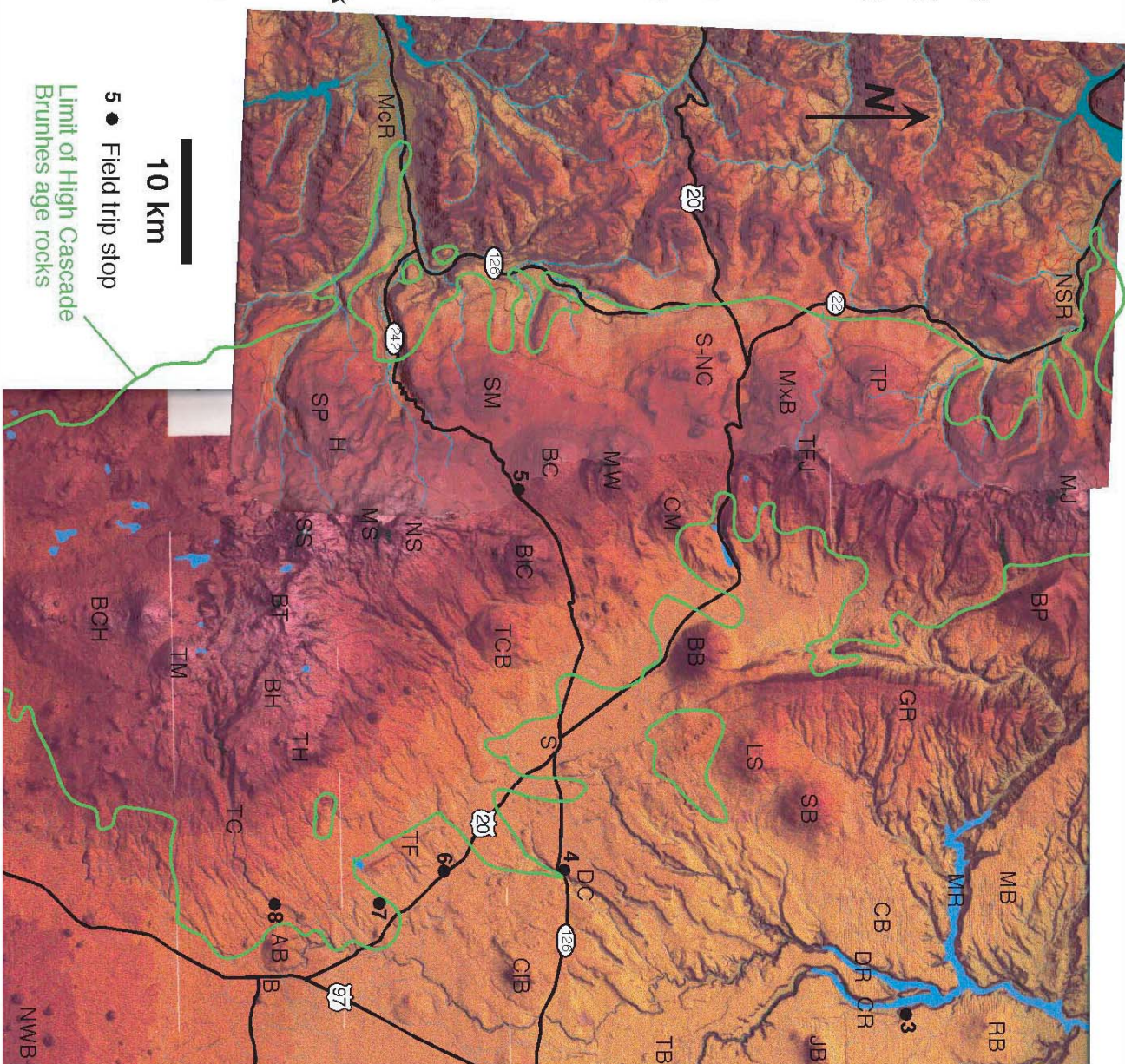
Figure 11. Distribution of seven prominent Dechutes Fm. ignimbrites in the northern Deschutes basin (adapted from Smith, 1986, with minor corrections by R.M. Conrey). Ignimbrites were emplaced along E-flowing drainages west of the ancestral Deschutes River channel, and along that N-trending channel in some cases, as shown by map patterns and confinement to E- or N-trending paleochannels. Ignimbrites were derived from sources to the west in the vicinity of modern Mt. Jefferson as indicated by increases in pumice and lithic fragment size, thickness, and degree of welding westward within each ignimbrite. Relative ages from oldest to youngest are Chinook, Jackson Buttes, Balanced Rocks, Fly Creek, Tenino, Coyote Butte, and Six Creek, respectively. The latter is one of a handful of tuffs high in the Deschutes section which can be traced to the west side of Green Ridge, the intra-arc graben-bounding fault block. Recent Ar-Ar dating of plagioclase yields ages for the Six Creek and Balanced Rocks tuffs of 5.38 ± 0.06 and 5.56 ± 0.06 Ma, respectively (Aubin, 2000). For comparison, Canadian Bench is underlain by 5.43 ± 0.05 Ma basalt (Smith, 1986), at nearly the same stratigraphic level as the Six Creek tuff.
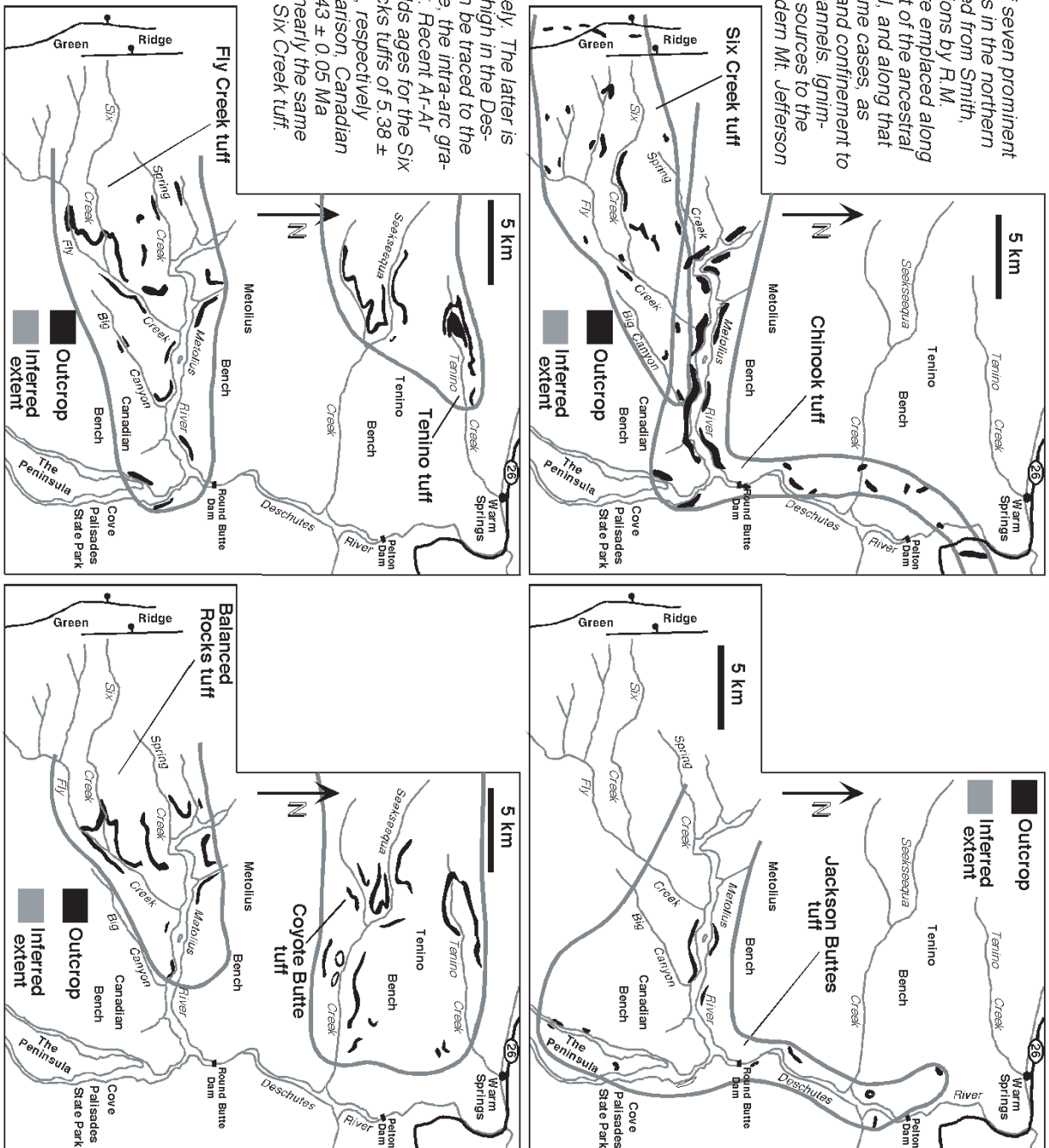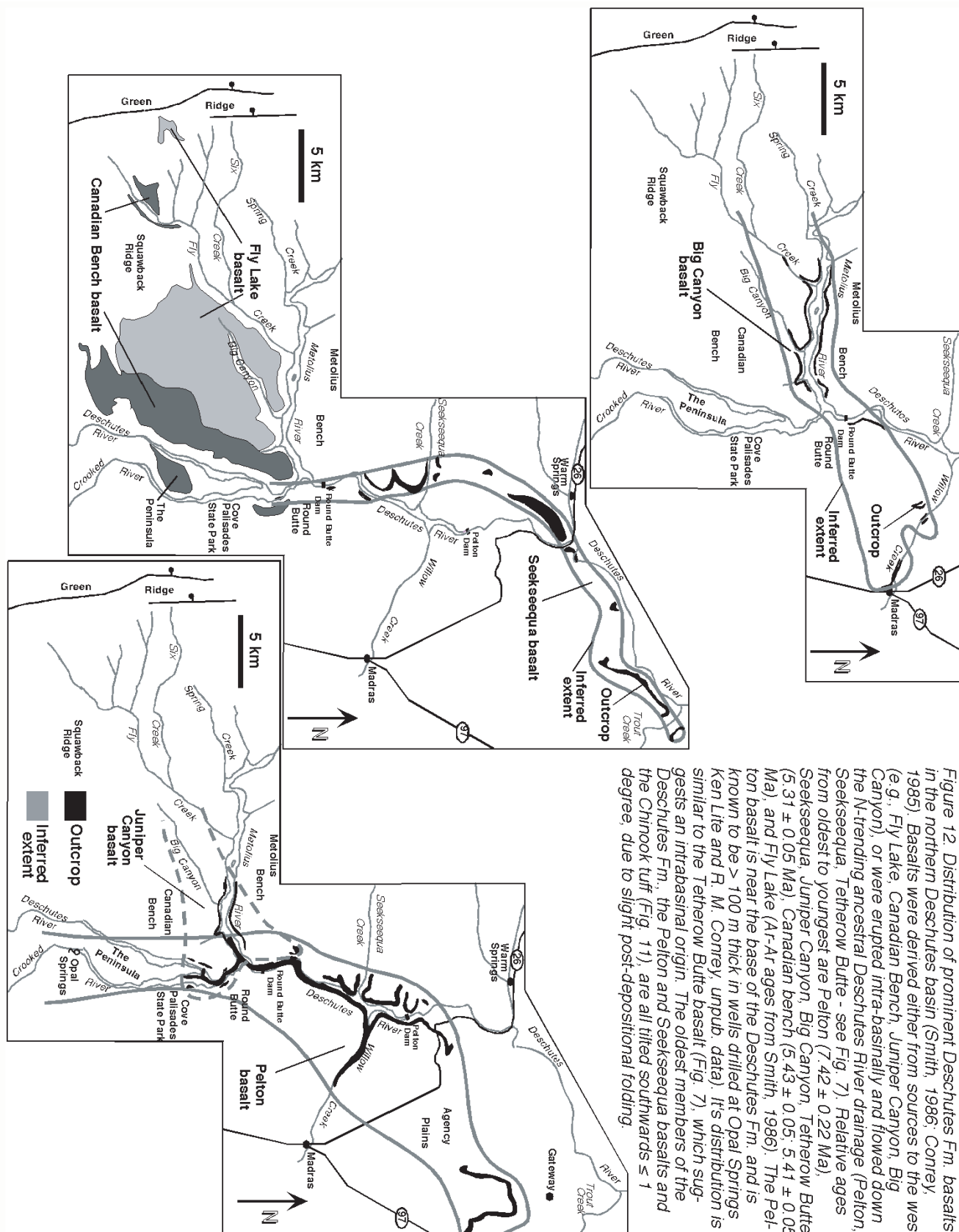
Figure 12. Distribution of prominent Deschutes Fm. basalts in the northern Deschutes basin (Smith, 1986; Conrey, 1985). Basalts were derived either from sources to the west (e.g., Fly Lake, Canadian Bench, Juniper Canyon, Big Canyon), or were erupted intra-basinally and flowed down the N-trending ancestral Deschutes River drainage (Pelton, Seekseequa, Tetherow Butte - see Fig. 7). Relative ages from oldest to youngest are Pelton (7.42 ± 0.22 Ma), Seekseequa, Juniper Canyon, Big Canyon, Tetherow Butte (5.31 ± 0.05 Ma), Canadian bench (5.43 ± 0.05, 5.41 ± 0.05 Ma), and Fly Lake (Ar-Ar ages from Smith, 1986). The Pelton basalt is near the base of the Deschutes Fm. and is known to be > 100 m thick in wells drilled at Opal Springs (Ken Lite and R. M. Conrey, unpub. data). It's distribution is similar to the Tetherow Butte basalt (Fig. 7), which suggests an intrabasinal origin. The oldest members of the Deschutes Fm., the Pelton and Seekseequa basalts and the Chinook tuff (Fig. 11), are all tilted southwards ≤ 1 degree, due to slight post-depositional folding.

157-142 **Juniper/Gray Butte area**: Juniper Butte is a John Day Fm. rhyolite dome complex; the Gray Butte area is underlain by a SE-dipping section of John Day age rocks (Smith et al., 1998).

Retrace route to junction with road to Cove Palisades.

Leg 4 synopsis: Cove Palisades to Deschutes River

The view south leaving the Cove Palisades takes in mostly old rocks of the John Day Fm. (Robinson and Brem, 1981). Some workers believe these rocks to be related to the Cascade Range, with a much wider arc prevailing in the mid-Tertiary. The road climbs over the east flank of Juniper Butte and descends back onto the Tetherow Butte basalt, offering distant views of the older rocks east of the highway.

John Day age rocks in central Oregon

The age of tuff and lava in the Gray Butte…Smith Rocks area has long been a puzzle. The southward apparent dip of the section should be evident from the highway south of Juniper Butte. A major anticlinal axis separates SE-dipping rocks beneath Gray Butte and Smith Rocks from NW-dipping rocks beneath Haystack Butte (east of Juniper). Recent work suggests these deposits are entirely of John Day age (Smith et al., 1998). Most of the section is too altered to yield reliable ages, but regional geochemical correlation combined with new Ar-Ar dating have allowed better estimation of the age of these deposits. The ages are critical to an evaluation of paleoclimatic variations through time, as there are several plant fossil sites distributed throughout the section (Smith et al., 1998). The fossil floras document a change from a subtropical Eocene to a temperate Oligocene.

The striking Crooked River gorge is cut in young intra-canyon basalt from Newberry volcano (Fig. 13). The gorge marks the last of the Tetherow Butte basalt, as the road now traverses the younger, lesser known Redmond and Dry River basalts all the way through Redmond. South of Terrebonne cinder quarries are cut in the Tetherow Buttes, the source of the Tetherow Butte basalt. On the western outskirts of Redmond (look right for the tennis court), a narrow tongue of young Newberry lava flowed down an ancestral Deschutes River gorge cut in walls of the Redmond and Dry River basalt. The final miles before the Deschutes River are underlain by young basalt from Newberry.

27.0 Turn left
27.2 Turn right on Frazier Drive
28.2 Turn right on Feather Drive
29.1 Turn left on Hubber Lane towards Highway 97 and town of Culver
30.0 Turn right at tee in Culver
30.4 Angle left toward Highway 97
32.6 Merge (angle right) with Highway 97 southbound
39.6 Crooked River bridge with gorge cut in intracanyon lava derived from Newberry volcano (Fig. 13).
42.1 Junction with Lower Bridge Road. **Recommended alternate route.** Turn right and follow Lower Bridge Road to where it crosses the Deschutes River at Lower Bridge. Enroute you initially cross the basalt of Tetherow Butte, followed by a tongue of younger basalt from Newberry volcano. A prominent dike of the Fe-rich basaltic andesite of Steamboat Rock (RC97-301) is obvious on the north side of the road ~4.5 miles from the junction. Steamboat Rock is one of several NNW-trending dikes that fed lavas, lapilli tuff cones (with surge deposited beds), and breccias from a ~15 km long fissure which in part coincided with the ancestral Deschutes River channel at 5.06 ± 0.03 Ma (Smith, 1986). Diatomite, once mined here, and believed to be of early Pleistocene age (Smith, 1986; Sherrod et al., in press), is exposed along the grade down to the Deschutes River. Newberry lavas are thought to have blocked drainage and created a lake. At Lower Bridge two prominent and widespread Deschutes Fm. ash-flow tuffs are well exposed along the Deschutes River. The pink tuff of Lower Bridge (first above road level) contains a range of pumice compositions from andesitic to rhyodacitic (62-70 % SiO_2; samples RCLBRG-1A + B; Cannon, 1985; Conrey, unpub. data). The overlying orange to red tuff of McKenzie Canyon is more bimodal with black Fe-rich andesitic pumice (RCMT-BL) and white rhyodacitic pumice (RCMT-WH; Cannon, 1985; Conrey, unpub. data). The latter tuff has more evolved rhyodacite than the former, and is notable for striking banded pumice (not as obvious but also found in the Lower Bridge tuff). Both tuffs are widespread marker beds in the southern Deschutes basin (Fig. 14), and were erupted from sources to the SW in the vicinity of the modern Three Sisters - Bend Highland, as shown by increasing thickness and degree of welding in that direction (Cannon, 1985; Smith, 1986). To regain the field trip route

continue SW on Lower Bridge Rd ~1.5 miles to its junction with Buckhorn Rd, turn left and follow Buckhorn Rd to Hwy 126, rejoining the road log at mile ~3.8 on leg 5. A good place to examine the McKenzie Canyon tuff is where Lower Bridge Rd. crosses Deep Canyon, ~0.25 miles west of the Buckhorn/Lower Bridge road junction. Buckhorn canyon offers access to the tuff of Deep Canyon (see Stop 4 below) as well as rimrock identical to that noted at mile 1.2 in leg 5.

42.2 Entering Terrebonne
43.7 Quarries in the Tetherow Buttes cinder cones are obvious on the right for the next mile.
45.2 O'Neil junction - stay on 97
48.2 Turn right at the Highway 97/126 junction in Redmond.
48.9 Tennis court on right is underlain by a thin intracanyon tongue of Newberry lava, partially filling the Redmond channel (see Figure 13), with scarps of older lava, mapped as the basalts of Redmond (RCS95-B312) and Dry River (RCS95-B313), both believed to be 3-4 Ma, on the west and east sides of the court, respectively (Robinson and Stensland, 1979; Smith, 1986; Sherrod et al., in press; D.R. Sherrod, unpub. data).
49.3 New roadcut in basalt of Redmond
52.4 Cross Deschutes River - reset odometer

Leg 5 synopsis: Deschutes River to Deep Canyon

The Deschutes River has been pushed westward during Brunhes time by extensive basalt lavas flowing from Newberry volcano, and crossing the river the road returns to older Deschutes Fm. strata. A sediment dominated section is well exposed at the crossing, but farther west lava flows cap the section and most overlying sediment has been eroded. Many of these lavas are distinctive and mapping shows that they were emplaced along NE-flowing drainages. NNW-trending strands of the Tumalo fault zone (Fig. 10) occur this far east, and form shallow basins and short scarps along the route. The prominent dome complex south of the highway is Cline Buttes. These buttes were long considered to be John Day age, but hydrogeologic investigation showed them to be highly permeable, unlike known John Day rocks in central Oregon (Sherrod et al., 2002). Recent Ar-Ar dating shows them to be equivalent in age to the Deschutes Fm. (6.14 ± 0.06 Ma; M.A. Lanphere, in Sherrod et al., in press). Deep Canyon is a major drainage, and a thin tongue of Brunhes age intracanyon basalt made it as far as the highway.

0.0 Deschutes River. A deep roadcut in Deschutes Formation sediment and airfall tuff on the west side of the river may be explored by turning right just past the bridge to park away from the highway.
1.2 Porphyritic Deschutes Formation lava is exposed discontinuously in roadcuts for the next 3 miles (RCS94-B72). Mapping here shows that these lavas flowed down NE-trending paleodrainages (Sherrod et al., in press).
5.2 Roadcut in Fe-, Ti-, and V-rich basalt (RCS94-B70; Table 2) similar to the basalt of Tetherow Butte. The shallow basin here is the result of downdrop along a NW-trending strand of the Tumalo Fault zone ~0.25 miles to the northeast.
5.7 Roadcut in another Fe-rich Deschutes Fm. basalt (RCS94-B69), not as Fe-rich as the B70 lava. The B69 lava also followed a NE-trending paleodrainage.
6.7 Roadcut exposes Fe-rich basalt dike (RC95-101) in a small vent.
7.0 Yet more Fe-rich basalt lava of the Deschutes Fm. (RC95-100) in roadcut.
7.2 Unimproved road to the left just before left-hand curve is on Pleistocene basalt of Plainview, a thin tongue of which is intracanyon here in Deep Canyon.
7.6 Begin long roadcut in tuff of Deep Canyon (Stensland, 1970; Smith, 1986) of the Deschutes Fm. If traffic and time permit this is **optional stop 4**.

Stop 4. Deep Canyon tuff on Deep Canyon grade

This stop offers a chance to examine an ignimbrite of the Deschutes Fm., the Deep Canyon tuff (Fig. 14). The tuff is ~20 m thick here and well exposed along the road for some distance. The base is nearly at the level of the highway bridge. The tuff was likely derived from a source to the SW as the degree of welding increases in that direction. Dacitic (RCDPCN-2) pumice is brown to black, the lighter color typically in more vesiculated pumice. The pumice shows reverse grading.

Continue west on Hwy 126

Leg 6 synopsis: Deep Canyon to Sisters

Up the grade toward Sisters from the Deep Canyon tuff is a good exposure of another Deschutes Fm. ash-flow tuff, capped by dated (4.9 ± 0.4; Armstrong et al., 1975) Deschutes lava.
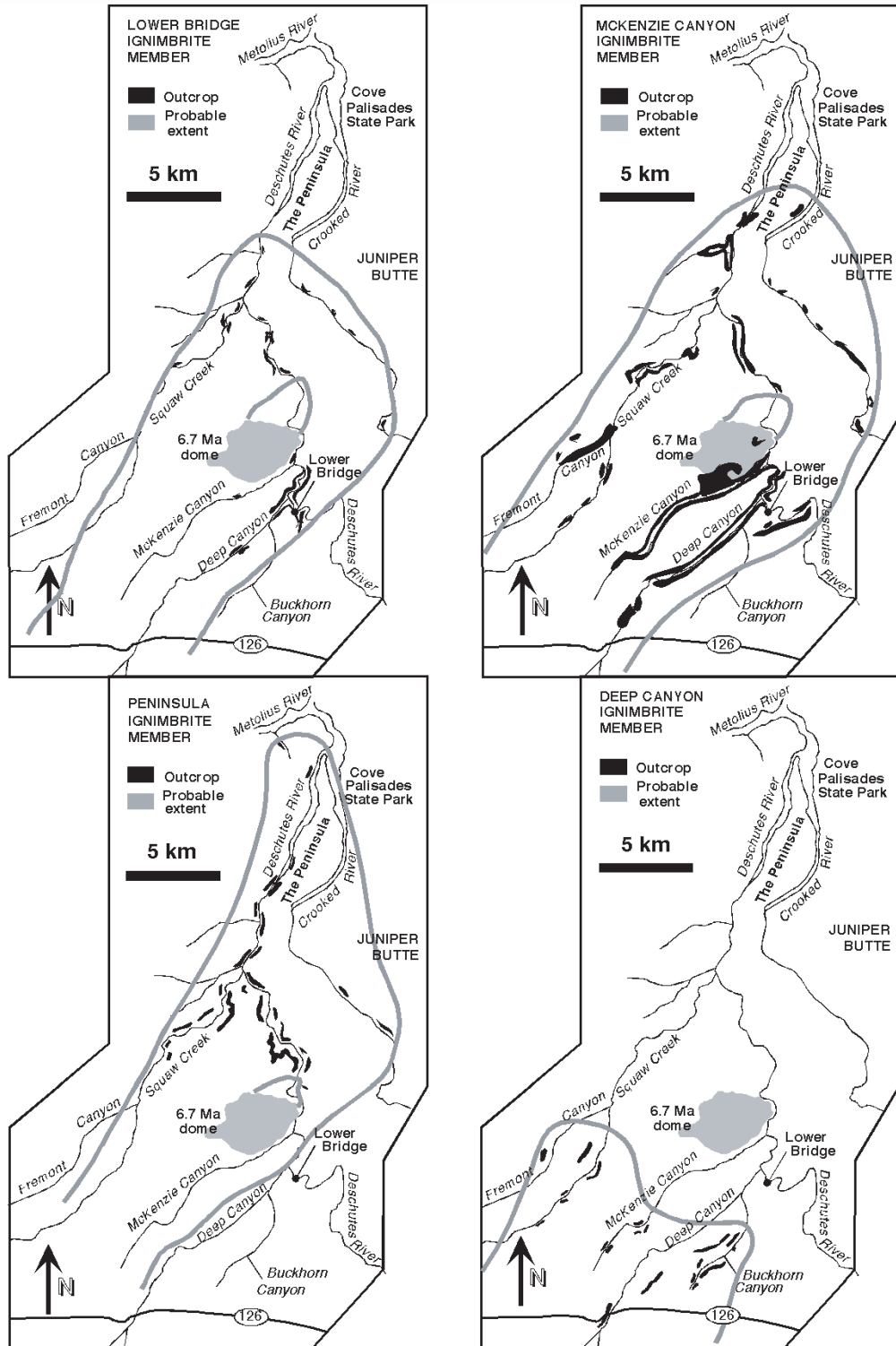
Figure 14. Distribution of four prominent Deschutes Fm. ignimbrites in the southern Deschutes basin (adapted from Smith, 1986). Ignimbrites were emplaced along NE-flowing drainages as shown by map patterns, local confinement in NE-trending paleochannels, "shadow zone" NE of a preexisting dome, and increases in pumice size and degree of welding to the SW in each ignimbrite. Sources to the SW in the vicinity of the modern Three Sisters and Bend Highland are suggested by these data. Relative ages from oldest to youngest are Lower Bridge, McKenzie Canyon, Peninsula, and Deep Canyon, respectively.

NNW-trending normal faults, part of the broad Tumalo fault zone, cut the tuff and the lava. The remainder of the route to Sisters offers only poor exposures of Deschutes Fm. lavas and one younger flow closer to Sisters. The road crosses the main strand of the Tumalo fault just before Sisters, and the town overlies a sediment-filled basin.

7.9 Roadcut in unnamed Deschutes Fm. ash-flow tuff (RCDPCN-1) cut by strands of the Tumalo Fault Zone.
8.0 Dated (K-Ar 4.9 ± 0.4 Ma; Armstrong et al., 1975) Deschutes Fm. lava (RC95-99) caps Deep Canyon section.
11.8 Outcrop at curve in Deschutes Fm. lava.
12.6 Road drops over edge of young (probably Brunhes age) basalt flow.
14.3 Junction with Hwy 20 - bear right.
14.6 Turn left on East Hood Street before "Welcome to Sisters" sign and proceed 3 blocks.
14.8 Turn left on South Fir.
14.9 Lunch at park (Sisters Village Green). Reset odometer.

Leg 7 synopsis: Sisters to McKenzie Pass

This leg first traverses young glacial outwash, and at Cold Spring passes onto an Fe-rich basaltic andesite lava derived from the Matthieu Lake fissure eruption. The highway offers only poor exposures up to the first sharp turns through the late Wisconsin lateral moraine. North of the highway is a slightly glaciated late Pleistocene mafic lava field derived from six cinder cones (Fourmile, Fivemile, Graham Buttes, etc.) that covers ~20 mi^2 (Sherrod et al., in press). Holocene basalt from Belknap Crater is obvious right of the road until Windy Point, a proposed young (< 50 ka) fault scarp.. Discontinuous exposures of older lavas in roadcuts up to and including Windy Point are chiefly derived from Black Crater. Windy Point offers a good view; the Holocene Yapoah Crater lava below the point overlies Belknap lava. The final miles to the pass are mostly in forest until the road is forced to cut through the Yapoah lava.

0.0 Return to Hood Street and turn left. Stay on Hood through Sisters.
0.5 Turn left (west) onto Hwy 242 toward McKenzie Pass.
0.8 Llama and elk ranch offers a nice view.
2.5 Roadcuts in glacial outwash.
4.3 Cold Spring campground. Cold Spring emerges beneath the terminus of a long, nearly aphyric, Fe-rich basaltic andesite lava flow erupted from the Matthieu Lake fissure (RC95-61).
6.8 Road junction. Road to north leads to Fourmile Butte, one of a cluster of several small late Pleistocene cinder cones including Graham, Sixmile, Fivemile, and Bluegrass Buttes. Collectively, these erupted a small field of basalt and basaltic andesite lava that covers approximately 20 mi^2 between Hwys 242 and 20.
7.9 Sharp curve to left curls around late Wisconsin lateral moraine.
8.4 Junction with spur road to right marks the toe of basaltic lavas from Belknap Crater (RCBKP-1).
10.3 Analyzed roadcut in basaltic andesite of Black Crater (RC99-35).
11.7 Windy Point. Prominent outcrop of basaltic andesite lava erupted from Black Crater. Excellent view of (S to N) Belknap Crater, glaciated Mt. Washington, forested Dugout Butte and Cache Mt., and Mt. Jefferson.

Potential evidence for faulting ~15 ka

A N-S trending, down-west normal fault was mapped across the western flank of Black Crater immediately west of Windy Point by Steve Bacon (1996), who studied Black Crater for a senior thesis at Humboldt State Univ. A fault is a possible explanation for the scarp here and its southward continuation across the flank of the volcano. The mapped fault is on strike with the ~8 km long late Pleistocene Matthieu Lake fissure (~15 ka; see age data below) between Black Crater and North Sister. The fissure eruption must have been dike-fed, and the dike could have followed a fault to the surface. The fissure eruption post-dates Black Crater, which is probably about 50 ka judging from the degree of glacial dissection.

14.3 Roadcut in olivine-rich basalt (RC95-46).
14.5 Margin of Yapoah Crater lava (RC95-45).
15.0 Dee Wright Observatory on McKenzie Pass. **Stop 5**.

Stop 5. View of the central Oregon Cascades from McKenzie Pass

   A volcanic paradise is evident here. Ed Taylor was responsible for nearly all of the original mapping in the Three Sisters area that backs up the following descriptions. Compilation of his mapping can be found in Sherrod et al. (in press). Following Taylor (1981), the main points of interest are indicated with reference to their compass direction:

0   **Mount Jefferson**

7   **Cache Mountain**: a deeply eroded remnant of a basaltic andesite shield. The lavas are normally polarized but the K-Ar age is 0.88 ± 0.05 Ma (Armstrong *et al.* 1975), so the shield is either of earliest Brunhes or Jaramillo age. A much younger cinder cone built on the eroded summit erupted a primitive K-rich basalt lava (Conrey *et al.* 1997).

11   **Bald Peter** (far distance)

20   **Dugout Butte** (forested in middle ground): small, glaciated basaltic shield volcano.

30   **Green Ridge** (far distance)

40   **Black Butte** (background):
   Bluegrass Butte (foreground): small basaltic andesite cinder cone. One of several glaciated, but likely late Pleistocene, cones that fed a modest size lava field north of Hwy 242.

82   **Black Crater**: a relatively uneroded and thus late Pleistocene (ca 50 ka) basaltic andesite shield volcano with several flanking cinder cones. The crater is a shallow cirque.

105-155   **Matthieu Lake fissure**   (eastern skyline): a nearly 8.5 km long N10E trending (beginning at the northern flank of North Sister and continuing to Black Crater) chain of cones and agglutinate vents, which erupted cinders, bombs, and thick, agglutinated lava flows. It is of basaltic andesite to andesite composition (SiO_2 53.5 to 60%) which forms a coherent trend (Figure 16), suggesting progressive deep crustal fractionation of North Sister type basaltic andesite. Glaciated, but overlies Black Crater. One fissure lava very close to North Sister yielded a $^{40}Ar/^{39}Ar$ date of 15.1 ±11.5ka (Schmidt et al, 2003).

167   **Yapoah Cone**: on the left at the base of the North Sister. Yapoah lava is undated but is younger than Little Belknap. The SiO_2 content of the lavas ranges from 54.5 to 57; no obvious spatial pattern is so far evident. The lavas are chemically similar, but not identical, to those of Collier Cone and North Sister.

168 **North Sister**: a large basaltic andesite shield volcano; oldest and most mafic of the Three Sisters. Recent $^{40}Ar/^{39}Ar$ dates bracketed the NE ridge, a stack of largely conformable thin lava flows between 191.2 ±28.7ka and 574.3 ±97.1ka (Schmidt et al, 2003). Regional stratigraphy suggests the age is younger than 260 ka (Sherrod et al., in press; Lanphere et al., 1999). The central plug, a large number of dikes, and a palagonitic complex on the E-NE side of the volcano, have been exposed by glacial erosion (Schmidt et al, 2002). The North Sister basaltic andesite is homogenous (53 to 55 wt% SiO_2) and noteworthy for its very low incompatible elements (Fig. 16).

171 **Collier Cone**: on the right at the base of the North Sister. The age is 1600 ± 100 ^{14}C years (Scott 1990). The lava from Collier Cone is heterogeneous and ranges in composition from basaltic andesite to andesite, with final erupted dacite (Schick, 1994).

174 **Middle Sister**: a complicated, poorly known cone with thick dacite lavas, stacks of intermediate rocks, including Fe-rich varieties, and large plagioclase-rich basaltic andesite. Recent dating shows that Middle and South Sister both erupted lavas 15-20 ka (Calvert and Hildreth, 2002), so the two cones were at least in part contemporaneous.

178 **Little Brother**: heavily eroded remnant of a basaltic andesite shield volcano, of Mount Washington type, with higher incompatible elements than the North Sister type. A new $^{40}Ar/^{39}Ar$ date of a stratigraphically young Little Brother sample yielded an age of 172.8 ±29.0ka, overlapping with younger North Sister. Field evidence also suggests that Little Brother is younger than North Sister (Taylor, 1981).

197 **The Husband**: the dark, cliffy peak is a large plug in the core of the deeply eroded remains of a large Brunhes age basalt-basaltic andesite shield volcano, some of which is of NS-type rock.

218 **Condon Butte**: a small basaltic andesite shield.

235 **Horsepasture Mtn.**(far skyline): ridgecap in the Western Cascades at the western margin of the graben above Horse Creek. Underlain by 5-6 Ma rocks that filled west-draining paleovalleys and whose proximal sources are now downdropped beneath the graben (Flaherty 1981; Priest *et al.* 1988).

256 **Scott Mountain**.: relatively young basaltic shield volcano. Has been glaciated but not heavily eroded.

282 **South Belknap Cone**: a small flank cone of Belknap Crater.

285 and 306   **Steptoes** of older rocks surrounded by lava from Little Belknap.

309 **Belknap Crater**: Holocene mafic shield volcano. Belknap s age is probably best indicated by a new AMS ^{14}C age of 2635 ± 50 yrs BP (Licciardi *et al.* 1999). A prior sample from the same location suggested a much younger age, ca. 1800 yrs BP, as did samples from the western margin of the Belknap lava field (Taylor 1965). Presumably the earlier samples were contaminated with younger carbon, a common difficulty in ^{14}C dating. Early erupted basaltic lavas spread over 8 mi west of the cone, and over 6 mi eastwards. Later basaltic andesite was erupted from the central crater and several flank vents.

321 **Little Belknap Crater**: Basaltic andesite flank vent of Belknap Crater.

340 **Mount Washington**: glaciated remnant of a large basaltic andesite shield volcano with a well exposed, resistant central plug. The progressive glacial erosion and increase in dissection with age of High Cascade shield volcanoes is well documented (Sherrod 1986; Scott *et al.* 1996). Mt. Washington once looked like Belknap Crater or Scott Mt.

The character of the arc in central Oregon

It should be obvious from this vantage that the character of the arc has changed considerably from the "sleepy" aspect it showed in northern Oregon. Eruption rates have been higher on the southern end of the graben, and the inner graben (of the graben-in graben) is partly filled by a section of Brunhes rocks > 500 m thick; that section is lacking around Mt. Hood. It is tempting to relate the increased volcanism southward to increasing extension because there is evidence for rifting into at least early Brunhes time in this part of the arc (Sherrod et al., in press; Conrey et al., 2000, 2002). There is also suggestive evidence for very young faulting, as noted above at Windy Point. Fissure style eruptions, with fissures ~10 km in length, are unique to this central part of the arc, further attesting to extensional conditions. The dramatic along arc increase in volcanism southward is especially evidenced by widespread eruption of mafic magma between the stratocones. Those eruptions have resulted in the growth of dozens of small mafic shield volcanoes, ten of which are evident from this vantage.

Mafic shield volcanoes in the central Oregon Cascades

Little Brother, The Husband, Scott Mt., Belknap Crater, Mt. Washington, Cache Mt., Black Butte, Black Crater, and North Sister are all remnants of mafic shield volcanoes visible from McKenzie Pass. These are merely a subset of the extensive collection of such volcanoes in central Oregon (Fig. 15). It should be born in mind that the visible volcanoes bury a "platform" (Taylor, 1981) of older eroded volcanoes, and thus the total number of such shields formed in the past few million years is probably many times the number (~50) evident today. Clearly, the development of these shields is an important aspect of Cascade volcanism, and the volcanoes preserve a record of the evolution and differentiation of mafic magma. As such, it is of interest to compare them to the stratocones, which are also often assumed to have mafic "parents". There are profound differences between the two styles of volcanism, however, because as we have seen, there is strong evidence that the stratocones mark very long-lived loci of intermediate and silicic volcanism. In contrast, mafic shield volcanoes represent ephemeral activity, with eruptions spanning a period of at most a few thousand years (e.g., Scott and Gardner, 1992); thus mafic shields are more akin to cinder cones than stratocones.

There are several compositional types of mafic shield in central Oregon (Hughes and Taylor, 1986; Conrey et al., 2000), and Figure 15 shows the designated type where it is known. The principal type is named after Mt. Washington (MW), and in these shields there appears to be a strong fractionation control on compositional variation. The other main type is named for the North Sister; in NS-type shields the concentrations of incompatible elements are considerably lower than in the MW-type, and in some volcanoes there is little evident fractionation control on compositional variation. It is common for many MW-type shields to finish their activity with a few eruptions of NS-type magma. The other compositional types are not as common, and are defined by Sr-enrichment, either accompanied by K-enrichment in shoshonite, or lacking K-enrichment, as in the "Sr-rich" type (Conrey et al., 2000).

Stratocones do not evolve from mafic shield volcanoes, and mafic shields only rarely erupt intermediate magma, so it appears that we have at least two choices in interpreting the difference in volcanic styles. There seem to be two very different processes (or two very different time scales?) generating the two contrasting styles. One choice would be that stratocones represent
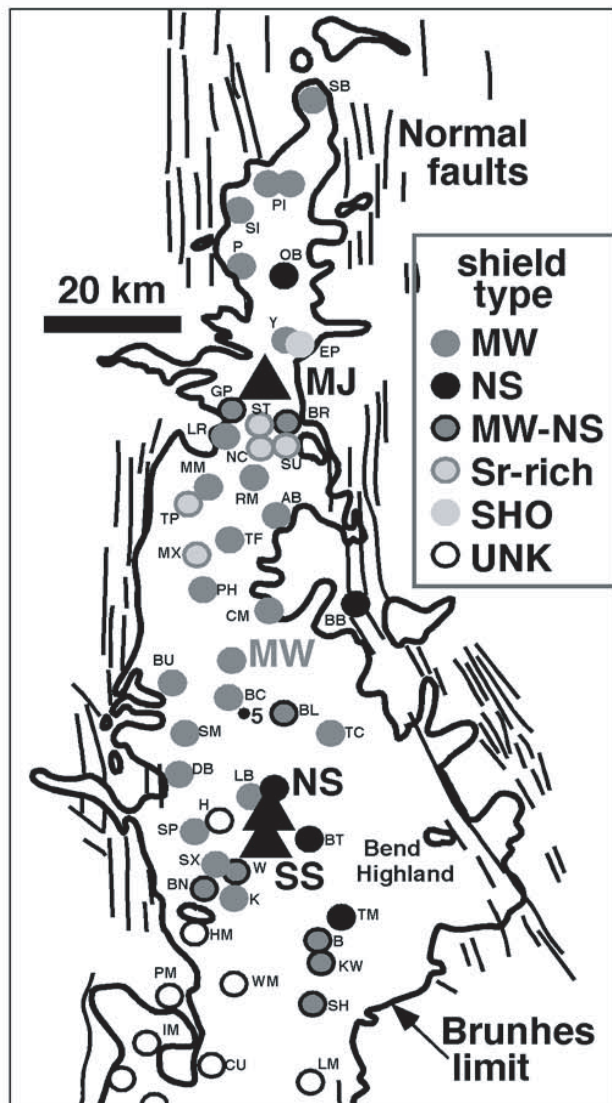
Figure 15. Distribution of Brunhes age volcanism and mafic shield volcanoes in the central Oregon Cascade Range. Location of field trip stop 5 is shown. Stratocones = dark triangles; MJ = Mt. Jefferson; SS = South Sister. Mafic shields (= circles) typified by composition (legend; R.M. Conrey, D.R. Sherrod, and Mariek Schmidt, unpub. data; Conrey, 1991; Webster, 1992; Gardner, 1994), with types defined as follows: MW = Mt. Washington; NS = North Sister; MW-NS = mixture of previous two types, typically with NS-type eruptions at termination of shield activity; Sr-rich = 800-1400 ppm Sr; SHO = shoshonite (Sr- and K-rich); UNK = insufficient data to classify. All are of Brunhes age with two exceptions (Black Butte and Packsaddle Mt.); the volcanoes indicated represent a minimum number due to burial of earlier, eroded shields; thus the total number of Brunhes age shields in this part of the arc is much >50, the number shown here.

Shields are: Abbot Bt. Trail (AB), Mt. Bachelor (B), Black Butte (BB), Belknap Crater (BC), Black Crater (BL), Burnt Top (BN), Bear Butte (BR), Broken Top (BT), Bunchgrass Ridge (BU), Cache Mt. (CM), Cultus Mt. (CU), Deer Butte (DB), East Park Ridge (EPR), Grizzly Peak (GP), The Husband (H), Horse Mt. (HM), Irish Mt. (IM), Koosah Mt. (K), Kwohl Bt. (KW), Little Brother (LB), Lookout Mt. (LM), Lizard Ridge (LR), Marion Mt. (MM), Mt. Washington (MW), Maxwell Bt. (MX), North Cinder Peak (NC), North Sister (NS), Olallie Bt. (OB), Potato Bt. (P), Potato Hill (PH), Pinhead Buttes (west and east; PI), Packsaddle Mt. (PM), Rockpile Mt. (RM), Summit Bt. (SB), Sheridan Mt. (SH), Sisi Bt. (SI), Scott Mt. (SM), Substitute - Proxy Pt. (SP), Skyline Trail (ST), Sugarpine Ridge (SU), Sphinx Bt. (SX), Trout Creek Bt. (TC), Three Fingered Jack (TF), Tumalo Mt. (TM), Turpentine Peak (TP), The Wife (W), Williamson Mt. (WM), Yogodzinski (Y).
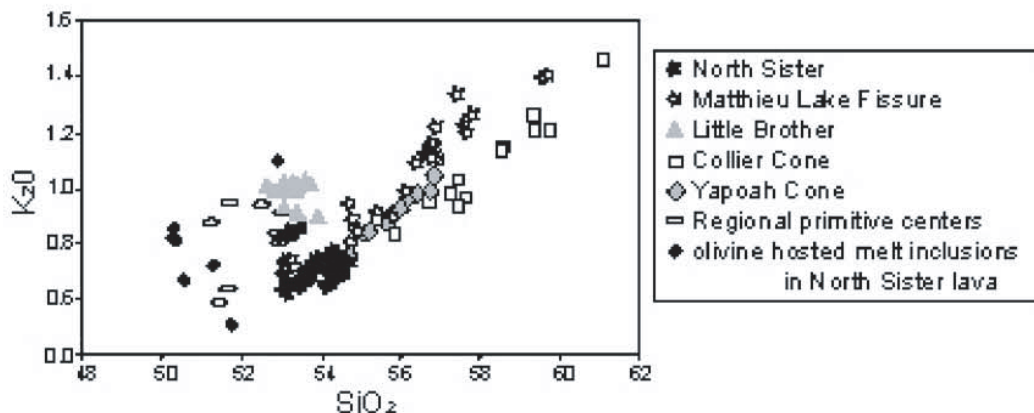
Figure 16. K_2O vs. SiO_2 for North Sister and her proximal centers. North Sister has very low incompatible element concentrations (here as K). The Matthieu Lake Fissure lavas include some very similar to North Sister and form a trend consistent with lower crustal fractionation.

long-lived foci of mafic magmatism, with focusing created by unspecified mantle processes. And the shields represent short-lived supply of mafic magma due to extension. One problem with this model is that the stratocones are fixed for such long periods, and even survive (rather flourish during) intra-arc rifting, so the mantle process that fixes the mafic flux beneath the cones cannot be the same process that results in wide spread extension-related mafic volcanism. And yet the mafic magmas found in the shields are also present in small volume in the stratocone systems, there is no unique type of stratocone mafic parent magma (cf. Conrey et al., 2001). The other choice would be to fix the stratocones by some lithospheric process, either lower crustal instability or partial melting or some combination of the two. In this model, similar to some recent models for emplacement of calc-alkaline plutons, upwelling of lower crust fixes the stratocones and mixing with a background flux of mafic magma (allowed through unmixed by extension away from the cone) generates intermediate magma.

Spacing of mafic shields and stratocones

The long-lived nature and systematic spacing of stratocones have been one of the primary themes of this trip. Evident from the discussion of mafic shields visible from this vantage, there are two diverse styles of volcanism in central Oregon. One is locally ephemeral but persistent over millions of years during extension, and it creates many small mafic shield volcanoes. The other style is the temporally persistent local focus of intermediate and silicic volcanism which creates stratocones. The fundamental difference between these styles of volcanism argues that each is generated by divergent processes. Current analyses of volcano spacing in arcs do not acknowledge these two diverse styles, and are thus unlikely to be good models. Mafic shields are bunched much closer together than stratocones, and a simple plate bending analysis can explain their ~20 km average spacing (ten Brink, 1991). Such a model fails to explain the much larger spacing between stratocones, and what causes their spacing remains unexplained.

Return down Hwy 242 and proceed to the Hwy 242/20 junction in Sisters. Reset odometer there.

Leg 8 synopsis. Sisters to Cascade Viewpoint

A leg with little topographic relief. The hill visible from the east side of Sisters is McKinney Butte, a very Fe-rich andesite vent dated at 3.3 Ma. The road recrosses the Tumalo fault zone and outcrops from here to the next stop are mostly in Deschutes Fm. lavas again, overlain locally by one younger lava, the basalt of Plainview, and glacial outwash.

0.2 Elm Street junction (road to Three Creek Lake below Tam McArthur Rim).
0.4 From the east side of Sisters the view to east is of McKinney Butte, a 3.3 ±0.2 Ma (Armstrong et al., 1975) vent of nearly aphyric, very Fe-rich andesite (RC95-89). The west side of the butte facing you is cut by a strand of the Tumalo Fault Zone.
0.7 Stay R on Hwy 20 at junction with Redmond Hwy 126.
1.9 Prominent bend in highway marks the location of the major down-west normal fault (buried here) that cuts McKinney Butte and defines the east side of the Sisters basin.
3.1 Roadcut at bend is in lava of the Deschutes Fm.
3.6 Outcrop to right of highway is in the Brunhes age Plainview basalt (RC95-37), a widespread unit mostly northeast of the highway.
4.7 Highway curves around another resistant outcrop of Deschutes Fm. lava.
5.1 Yet another curve in Deschutes lava.
6.3 Plainview; road ahead traverses irregular contact between Plainview basalt and glacial outwash. Cline Buttes visible to left; Bend Highland to right.
8.6 Fryrear Rd. junction; Deschutes Fm. outcrops right of road.
9.9 Cascade Viewpoint on Hwy 20. **Stop 6**.

Stop 6. Overview of Three Sisters and Bend Highland

The viewpoint lies on glacial outwash; most of the small buttes visible in the near and middle ground are underlain by Deschutes Fm. lava or cinder as a significant number of eroded vents occur east of the Tumalo Fault Zone (Taylor and Ferns, 1994). The Bend Highland (see below) is the prominent skyline ridge to the south that extends east of the Three Sisters toward Bend (Figs. 10 and 17).

Prominent features are as follows (again by azimuth):

SE

Unnamed cinder cone

BEND

Triangle Hill

HIGHLAND

Tam McArthur Rim

Broken Top

Three Creek Butte

South Sister

Unnamed dome

Melvin Butte

Middle and North Sisters

Matthieu Lk. fissure

Trout Creek Butte

Black Crater

Mt. Washington

Deschutes Fm. lava

Three Fingered Jack

Black Butte

Mt. Jefferson

Little Squawback

NW
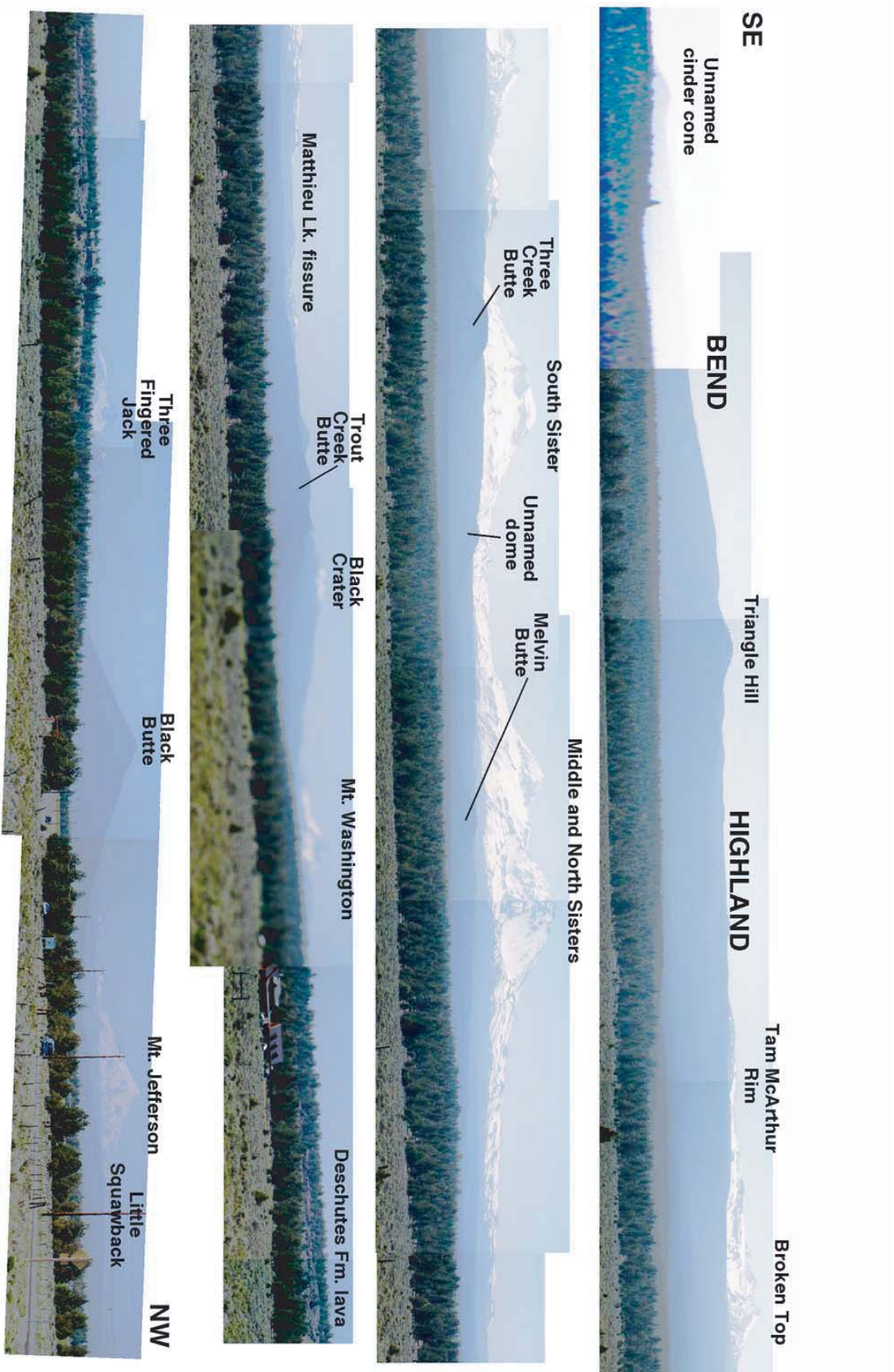
Figure 17. Panorama looking south and west from the Cascade Viewpoint on Hwy 20. The prominent skyline ridge to the south, east of the Three Sisters, is the Bend Highland, a broad WNW-trending ridge of Brunhes age volcanic rocks (see Fig. 10). The unusual nature of the Bend Highland suggests a relationship with the Brothers Fault Zone, a major lateral zone of faulting on strike with the Highland to the ESE. Triangle Hill is an andesite cinder cone constructed over the vent for the 440 ka Bend pumice/Tumalo tuff (Fig. 17). Several domes with a composition equivalent to that of the Tumalo tuff are evident from here: Three Creek and Melvin Buttes, and an unnamed dome. Mafic shield volcanoes visible from here include Broken Top, Nortah Sister, Black Crater, Trout Creek Butte, Mt. Washington, Three Fingered Jack, Black Butte, and Little Squawback. Note again the large distance (~60 km) between the Mt. Jefferson and South/Middle Sister stratocones.

340 **Squawback Ridge**

337 **Bald Peter**

333 **Little Squawback Ridge**

330 **Mt. Jefferson**

321 **Black Butte**

312 **Three Fingered Jack**

293 **Mt. Washington**

285 **Black Crater**

281 **Trout Creek Butte**: A broad, flat-topped, normally-polarized basaltic andesite shield volcano (Taylor, 1987).

280 **Millican Crater**: A basaltic andesite cinder cone on the south flank of Black Crater (Taylor, 1987).

276 **Matthieu Lake fissure vent**

262 **North Sister**

260 **Melvin Butte**: A rhyolite dome with a high-silica composition (74% SiO_2) similar to the Bend Pumice (Taylor and Ferns, 1995; Hill, 1991).

258 **Middle Sister**

251 **Unnamed butte** beneath Middle Sister…South Sister saddle: A rhyolite dome with a high-silica composition (74% SiO_2) similar to the Bend Pumice (Taylor and Ferns, 1995; Hill, 1991)

248 **South Sister**: The stratocone of the Three Sisters. Recent age dating demonstrates that youthful eruptions at South and Middle Sisters have been in part contemporaneous (15-20 ka; Calvert and Hildreth, 2002). South Sister is chiefly andesite, but it also erupted basaltic andesite and rhyodacite. A compositional gap extends from 66-72% SiO_2 (Wozniak, 1982; Hill, 1991; Brophy and Dreher, 2000). Silicic rocks there differ from Middle Sister and Bend Highland silicic rocks in that they bear traces of amphibole and have lower heavy rare-earth element and Y contents, and lower Zr concentrations. The intermediate and silicic rocks at Middle Sister and on the Bend Highland have the typical amphibole-absent geochemical patterns associated with rifting. The South Sister, in contrast, has a pattern more akin to that found in extension-absent, amphibole-bearing rocks. The change with time may reflect the decline of extension rates in central Oregon, and consequent crustal cooling. All silicic rocks from the Bend Highland are likely older than approx. 200 ka (Hill and Duncan, 1990). In addition, all of the silicic rocks in the Devils Lake borehole, drilled 10 km south of the South Sister, are all certainly older than South Sister, and are of the Middle Sister type.

246 **Three Creek Butte**: A rhyolite dome with a high-silica composition (74% SiO_2) similar to the Bend Pumice (Taylor and Ferns, 1995; Hill, 1991).

242 **Snow Creek cinder cone**: Glaciated remnant of an Fe-rich basaltic andesite cinder cone near the headwaters of Snow Creek (Taylor, 1978).

239 **Broken Top**: A large, heavily dissected basaltic andesite shield volcano, with a crater open to the south (Taylor, 1978), younger than the Tam McArthur Rim (see next).

237 **Tam McArthur Rim**: Prominent cirque headwall above the Three Creek Lakes comprised of diverse lava including basaltic andesite, dacite, and rhyodacite (Taylor, 1978). Several large dikes beneath the rim suggest most of the lava was vented locally. Hill and Duncan (1990) obtained a K-Ar age of 213 ± 9 ka on a thick rhyodacite lava that caps the section.

223 **Triangle Hill**: A prominent cone-shaped hill on the east end of the Bend Highland. Triangle Hill is a 340 ± 20 ka andesitic cinder cone (Hill, 1991; Hill & Duncan 1990), which overlies the probable vent for the Bend Pumice/Tumalo Tuff, (see next stop). Several rhyolite domes and mafic-intermediate cinder cones lie in a 3 km diameter circle centered on Triangle Hill (Sherrod et al., in press), and the Triangle Hill andesite contains fragments of Tumalo Tuff (Hill, 1991). The circle corresponds to a prominent negative gravity anomaly (Fig. 17).

205 **Unnamed cinder cone** on east flank of Bend Highland: A basaltic andesite cinder cone that fed a small lava flow.

58 **Cline Buttes**

A persistent Bend Highland and Brothers Fault Zone Connection?

The Bend Highland (a term suggested by Larry Chitwood at the Bend USFS office) is a prominent, broad, WNW-trending ridge of young volcanic rocks that extends southeast of the Three Sisters some 20 km toward Bend. All surface exposures on the highland are of normal-

polarity rocks (Sherrod et al., in press) and one drill core penetrates 1200 feet of Brunhes age rocks. Thus the highland is capped with a thick welt of Brunhes age rocks. Because the highland trends WNW, Brunhes age lavas were channelized in northeast-flowing drainages on its northern flank. This situation seems to have existed for a considerable time, as ~5 Ma Deschutes Fm. lavas northeast of the highland (including the exposures along Hwy 20) and ash-flow tuffs in the southern Deschutes basin were also channelized along northeast-flowing paleodrainages (Fig. 14). The Brunhes age ash-flow tuffs (Desert Spring, Tumalo Tuff, Shevlin Park - see next two stops) with sources on or near the highland have counterparts in the petrologically similar and even more numerous and voluminous ash-flow tuffs of the Deschutes Fm. Several of the older tuffs can be traced from the Deschutes Basin upstream along the Deschutes River and its tributary creeks a considerable distance back to the southwest where they are truncated by the Tumalo Fault Zone. Their map distribution therefore suggests that they had sources in the vicinity of the modern Bend Highland (Smith and Taylor, 1983; Smith, 1986). These considerations suggest that the Bend Highland has been a long-lived feature of central Cascade geology.

The Brothers Fault Zone is a broad WNW-trending zone of small offset en echelon normal faults that extends for some 240 km across eastern Oregon (Lawrence, 1976; Walker and Nolf, 1981). North of the zone, Cenozoic and pre-Cenozoic rocks are exposed in northeast- and east-trending anticlines in the Ochoco and Blue Mountains. South of the zone only Cenozoic rocks are exposed, and they are broken and tilted by NNE-trending normal faults, some of which have formed major escarpments. Basin and Range faults south of the Brothers Fault Zone either die upon reaching, or merge into, the latter. WNW extension of the Basin Range south of the zone, and its absence to the north, strongly suggests the Brothers is a major right-lateral fault zone (Lawrence, 1976). It is likely that it is a broad zone of lateral disruption, not a single fault like the classic San Andreas. The Brothers Fault Zone is of considerable antiquity (Walker and Nolf, 1981); the tectonic pattern in east-central Oregon has remained unchanged since at least the middle Miocene (Hooper and Conrey, 1989).

The Brothers Fault Zone may extend along its long WNW strike through the Cascade Range beneath the Bend Highland and the Three Sisters to the complex set of northwest-trending faults at the graben margin around the area of the McKenzie River bend at Foley Ridge. These faults perhaps connect farther along strike to WNW-trending right-lateral faults beneath the southern Willamette Valley (Yeats et al., 1996). A buried Brothers Fault Zone beneath the Bend Highland would explain its orientation, longevity, the presence of two uniquely WNW-trending vent alignments there, and account for the ability of both silicic and mafic magma to easily penetrate the crust along the length of the highland over a span of many millions of years.

Continue east on Hwy 20.

Leg 9 synopsis: Cascade Viewpoint to Tumalo State Park

The road towards Bend continues to weave around Deschutes Fm. rocks east of the Tumalo Fault. Younger cover includes glacial outwash and the ~0.6 Ma Desert Spring tuff (orangish-pink, welded). Near Tumalo, the road cuts the ~0.4 Ma Tumalo tuff (pink, unwelded). Both tuffs were derived from vents on the Bend Highland.

10.4 Ditch exposes early Brunhes age Desert Spring Tuff on both sides of highway. **2.7**
13.9 Pinehurst Rd. Laidlaw Butte, believed to be a Deschutes Fm. vent, is on the right.
14.4 Powell Buttes, visible in the distance from here at 10-11 o clock, is a large dome complex of the John Day Fm.
15.0 Roadcuts expose Tumalo Tuff (see below).
15.6 Turn R on Tumalo State Park Rd. Note the gravel quarry operation along the Deschutes River here. Tumalo Tuff is exposed in the valley walls on both sides of the river. Ahead is Awbrey Butte, a small mafic shield thought to be of Deschutes Fm. age, but undated.
16.4 Deschutes Fm. lava in roadcut.
16.5 Desert Spring Tuff in roadcut.
16.6 Turn R on Tumalo Reservoir Rd.
16.9 Pullout and park for **Stop 7**.
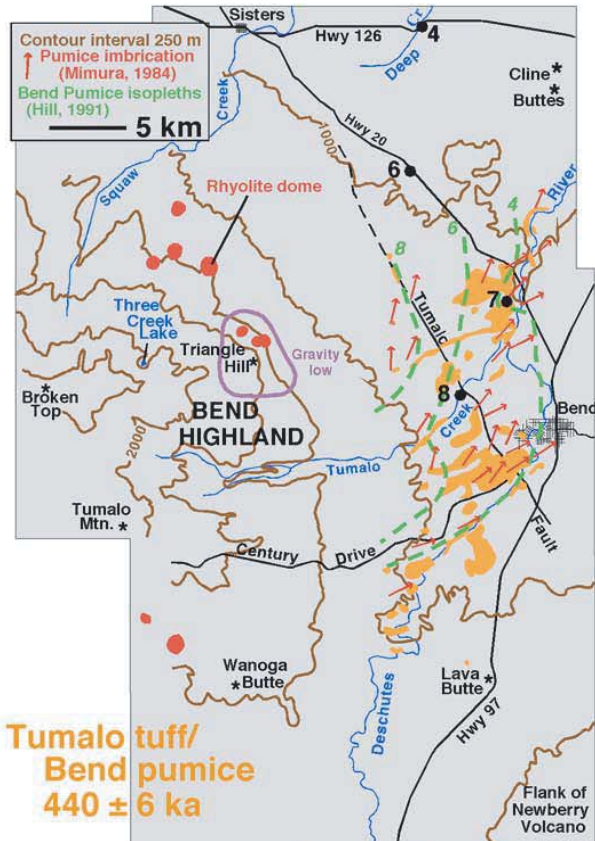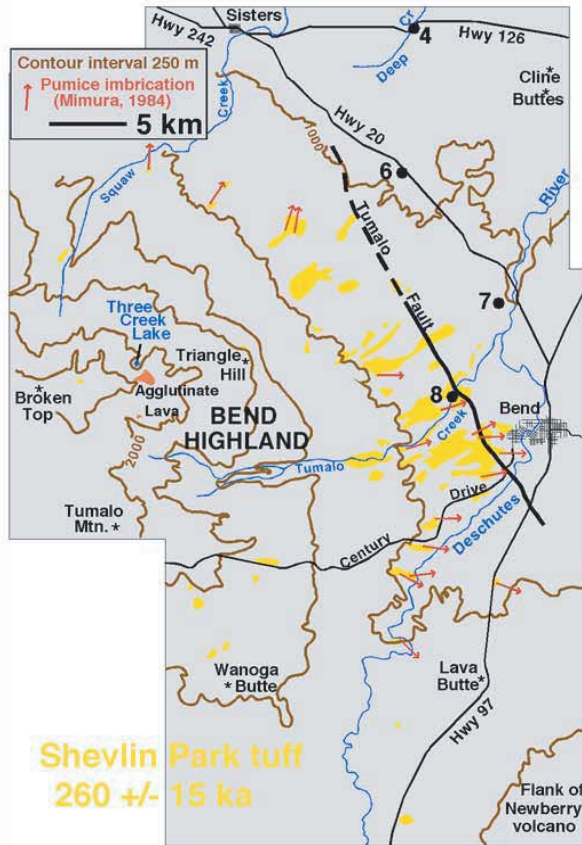
Figure 18. Distribution of four Brunhes age ash-flow tuffs around the Bend Highland. Ar-Ar ages are from Lanphere et al., 1999 and M.A. Lanphere and D.E. Champion, unpub.). Pumice imbrication orientations, presumed to equate to flow directions during emplacement, are from the work of Koji Mimura (1984). The Tumalo Creek tuff is known only in a single outcrop, formerly mapped as Desert Spring tuff. The three widespread ash-flows comprise the largest volume silicic eruptions during Brunhes time in all of the northern Oregon Cascades. Bulk composition, mineral chemistry, and paleomagnetic orientation suggest the Desert Spring tuff is related to a poorly exposed dome near Tumalo Lake. The gravity low around Triangle Hill likely marks the vent for the Tumalo tuff eruption, and the younger Triangle Hill cinder cone includes xenoliths of Tumalo tuff. Pumice isopleths (Hill, 1991) are consistent with that source, but pumice imbrication suggests flow from the SW. Rhyolite domes shown are compositionally similar to the Tumalo tuff. The vent for the Shevlin Park tuff is not exactly known, but must be in the neighborhood of Three Creek Lake, where a compositionally and temporally similar welded agglutinate crop out. Contrast the much more limited distribution of these tuffs with those of the Deschutes Fm. in the southern Deschutes basin (Figs. 3 and 14); both are presumed to have sources in or near the Bend Highland.
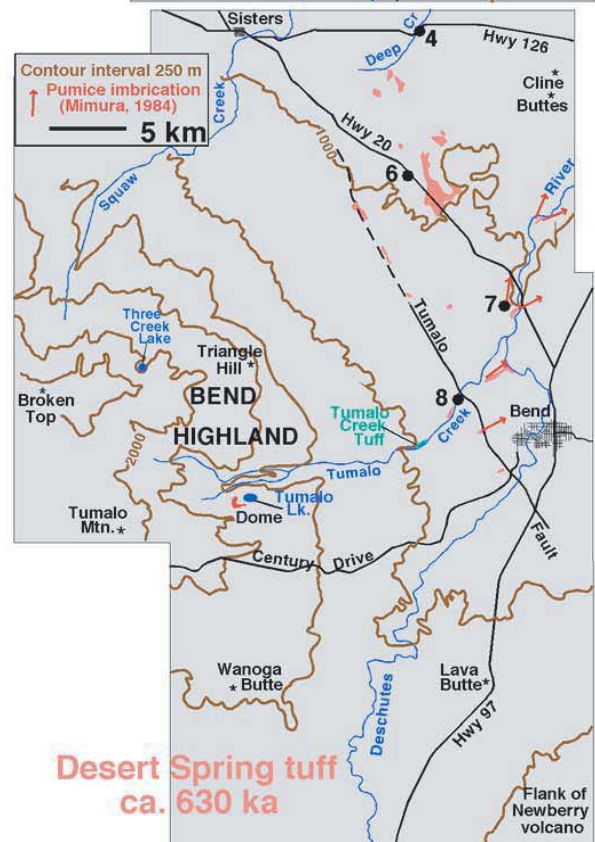
Stop 7. Tumalo Tuff/Bend Pumice and Desert Spring Tuff
Finally a stop to look at rocks! The tuff exposed at and below road level is the Desert Spring, the quarry above the road has Tumalo tuff over Bend Pumice. The distribution of the three prominent Brunhes age tuffs erupted from the Bend Highland is shown in Figure 18.

Desert Spring Tuff
The rhyodacitic Desert Spring Tuff is the oldest of three voluminous Brunhes age pyroclastic deposits on the east flank of the Bend Highland (Taylor, 1981). The erupted volume is thought to be on the order of 2 km^3 (Hill, 1991), but this is a very rough estimate as much of the tuff has been buried by younger eruptions, and the tuff is not uniform in thickness but rather was emplaced in channeled and faulted topography. Correlative distal Rye Patch Dam Ash is thought to be approx. 0.63 Ma, based on interpolation of lake-core sedimentation rates (Rieck et al., 1992). The Desert Spring was likely vented from a chemically and petrographically equivalent dome near Tumalo Lake (Conrey et al., 2002b), ~20 km SW of here, consistent with its map distribution (Fig. 18) and NNE- to ENE-trending pumice imbrication (assumed flow direction; Mimura, 1984). Paleomagnetic directions of the dome and tuff are similar, and preliminary Ar-Ar results from a sample of the dome are consistent with the above age (D.E. Champion, pers. comm., 2003). The tuff contains large dark pumice (sometimes with blebs of lighter glass) bearing ~10% of 5-7 mm plagioclase phenocrysts, and also those of orthopyroxene, clinopyroxene, magnetite, ilmenite, and apatite (Conrey et al. 2002b, Hill, 1991). The chemical signature is notable for its high Rb (80-90 ppm), unlike most other silicic rocks in central Oregon.

Tumalo Tuff/Bend Pumice
The quarry here provides an excellent exposure of the Bend Pumice (plinian airfall) and coeval, overlying 440 ± 6 ka (Lanphere et al., 1999) Tumalo Tuff (Taylor, 1981). A prior field trip guide also used this quarry and that guide should be consulted for more details (Hill and Taylor, 1990). Briefly, the Tumalo tuff is rhyolitic (~ 74 % SiO_2) with rare admixed dacitic pumice (Hill, 1985). The ~10 km^3 tuff was emplaced very soon after deposition of coeval plinian airfall (Bend Pumice). The mineralogy is highly evolved, with oligoclase (An_{20}), ferrohypersthene (En_{30}), pargasite, magnetite, ilmenite, apatite, augite, and zircon (Hill, 1991). The map distribution and pumice isopleths (Fig. 18) suggest a source on the Bend Highland, probably coincident with the prominent gravity low centered on Triangle Hill. Still puzzling are the pumice imbrication directions, however.

Return back down road.

Leg 10 synopsis: Tumalo State Park to Shevlin Park
This short final leg passes exposures of both Desert Spring and Tumalo tuffs in roadcut, and then climbs onto a tongue of Brunhes age lava. Near Shevlin Park, the route drops into the Tumalo Creek drainage and crosses the Tumalo Fault. Gray Shevlin Park tuff is exposed on the grade down to Shevlin Park.

17.2 Turn R on Johnson Rd.
17.3 Desert Spring Tuff in roadcut (drilled here by D.E. Champion); tuff forms bluffs along Deschutes River left of road in Tumalo State Park.
17.6 Tumalo Tuff in roadcuts for the next 0.3 mi.
18.5 Road climbs onto lava rim over Tumalo Tuff.
19.3 Sharp L corner at junction with Tyler Rd. - stay on Johnson Rd.
20.7 Tumalo Butte, a small mafic vent, left of the road.
21.5 Bull Springs Rd. Roadcuts down this grade are in Shevlin Park tuff.
21.8 Turn R into Shevlin Park for **Stop 8** and dinner.

Stop 8. Shevlin Park tuff
This tuff is the youngest of the three major Brunhes age pyroclastic deposits east of the Bend Highland (Fig. 18; Taylor, 1981; Conrey et al., 2001b). The volume of the tuff is difficult to calculate, due to erosion and burial by younger eruptions, but must be at least several km^3. New $^{40}Ar/^{39}Ar$ data on plagioclase indicate an age of 260 ± 15 ka (Lanphere et al., 1999). A Bend

Highland source for the tuff is indicated by a radial distribution of pumice imbrication (assumed equal to flow direction) centered on the Highland (Fig. 18; Mimura, 1984), and an increase in degree of welding and pumice size toward the Highland (Hill, 1991). The Shevlin Park source was probably near lava or near-vent welded agglutinates east and southeast of Three Creek Lake (Fig. 18). The welded agglutinate nearest Three Creek Lake is petrographically and chemically similar to pumice clasts in the Shevlin Park. The relative age of the near-vent agglutinate is correct: it is overlain by Tam MacArthur Rim rhyodacite dated at 213 ± 9 ka (Hill and Duncan, 1990). A source near Three Creek Lake can account for the radial distribution of the Shevlin Park around the Bend Highland, and especially for the westernmost Shevlin Park outcrop in Squaw Creek (Fig. 18).

The Shevlin Park Tuff is dark (black pumice flow of Mimura, 1984) due to the presence of black andesitic pumice and glass. In good exposures, the tuff commonly includes two flow units, both of which are pumice-rich, but the lower unit has few pumice clasts larger than 1-2 cm, whereas large pumice is common in the upper flow unit. In some quarry exposures there are as many as four flow units, some as thin as one meter. In photographs taken by Ed Taylor of now backfilled quarry exposures, the contact between the lower and upper flow units seems to be marked by surge-bed deposits.

The bulk composition of the heterogeneous Shevlin Park Tuff is dacitic. The tuff is compositionally bimodal, with black pumice ranging from 55-62% SiO_2, and commonly paler silicic pumice from 64-68%. Rare banded pumice is present with compositions in the gap between 62% and 64% SiO_2. Lower flow units of the tuff seem to contain more silicic pumice, whereas the upper flow units contain a mixture of both silicic and mafic pumice. Pumice is sparsely porphyritic and contains phenocrysts of plagioclase, clinopyroxene, orthopyroxene, olivine, magnetite, and ilmenite (Hill, 1991; Conrey et al., 2001b).

Directions to Hwy 97 south from Shevlin Park:
Head east toward Bend on Shevlin Park Rd. Go straight through a roundabout and a stop sign onto Newport Ave. Turn R onto 14th and go straight through two roundabouts. At the third roundabout turn L onto Colorado Ave. Stay on Colorado through one roundabout and two stoplights. About 0.5 mi past the second light turn L (*before* the underpass) at a junction onto the Hwy 97 on-ramp (Klamath Falls).

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Table 1. Selected XRF analyses (major elements wt% oxide; trace elements ppm) of Cascade Range rocks

Unit	Sample#	Source^	SiO₂	Al₂O₃	TiO₂	Fe₂O₃*	MnO	CaO	MgO	K₂O	Na₂O	P₂O₅	FeO*/MgO	Ni	Cr	Sc	V	Ba	Rb	Sr	Zr	Y	Nb
Salmon R Mdws	S5-45	1	50.46	16.88	2.06	10.62	0.16	8.10	5.99	1.16	4.06	0.51	1.59	74	135	23	173	255	13	548	215	25	26.4
Salmon R Mdws	98-2	2	57.49	17.53	1.21	7.26	0.12	6.68	3.87	1.31	4.26	0.27	1.69	39	57	18	135	334	19	567	162	20	12.2
QTb	93-MW 10	1	50.78	17.26	1.40	10.56	0.15	9.60	5.85	0.84	3.31	0.23	1.62	39	95	30	196	248	10	742	130	24	8.9
Andesite of Wapinitia	98-1	2	63.08	16.33	0.89	5.85	0.09	4.79	2.66	1.88	4.24	0.18	1.98	23	29	15	100	400	27	468	224	24	11.5
Blue Box Pass	98-3	2	60.58	16.48	0.96	6.20	0.10	5.81	4.01	1.57	4.09	0.20	1.39	54	117	14	115	337	23	469	188	21	11.1
Andesite of Wapinitia	98-5	2	58.38	17.60	1.22	7.58	0.13	6.18	3.05	1.21	4.32	0.32	2.24	21	29	12	114	301	14	624	189	23	12.9
Clear Lake Bt	99-79	2	56.77	18.42	0.96	7.38	0.12	7.14	4.25	0.76	3.97	0.22	1.56	46	51	17	144	224	8	570	120	18	7.9
Andesite of Wapinitia	99-8	2	54.32	16.97	1.54	9.64	0.15	7.47	4.60	1.10	3.73	0.48	1.89	64	105	17	165	398	14	532	225	46	18.7
Andesite of Wapinitia	S5-44	1	61.61	17.29	0.92	6.41	0.10	5.37	2.41	1.42	4.25	0.23	2.39	19	13	15	89	278	17	524	187	22	13.1
Andesite of Wapinitia	98-211	2	60.44	17.46	1.02	6.37	0.10	5.53	3.31	1.56	4.00	0.21	1.73	42	51	15	116	343	22	493	190	22	10.9
N Wilson	93MW -23	1	56.43	18.00	1.13	8.04	0.13	6.81	3.73	1.03	4.36	0.34	1.94	38	58	23	116	321	13	520	200	27	14.9
Rocky Point	93MW -20	1	65.01	15.93	0.72	5.72	0.15	3.57	1.00	2.34	5.31	0.29	5.16	4	4	16	22	594	54	311	313	41	25.8
Shitike Fm.	93-38	2	48.62	17.28	1.26	11.80	0.18	10.01	7.32	0.30	3.11	0.14	1.45	79	192	32	189	109	4	259	96	25	6.7
Shitike Fm.	93-39	2	54.28	17.91	1.20	8.16	0.12	8.09	4.94	1.12	3.81	0.37	1.49	66	86	20	146	640	17	790	187	28	11.9
Shitike Fm.	GSPP5	2	49.96	16.63	1.35	11.94	0.17	9.49	6.97	0.28	3.12	0.09	1.54	69	241	30	198	124	5	229	87	25	5.1
Shitike Fm.	GSW S15	2	48.88	16.60	1.50	12.04	0.17	10.04	7.11	0.36	3.12	0.16	1.52	72	215	33	108	108	5	266	94	24	7.2
Deschutes Fm.	93-36	2	71.67	14.60	0.37	2.91	0.08	1.43	0.38	4.67	3.81	0.08	6.96	9	0	11	4	773	65	156	286	37	14.9
Steamboat Rock dike	97-301	2	54.20	14.94	2.12	10.87	0.20	7.84	4.32	1.33	3.35	0.83	2.27	22	48	36	255	496	23	343	144	41	7.9
Lower Bridge tuff	LBRG -1A	2	61.83	15.11	1.23	6.70	0.15	4.31	2.01	1.72	5.26	0.55	3.00	3	4	20	76	636	30	385	207	41	14.6
Lower Bridge tuff	LBRG -1B	2	69.74	16.24	0.53	3.28	0.09	1.84	0.67	4.51	4.09	0.14	4.43	7	2	9	23	867	51	173	329	46	19.3
Mckenzie Canyon tuff	M T-BL	2	59.17	16.31	1.51	7.69	0.18	5.48	2.57	1.48	4.92	0.69	2.69	3	0	23	76	493	29	465	175	40	15.2
Mckenzie Canyon tuff	M T-W H	2	72.14	14.76	0.23	2.53	0.08	1.22	0.24	4.35	4.42	0.04	9.60	10	0	11	5	822	90	105	279	45	19.3
Redmond basalt	S95-B312	3	48.61	16.84	1.44	10.70	0.17	9.99	8.45	0.43	3.06	0.31	1.14	163	248	34	227	232	6	302	103	26	6.8
Dry River basalt	S95-B313	3	48.30	15.88	1.84	12.05	0.19	9.65	7.91	0.40	3.30	0.49	1.37	144	282	32	213	219	3	317	153	35	11.3
Deschutes Fm.	S94-B72	3	52.37	19.69	1.18	7.90	0.13	9.74	3.93	0.92	3.80	0.35	1.81	22	89	28	209	427	11	724	133	22	8.3
Deschutes Fm.	S94-B69	3	51.80	16.34	2.07	11.98	0.18	8.15	4.31	0.86	3.94	0.37	2.50	10	36	34	325	372	11	461	134	36	8.6
Deschutes Fm.	95-101	2	51.36	16.11	1.80	12.05	0.18	8.76	4.87	0.59	3.98	0.30	2.23	15	66	35	341	290	2	423	108	27	5.4
Deschutes Fm.	95-100	2	49.42	16.04	1.74	12.17	0.20	10.37	6.34	0.30	3.18	0.22	1.73	37	149	41	341	158	2	274	108	33	5.2
Deep Canyon grade	DPCN-2B	2	63.96	15.66	0.98	5.67	0.16	3.50	1.47	1.97	6.37	0.27	3.48	3	2	18	64	717	27	358	255	46	14.1
Deep Canyon grade	DPCN -1B	2	69.95	15.03	0.47	3.18	0.07	1.52	0.49	3.74	5.46	0.08	5.82	9	0	10	7	768	54	114	376	46	18.4
Deschutes Fm.	95-99	2	53.61	16.30	1.58	10.82	0.16	7.93	4.13	0.96	4.16	0.35	2.36	16	60	25	297	398	11	546	132	26	6.1
Cold Spring lava	95-61	2	56.86	16.57	1.54	9.06	0.15	6.49	3.28	1.22	4.53	0.32	2.49	0	0	17	235	400	18	444	169	27	10.0
Belknap Crater	BKP-1	2	49.81	17.36	1.68	9.85	0.16	9.10	7.20	0.72	3.78	0.35	1.23	107	168	30	203	203	10	515	154	27	15.1
Black Crater	99-35	2	54.12	18.02	1.07	8.04	0.13	8.69	9.21	0.64	3.56	0.33	0.95	50	94	22	170	372	11	568	147	23	7.4
Qb	95-46	2	49.57	16.60	1.51	9.75	0.16	8.67	5.22	0.88	3.56	0.28	1.37	200	343	35	188	220	8	427	131	22	15.2
Yapoah Crater	95-45	2	56.82	18.55	0.84	6.42	0.11	7.59	4.21	1.05	4.24	0.17	1.05	38	55	26	140	322	18	576	119	16	7.2
McKinney Bt	95-89	2	59.26	14.31	1.53	10.41	0.35	4.38	1.73	0.98	6.52	0.52	5.41	0	6	38	99	909	14	232	121	42	10.8
Plainview basalt	95-37	2	52.44	18.09	1.35	8.67	0.15	8.65	5.76	0.75	3.89	0.26	1.36	84	63	21	214	298	10	517	124	24	9.1

#RC (Conrey samples) or SHE (Sherrod data) prefixes removed.
^ Sources: 1 = D.R. Sherrod and R.M. Conrey, unpub.; 2 = R.M. Conrey, unpub.; 3 = D.R. Sherrod, unpub.
* Total Fe as Fe₂O₃. Major element analyses are normalized to 100%.

Table 2. Comparison of Fe-rich Deschutes Fm. lavas with evolved MORB

Area	Tetherow Bt.	Deschutes Fm.	EPR10-12N	Gulf of CA	Iceland
No.	RB-66	S94-B70	DR53	2,18	NAL17
SiO_2	50.11	49.84	51.15	49.28	51.35
TiO_2	2.47	2.44	2.23	2.56	2.16
Al_2O_3	13.57	14.56	13.81	13.70	13.93
FeO *	12.73	12.51	12.59	12.75	12.74
MnO	0.23	0.20		0.25	0.22
MgO	4.48	4.76	6.11	6.08	5.66
CaO	8.38	7.87	10.70	10.47	10.64
Na_2O	3.76	3.55	3.04	4.23	2.70
K_2O	0.83	1.08	0.18	0.30	0.45
P_2O_5	0.58	0.40	0.19	0.39	0.16
FeO */ MgO	2.84	2.63	2.59	2.96	2.25
Ni	0	16	52	30	45
Cr	15	34	65	47	53
Sc	45	39			
V	373	398	374	340	345
Ba	361	374		36	
Rb	10	21	3.0	2.9	4
Sr	369	293	128	224	200
Zr	130	186	139		155
Y	44	46	47		31
Nb	6.1	12.1	5.0		

* Total Fe as FeO*; note difference with Table 1.