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DISCUSSION

INTRODUCTION

The Bend 30- × 60-minute quadrangle has been the locus of volcanism, faulting, and sedimentation for the past 35 million years. It encompasses parts of the Cascade Range and Blue Mountains geomorphic provinces, stretching from snowclad Quaternary stratovolcanoes on the west to bare rocky hills and sparsely forested juniper plains on the east. The Deschutes River and its large tributaries, the Metolius and Crooked Rivers, drain the area (fig. 1, sheet 1). Topographic relief ranges from 3,157 m (10,358 ft) at the top of South Sister to 590 m (1,940 ft) at the floor of the Deschutes and Crooked Rivers where they exit the area at the north-central edge of the map area (cross sections *A–A'''* and *B–B'''*). The map encompasses a part of rapidly growing Deschutes County. The city of Bend, which has over 50,000 people living in its urban growth boundary, lies at the south-central edge of the map. Redmond, Sisters, and a few smaller villages lie scattered along the major transportation routes of U.S. Highways 97 and 20 (fig. 1).

This geologic map depicts the geologic setting as a basis for structural and stratigraphic analysis of the Deschutes basin, a major hydrologic discharge area on the east flank of the Cascade Range. The map also provides a framework for studying potentially active faults of the Sisters fault zone, which trends northwest across the map area from Bend to beyond Sisters. A series of index maps shows the sources of mapping used for our geologic depiction and other sources consulted during the preparation of the map (fig. 2, sheet 1).

ABOUT THE MAP UNITS

Conventional lithologic criteria were used to assign rocks and deposits to geologic map units. For sedimentary strata, grain size and shape, sorting, and bed thickness are the main features used in interpreting origin of deposits. For volcanic rocks, two major subdivisions distinguish lava flows or domes from pyroclastic-flow deposits or tephra-fall deposits. Chemical composition is also used as much as possible; compositional classification relies on the recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks (Le Bas and Streckeisen, 1991) but is modified to include a field for rhyodacite and simplified to use 72 percent SiO_2 as the cutoff for rhyolite, regardless of alkali content. Thus, the compositional divisions are basalt (<52 percent SiO_2), basaltic andesite (≥52 and <57 percent SiO_2), andesite (≥57 and <63 percent SiO_2), dacite (≥63 and <68 percent SiO_2), rhyodacite (≥68 and <72 percent SiO_2), and rhyolite (at least 72 percent SiO_2). Unanalyzed rocks were assigned compositions by visual comparison with analyzed rocks. Features such as phenocryst abundance or remanent magnetization provided additional criteria for distinguishing volcanic units.

Formal stratigraphic member names have been established previously for some strata of the John Day Formation, which is found in the eastern part of the map area. The Deschutes Formation, in the central part of the map area, is also formally named, but separate strata within it are presently named only informally. Few Cascade Range units have been formally named; exceptions are some of the major pyroclastic-flow and tephra-fall deposits exposed in the Bend area. Therefore, informal stratigraphic names are applied to many units in the Cascade Range. For example, the broadly defined unit of Quaternary basaltic andesite (Qba) is subdivided locally to distinguish the lava from major shield volcanoes or other extensive lava flows that can be recognized separately.

Numerical ages are assigned to dated units or to units emplaced over a short period of time and for which the depositional episode is bracketed by events of known age. We use the standard conventions of reporting age in millions of years ago (mega-annum, abbreviated Ma), or, for radiocarbon ages, in carbon-14 years before 1950 A.D. (^{14}C yr B.P.). For stratigraphic units emplaced between 10,000 yr B.P. and 200,000 yr B.P., age is reported in thousands of years ago (kilo-annum, abbreviated ka). All isotopic ages from the map area are listed in tables 1 and 2. Potassium-argon ages (table 2) have been recalculated using modern decay constants (Steiger and Jäger, 1977) and therefore

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may differ slightly from original source publications. A simplified location map (fig. 3, sheet 1) plots the samples reported in table 2.

In our discussion of carbon-14 ages, we distinguish between calibrated years and ^{14}C years to avoid confusion. The ^{14}C time scale diverges from conventional calendar or sidereal years because the relative abundance of ^{14}C in the atmosphere has varied over time (for example, Faure, 1986). Actual age (in sidereal years) generally increases when radiocarbon ages are calibrated for organic materials older than about 2,500 ^{14}C years and decreases for the younger samples (Stuiver and Reimer, 1993).

Magnetic polarity reversals, commonly preserved by volcanic rocks and readily measured during field work, provide another means to constrain the depositional period for some strata and, for Quaternary volcanic rocks, even to assign limiting numerical ages. A simplified stratigraphic column shows several stratigraphic units positioned on the paleomagnetic time scale (fig. 4).

The Description of Map Units explains the basis for subdividing rocks into stratigraphic units shown on the geologic map. It is preceded by the Correlation of Map Units, which shows the relative stratigraphic position of all units. The following explanatory text is devoted to describing in greater detail the age assigned to several stratigraphic units, thereby providing both a stratigraphic synopsis and a summary of recent work.

JOHN DAY FORMATION

The John Day Formation in the map area comprises as much as 4,300 m in thickness of sandstone, shale, ash-fall and ash-flow tuff, and lava flows, including rhyolite domes. Regionally the formation is perhaps best known for fallout tuff and stream-reworked tuffaceous strata exposed at the Painted Hills unit of the John Day National Monument, 100 km east of the map area. Some of the fallout tuff may have been derived from ancestral volcanoes in the Cascade Range (Robinson and others, 1984), but ash-producing volcanoes were also present in the Deschutes basin at the time. The John Day Formation has low permeability owing to diagenetic and hydrothermal alteration of once-glassy material to clay and zeolite minerals, resulting in loss of porosity.

An extensive sequence of southeast-dipping John Day strata is exposed from Haystack Butte southeast nearly to the Crooked River, including the area of Smith Rock State Park. These beds form the upthrown block of the northeast-striking Cyrus Springs fault zone (Smith and others, 1998), and rocks as young as Prineville Basalt (unit Tp) are tilted southeasterly by the deformation. The Deschutes Formation, the next-youngest stratigraphic unit, is undeformed. Thus the age of deformation is bracketed between early Oligocene and late Miocene time. Stratigraphic units across the fault are poorly matched, suggesting more than 7 km of right-lateral slip (Smith and others, 1998).

The John Day Formation is divided into members A through I elsewhere in the central-Oregon region (Peck, 1964; Robinson, 1975). The base of most members is defined by extensive ash-flow tuffs. Of these tuffs, only the member-H basal tuff reaches into the map area, where it forms the youngest John Day strata north of the Cyrus Springs fault zone. Additional temporal correlations are provided by newly obtained isotopic ages of 28.82±0.23 Ma from rhyolite lava at Gray Butte (in unit Tjr) and 29.53±0.09 and 29.57±0.17 Ma from the tuff of Haystack Reservoir (Tjth), which indicate these rocks correlate with member-G strata (Smith and others, 1998). Member-G tuff north of the map area has newly obtained isotopic ages of 29.54±0.10 and 29.61±0.10 Ma (both single-crystal sanidine ages by $^{40}Ar/^{39}Ar$ method; Smith and others, 1998). Previous age estimates were slightly younger—a weighted mean age of 28.3±0.2 Ma on the basis of four sanidine K-Ar ages (Fiebelkorn and others, 1983; Robinson and others, 1990). A lapilli-fall deposit beneath rhyolitic lava at Gray Butte is correlated herein with a deposit found near the base of member F northeast of the map area. This deposit, the tuff of Rodman Spring (Smith and others, 1998), has a $^{40}Ar/^{39}Ar$ sanidine age of 32.49±0.30 Ma. Correlations with members E and B are suggested by the composition of basalt and basaltic andesite lava flows in the lower part of the sequence north of Gray Butte (units Tjb and Tjba). A tentative correlation between poorly exposed, altered welded tuff in the oldest beds of the map area (unit Tjl) and member-A welded tuff elsewhere in the region is the basis for extending the age of the John Day Formation within the map area back as far as late Eocene time.

A K-Ar age of 30.8±0.5 Ma (whole rock; Fiebelkorn and others, 1983) was reported from basaltic andesite lava, but we interpret that rock as an intrusion of John Day age (Tjbi). The dated intrusion cuts rocks as young as the basaltic andesite unit (Tjba). Other ages ranging from about 19 to 17 Ma were reported by Obermiller (1987; table 2) but are too young in view of Oligocene paleontologic ages from interbedded fossil flora and the newly obtained isotopic ages ranging from about 32 to 27 Ma. Isotopic whole-rock ages as young as 10 Ma were reported from rhyolite exposed at Gray Butte, but we consider these ages spurious because the dated material is extensively hydrated (Obermiller, 1987).

Powell Buttes, at the southeast edge of the map area, is made of rhyolite domes and associated strata also of John Day age. The Powell Buttes rocks are relatively undeformed and untilted, unlike the John Day strata in the Gray Butte area. A K-Ar age of 28.3±1.0 Ma was obtained from Powell Buttes east of the map area (table 2). Core from drill holes on the west flank of Powell Buttes penetrated moderately weathered basalt or basaltic andesite lava beginning at 240 m depth; a K-Ar age of 30.1±1.1 Ma (table 2) was obtained from a sample collected at 310- to 320-m depth (Brown and others, 1980a, p. 5; Evans and Brown, 1981). This sample may be reasonably assigned to basaltic andesite of the John Day Formation (unit Tjba) on the basis of its age.

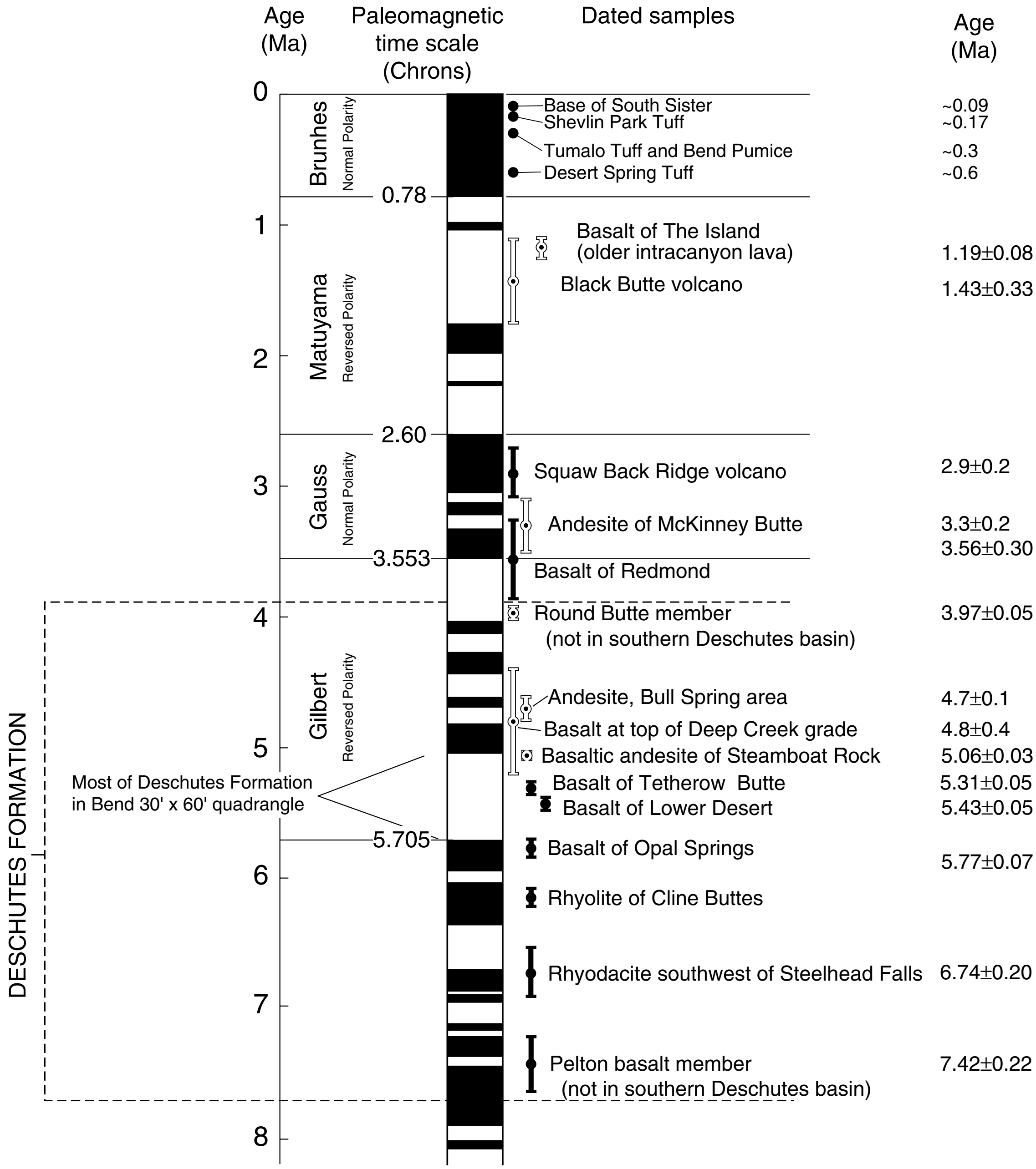


Figure 4. Correlation of selected dated samples with paleomagnetic time scale. Patterns show remanent magnetization: dark fill, normal polarity; white fill, reversed polarity. Bars showing age and standard deviation are similarly patterned. See table 2 for references to age data except those for Pelton basalt and Round Butte members of Smith (1986). Remanent magnetization determined by using portable fluxgate magnetometer. Time scale from Cande and Kent (1992).

DESCHUTES FORMATION

Sedimentary strata, pyroclastic rocks, and fewer lava flows of the Deschutes Formation are found in picturesque exposures along canyons of the Deschutes River and its tributaries north of Bend. The Deschutes Formation sedimentary and pyroclastic rocks were deposited chiefly in a fluvial basin on the east flank of the Cascade Range. Closer to the range crest, lava flows become increasingly abundant near major eruptive centers. Lava flows are also dominant in outcrops and the subsurface to depths of 300 m near Bend. A few lava flows were erupted east and southeast of the basin (Smith and others, 1987a), and intrabasinal cinder cones and small shield volcanoes are located in the area between Sisters, Redmond, and Bend. Isotopic ages indicate that the Deschutes Formation formed between about 7.4 and 4.0 Ma (Armstrong and others, 1975; Smith, 1986; Smith and others, 1987a), but the oldest parts are exposed only north and perhaps east of the map area.

Lava flows and partially to moderately welded ash-flow tuff (ignimbrites) form stratigraphic markers throughout the Deschutes Formation. Many have been named informally by Smith (1986), and his terminology is adopted herein. One ash-flow tuff not previously named, the tuff of Fremont Canyon (Stensland, 1970, tuff 5), and a few lava flows are introduced as additional informally named members of the Deschutes Formation.

As described by Smith (1986, 1987) and Smith and others (1987a), sedimentation in the lower part of the Deschutes Formation was induced by pyroclastic volcanism in the nearby Cascade Range during late Miocene time. Substantial volcaniclastic sediment was deposited in the wake of pyroclastic eruptions that choked the drainage system with volcanic debris. Pyroclastic-flow deposits are found commonly in the lower part of the Deschutes Formation, where they form the ignimbrite members of the unit. In contrast, the upper part of the Deschutes Formation lacks widespread pyroclastic-flow deposits and is dominated by paleosols and minor ash-fall deposits, suggesting that sediment ceased to overwhelm the alluvial system and that pyroclastic flows no longer entered the basin. In the map area, this transition occurred prior to the emplacement of lava flows of the Tetherow Butte member, one of which yielded a whole-rock age of 5.31±0.05 Ma ($^{40}Ar/^{39}Ar$; Smith, 1986) from a sample collected north of the map area.

Most of the Deschutes Formation exposed in the map area was emplaced between 6.74 and 4.7 Ma. The older age is that of the rhyodacite southwest of Steelhead Falls (fig. 4 and table 2), and the younger age is from basaltic andesite (in unit Tda) that caps exposures of Deschutes Formation lava flows near Bull Spring.

PLIOCENE VOLCANIC AND SEDIMENTARY ROCKS YOUNGER THAN THE DESCHUTES FORMATION

Lava flows are the predominant pre-Quaternary strata younger than the Deschutes Formation in the map area. The flows mantle broad areas east of the Deschutes River and accumulated near vents to form small shield volcanoes west of the river. Sedimentary deposits probably once overlay much of the lava east of the Deschutes River but are preserved only adjacent to Powell Buttes and on the lower slopes of terrain underlain by John Day Formation strata northeast and northwest of Gray Butte.

Isotopic ages have been obtained from few Pliocene lava flows emplaced after Deschutes time. The basalt of Redmond (unit Tbr), a plains-forming lava flow that underlies the Redmond area, has an age of 3.56±0.30 Ma ($^{40}Ar/^{39}Ar$, whole rock; Smith, 1986). The basaltic andesite of Squaw Back Ridge (Tbas) forms a shield volcano in the north-central part of the map area; its age is 2.9±0.2 Ma (K-Ar, whole rock; Armstrong and others, 1975). Andesite of McKinney Butte north of Sisters has an age of 3.3±0.2 Ma (K-Ar, whole rock; Armstrong and others, 1975).

The sedimentary deposits (unit QTs) are undated, although ash-fall beds are present locally within the unit and could provide ages. Conceivably some of the sedimentary deposits may be as young as Quaternary.

PLEISTOCENE PYROCLASTIC DEPOSITS FROM THE EAST FLANK OF THE HIGH CASCADES

Several pyroclastic eruptions of Pleistocene age are recorded by deposits exposed near Bend and in adjacent parts of the Cascade Range. From oldest to youngest, the major deposits are the Desert Spring Tuff, the Bend Pumice and Tumalo Tuff (tephra-fall and ash-flow deposits of a single magmatic episode), and the Shevlin Park Tuff. Each is sufficiently unique to form a marker bed useful for assigning relative ages to overlying and underlying units. The most extensive exposures occur along the Sisters fault zone, thus aiding our understanding of the fault history there. Our knowledge of the age of these deposits is derived mainly by stratigraphic correlation with distal tephra in the Basin and Range province of northern California and Nevada, the details of which are scattered throughout the geologic literature and constantly being refined. Other isolated pumice-fall deposits are found throughout the map area, but their age and correlation remain poorly understood.

Desert Spring Tuff

The Desert Spring Tuff is a rhyodacitic pyroclastic-flow deposit erupted about 0.6-0.7 Ma. This age is based on (1) a geochemical correlation of the Desert Spring Tuff with its distal fallout equivalent, the Rye Patch Dam ash bed in the Great Basin of western Nevada (Sarna-Wojcicki and others, 1989), and (2) the fact that the Rye Patch Dam ash bed underlies the Lava Creek B ash bed with small stratigraphic separation in cores from Tulelake, Calif. The age of the Lava Creek B ash bed is 0.62 Ma (Izett and Wilcox, 1982).

An age of 0.63 Ma was suggested for the Desert Spring Tuff (Sarna-Wojcicki and others, 1989) by correlating it to similar ash in a cored section near Tulelake, Calif., and thence by interpolation between the ages of Lava Creek B bed stratigraphically close above it and the Brunhes-Matuyama Chron boundary below (Rieck and others, 1992). In the 1980s, the chron boundary was customarily taken to be 0.73 Ma, but subsequent work has determined a more precise age of 0.78 Ma (Shackleton and others, 1990; Baksi and others, 1992). Presumably the slightly older chron boundary implies a slightly older age for the Desert Spring Tuff. The age range we suggest (0.6–0.7 Ma) is as accurate as is warranted currently, but more precise estimates could be made by assuming constant sedimentation rate in the Tule Lake basin during the 0.17 million years between known dated events (magnetic chronozone boundary and age of Lava Creek B ash bed).

Bend Pumice and Tumalo Tuff

A single eruptive sequence is recorded by rhyolitic fallout tephra and overlying pyroclastic flow deposits, the Bend Pumice and Tumalo Tuff. The Bend Pumice has been geochemically correlated with the Loleta ash bed (Sarna-Wojcicki and others, 1987), whose age is probably about 0.4 to 0.3 Ma. Several K-Ar ages ranging from 0.19±0.08 to 0.44±0.01 Ma have been obtained from (1) plagioclase separated from pumice in the Tumalo Tuff and (2) whole rock obtained from obsidian clasts in epiclastic strata that immediately underlie the Tumalo Tuff (Sarna-Wojcicki and others, 1989). A weighted mean of four ages from plagioclase in the Tumalo Tuff is 0.3±0.1 Ma and is the preferred age (Sarna-Wojcicki and others, 1989). In contrast, hornblende separated from dacitic pumice of the Tumalo Tuff has ages of 1.30±0.23 and 1.04±0.20 Ma (Sarna-Wojcicki and others, 1989). These older ages are explained as a consequence of inherited radiogenic argon or xenocrysts (nonmagmatic crystals incorporated into the magma before or during eruption). Previously determined plagioclase ages of 3.98±1.9 Ma from the Tumalo Tuff and 2.50±2.0 Ma from the Bend Pumice had large analytical errors (Fiebelkorn and others, 1983). An equally ambiguous glass age of 0.83±1.5 Ma was obtained from the fresh core of a dacitic pumice bomb (Armstrong and others, 1975).

Shevlin Park Tuff

Youngest of the Bend pyroclastic deposits is the Shevlin Park Tuff, an andesitic ash-flow tuff. Associated proximal or medial fallout deposits are unknown. The Shevlin Park Tuff is thought to be younger than about 0.17 Ma on the basis of several correlations.

(1) The unit has a distal fallout tephra thought to be the Summer Lake JJ ash bed on the basis of geochemical and paleomagnetic correlations (Gardner and others, 1992).

(2) The Summer Lake JJ ash bed is underlain by the Summer Lake KK ash bed, which is the distal fallout of an andesitic ash-flow tuff at Medicine Lake volcano, Calif. Stratigraphic separation between these two units is 30 to 40 cm (Davis, 1985, fig. 4).

(3) The Medicine Lake-derived andesitic ash-flow tuff has a newly determined $^{40}Ar/^{39}Ar$ age of 0.171±0.043 Ma (Herrero-Bervera and others, 1994); its age was previously known as 0.160±0.025 Ma on the basis of conventional K-Ar ages from stratigraphically bracketing units at Medicine Lake volcano (J.M. Donnelly-Nolan and L.B. Gray, in Rieck and others, 1992).

Other Pleistocene pumice-fall deposits

Pumice lapilli and ash of fallout origin are exposed sporadically in roadcuts, streambanks, and quarries throughout the area. Some of these deposits correlate with the Bend Pumice, itself the most notable of Pleistocene tephra-fall deposits in the area. Several deposits, however, lie above the Tumalo Tuff and are therefore younger than Bend Pumice. Compositionally the deposits range from rhyolite to andesite, with andesitic fallout tephra being uncommon.

Aside from Bend Pumice, the only other Pleistocene tephra-fall deposit of known regional correlation is the pumice of Columbia Canal, which is as thick as 3 m in exposures along the Columbia Southern Canal, sec. 20, T. 17 S., R. 11 E. This deposit has also been called the pumice of Columbia Canyon (Hill and Taylor, 1990), but we modify the title here to more closely approximate a named geographic feature. The relatively coarse size of pumiceous lapilli (to 2 cm) and obsidian clasts (to 4 cm) suggests the deposit was erupted from a nearby source, probably from a vent near Bearwallow Butte, about 10 km to the west.

The pumice of Columbia Canal is chemically similar to ash bed NN at Summer Lake (Sarna-Wojcicki and others, 1989). Ash bed NN is older than bed KK, whose age is 0.171±0.043 Ma (Herrero-Bervera and others, 1994); stratigraphically, NN underlies KK by about 4.5 m (Davis, 1985). Given the large analytical uncertainty in the KK age and the large stratigraphic separation between beds NN and KK, it is difficult to place the age of NN more convincingly than between about 170,000 and 300,000 years.

Eruptive sources

The Desert Spring, Tumalo, and Shevlin Park Tuffs were erupted from volcanic centers west of Bend, on the basis of their distribution and diminished welding outward from the proposed source area. The two major fallout deposits, Bend Pumice and pumice of Columbia Canal, become coarser grained westward toward the same general area. This area has been called the Tumalo volcanic center and defined to include a 25-km-long, south-trending belt of rhyolite domes extending from Melvin Butte to Edison Butte (fig. 1; Hill, 1988; Hill and Taylor, 1990). We prefer a more restricted definition that encompasses the volcanic highland from Melvin Butte south to Tumalo Creek valley, an area about 15 km across.

Neither the precise location nor the size and structure has been determined for the volcanoes that erupted the major pyroclastic deposits. The largest buildup of middle and late Pleistocene rhyolite and rhyodacite domes (units Qr and Qrd), however, underlies the area surrounding Triangle Hill and includes domes compositionally similar to the Bend Pumice and Tumalo Tuff (Hill, 1992a). Silicic vent deposits (Qsv) are exposed locally adjacent to the domes and have been penetrated by drill hole CEBH–7, 1 km southwest of Triangle Hill (drill hole labeled on map sheet). The Triangle

Hill area is also remarkable for its abundance of andesitic cinder cones (in unit Qc), similar in composition to the Shevlin Park Tuff. Elsewhere, most Quaternary cinder cones shown on the geologic map are basaltic andesite or basalt in composition, and nowhere do they form such a broadly coalesced field as in the Triangle Hill area. A 10-mGal negative gravity anomaly about 5 km across coincides with the cluster of rhyolite domes and andesitic cinder cones in the Triangle Hill area (fig. 5, sheet 1).

GLACIATION

Cascade Range glaciers have expanded and shrunk repeatedly in Quaternary time. Deposits of two major Pleistocene glaciations have been described from the map area, the older Jack Creek and younger Cabot Creek glaciations (Scott, 1977). The Cabot Creek glaciation is customarily divided into Suttle Lake and Canyon Creek advances. Areally restricted Holocene glacier advances occurred at least twice during the past few thousand years, during what is commonly referred to as Neoglaciation. The distinction among various deposits is based largely on soil profile development, thickness of weathering rinds on clasts in soils formed in the deposits, and the degree of preservation of moraines. For example, originally sharp-crested moraines become increasingly rounded with time. The following summary of deposits is drawn mainly from work by Scott (1977).

The Jack Creek glaciation is the oldest from which moraines are preserved. Mass wasting has modified lateral and terminal moraines so they display broadly rounded crests. Till (unit Qgj) and outwash (Qoj) of the Jack Creek glaciation bear soils about 2 m thick with textural B horizons (evidence of clay accumulation). Clasts in the B horizon have mean weathering-rind thicknesses of 0.5–0.7 mm. Deposits of Jack Creek age are restricted to an area east of Three Fingered Jack. Evidently glaciers of the subsequent Suttle Lake advance were more extensive than those of Jack Creek age along most of the Cascade Range in the map area. The preservation of till in the Jack Creek area was aided by the growth of Three Fingered Jack volcano, the presence of which forced glaciers of Suttle Lake age into the areas now occupied by Canyon and First Creeks, thus saving the Jack Creek moraines from erosion and burial (Scott and others, 1996). Although not dated directly, Jack Creek glaciation is believed correlative with the Hayden Creek glaciation in Washington, which is thought to be about 140,000 years in age (Colman and Pierce, 1981; Easterbrook, 1986).

Deposits of the Cabot Creek glaciation are commonly assigned to an older Suttle Lake advance (unit Qgs) and a younger Canyon Creek advance (unit Qgc). A mountain ice sheet covered the High Cascades during the Suttle Lake advance, which is the last major glacial advance in the area, and the resulting deposits form a widespread band at middle elevations on both flanks of the High Cascades. Suttle Lake itself is impounded by prominent moraines left by the ice advance. Outwash of Suttle Lake age (Qos) floors much of the Metolius River valley and forms low terraces only a few meters above present streams. Deposits of Suttle Lake age bear soils about 1 m thick that have cambic B horizons. Weathering rinds on clasts in B horizons are 0.2 mm or thinner. Although not directly dated, the Suttle Lake advance is correlative with the Evans Creek stade of the Fraser glaciation of Washington on the basis of weathering similarities. The Evans Creek probably culminated in alpine areas about 20,000 years ago (Porter and others, 1983).

Deposits of the Canyon Creek advance (unit Qgc) of the Cabot Creek glaciation are restricted to cirques and valley heads near the Cascade Range crest. Moraines are found on northerly and easterly cirques of Three Fingered Jack and Mount Washington and on the flanks of the Three Sisters and Broken Top. The Canyon Creek advance is thought to be correlative with the Hyak advance of the Fraser glaciation, which occurred in the Cascade Range of Washington between about 12,500 and 11,000 years ago (Porter and others, 1983). Canyon Creek drift on Broken Top is overlain by Cayuse Crater scoria (see unit Qbcy), which is older than 9,500 years. No other data bear on the age of the Canyon Creek advance in the map area.

Two minor glacial advances, described here informally as early and late Neoglacial episodes, postdate the deposition of ash from the Mazama eruption (6,845 ^{14}C yr B.P.; about 7,650 years ago when calibrated to sidereal years). The deposits (unit Qgn) are too restricted to subdivide by age at the scale of this map. Moraines of early Neoglacial age are slightly more degraded than those of late Neoglacial age (Scott, 1990). The approximately 2,000-yr-old tephra from Rock Mesa and Devils Hill chain of vents lies upon moraines of early Neoglacial age in the Three Sisters area but was buried or destroyed by glacial advances that deposited the younger moraines.

VOLCANOES OF THE THREE SISTERS AREA

The Three Sisters and Broken Top form a volcanic field active since middle Pleistocene time. Taken together, the group accounts for 30–40 km^3 of eruptive products. Oldest is Broken Top, a basaltic andesite volcano containing a few andesitic, dacitic, and rhyodacitic domes and lava flows (Taylor, 1978, 1990). A small-volume dacitic pyroclastic-flow deposit was emplaced high on the southwest flank and today is well-exposed in a cirque wall. Early-erupted lava on Broken Top's east flank was emplaced before 213±9 ka, the age of interlayered rhyodacite of Tam MacArthur Rim (unit Qrdt), and some Broken Top lava is slightly younger (Hill, 1992a).

The Three Sisters themselves are progressively younger from north to south. North Sister, the oldest of the three, is a steep-sided basaltic andesite shield volcano. The North Sister is younger than 171 ka because its lava overlies the Shevlin Park Tuff (Taylor, 1990).

Middle and South Sisters are diverse in composition, in contrast to North Sister. The Middle Sister cone, entirely younger than North Sister, grew by eruptions of andesite, dacite, and basaltic andesite lava. Rhyolite is found only in a flow on the northwest side, which at its northwest terminus forms the Obsidian Cliffs. A highly porphyritic basaltic andesite (SiO_2 approximately 52–53 percent; Taylor, 1987) was erupted late in cone growth and now mantles most of the volcano's southwest sector. Dacitic lava flows are the youngest known eruptive product from Middle Sister.

South Sister began to grow about the same time as Middle Sister, but its eruptions have continued into Holocene time, making it the youngest of the Three Sisters. Its products range in composition from basaltic andesite to rhyolite, and rhyolite is more abundant than at any other Quaternary volcano in the map area. Dacitic lava from the volcano's northeastern base has a K-Ar age of 93±11 ka (Hill, 1992a) and its summit is indented by a crater of presumed latest Pleistocene age (older than 10,000 yr B.P.). This age is deduced on the basis of substantial erosion that has gutted the summit cone and isolated lava flows on an eastern prominence that was once connected to the summit area (Wozniak, 1982). The main-cone eruptive sequence indicates no sequential pattern of composition or eruptive style. Explosive eruptions that produced thick near-vent tephra deposits occurred on several occasions during Pleistocene and Holocene time. The volcano's summit comprises interlayered lava and scoria of basaltic andesite, andesite, and dacite.

A latest Pleistocene or Holocene basaltic andesite lava flow erupted from Le Conte Crater, a cinder cone at the southwest base of South Sister. Even younger Holocene rhyolite erupted from fissures on the southwest, southeast, and northeast flanks. The young rhyolitic eruptions (unit Qrrm), which formed the Rock Mesa and Devils Hill chain of vents, occurred during two brief episodes between 2,300 and 2,000 ^{14}C yr B.P. (Scott, 1987). In addition to thick stubby lava flows, the eruptions produced tephra showers and small pyroclastic flows. The fallout accumulated to a thickness in excess of 10 m near the vents. Rapid snowmelt early in each eruption triggered a few small lahars (Scott, 1987).

South Sister poses a potential volcanic hazards threat if future eruptions resemble those of the recent past. Tephra fallout might accumulate to 1–2 cm thick in the Bend area, and small-volume lahars and pyroclastic flows would endanger anyone on the slopes or areas nearby.

Nearby Mount Bachelor, south of the map area, is a basaltic andesite shield better known for its downhill skiing than its volcanic history. It forms the northernmost part of the Mount Bachelor volcanic chain, a string of shield volcanoes active from about 18 to 7 ka and amassing 30-50 km^3 of lava and near-vent deposits (Scott, 1990; Scott and Gardner, 1992; Gardner, 1994). Eruptions along the chain progressed generally northward, with youngest activity on the north flank of Mount Bachelor at a cinder vent known informally as Egan cone* (south edge of map area). Age of the Egan cone is known only imprecisely. The Egan cone and its lava flows are older than the Mazama ash bed (older than about 7,650 calibrated yr B.P.). They were only slightly weathered prior to Mazama time, so they may be only slightly older than 7,650 yr. On the other hand, paleomagnetic field directions suggest that distal lava from Egan cone may be closer in age to lava from the summit cone of Mount Bachelor, that is, about 11,000–12,500 yr (Scott and Gardner, 1992).

HOLOCENE LAVA FLOWS NEAR SANTIAM AND MCKENZIE PASSES

Basalt and basaltic andesite lava flows were erupted from cinder cones and small shield volcanoes in the area from Santiam Pass to McKenzie Pass. Most are younger than the Mazama ash bed (younger than 7,650 yr), and their rugged surfaces provide striking contrast to older glaciated lava in the region. Substantial ash issued from the vents and accumulated in downwind areas to as much as 3 m thick.

Radiocarbon ages from organic material trapped within or closely underlying some eruptive products span the time from nearly 4,000 to 1,300 years ago and cluster into three groups. The oldest group (1), with only two ages, indicates eruptions 4,000 to 3,000 years ago but is poorly constrained. Better established are (2) a group comprising several ages from the time between 2,900 and 2,500 years ago; and (3) the youngest group, with ages between about 2,000 and 1,300 years ago (table 1). The ages indicate no discernible geographic pattern of age progression; eruptions occurred sporadically in both the McKenzie Pass and western Santiam Pass areas through most of the approximately 2,700-year duration. Two small eruptive centers (in unit Qyc) are known from the eastern Santiam Pass area at Blue Lake and a chain of spatter cones on the lower northeast flank of Mount Washington.

In the following discussion, all ages are carbon-14 ages (reported as ^{14}C years before present) and calculated using the preferred half-life of 5,568 yr. We have provided the comparison between noncalibrated and calibrated ages (using the method of Stuiver and Reimer, 1993) for the Holocene lava flows near Santiam and McKenzie Passes (figs. 6*A*, *B*). None of the calibrations change our observations about the apparently random north-south position of vents with time (no age progression).

The oldest age from post-Mazama lava flows in the area of Santiam and McKenzie Passes is 3,850±215 ^{14}C yr B.P, the age assigned to the Fish Lake lava flow from Nash Crater (Taylor, 1968, 1990; Chatters, 1968). An age of 3,440±250 ^{14}C yr B.P. was obtained from a charred conifer limb above fine ash from the Sand Mountain chain of vents and beneath coarse ash and lapilli from the Blue Lake vent (sampled near Suttle Lake). If correct, the age places a minimum age on part of the Sand Mountain volcanic field and a maximum age for the Blue Lake volcano (can't be older than 3,440 ^{14}C yr B.P.). The age of Blue Lake volcano is discussed as part of the youngest episode.

*Informal geographic name

The middle group (2) has ages of eruptive activity dating back to about 3,000 ^{14}C yr B.P. An age of 2,800±150 ^{14}C yr B.P. is the maximum age for Twin Craters, a vent near the southern part of the Holocene lava field near McKenzie Pass. Clear Lake, at the west-central edge of the field, is thought to have been created by lava flows after 2,750±45 ^{14}C yr B.P. (J.M. Licciardi, unpub. data, 1999). This age, newly determined by accelerator mass spectrometric methods and possessing small analytical uncertainty, was from a sample of wood from a drowned snag originally collected in 1964 by E.M. Taylor. A corroborating age—2,705±200 ^{14}C yr B.P., also with large analytical uncertainty—was obtained from wood collected from the outer layers of a different drowned tree in the lake (Benson, 1965). Another age determination from the same area—this sample from a charred log buried by the lava flow on the east side of the lake—produced an age of 2,990±300 ^{14}C yr B.P. (E.M. Taylor in Champion, 1980; also reported as 3,000 yr B.P. without error in Taylor, 1968, 1981). All these ages overlap at the reported analytical uncertainty (fig. 6*A*), but the 2,750-yr age is most precise.

At the north end of the Sand Mountain volcanic field, an age of 2,590±150 ^{14}C yr B.P. was obtained from charcoal at the contact between soil developed on a lateral moraine and scoriaceous fine ash from Nash Crater or the Sand Mountain chain of vents (table 1). This age places a maximum age on eruptive activity in the immediate area of Santiam Junction, including Little Nash Crater, the youngest vent in that area. An age of 2,883±175 ^{14}C yr B.P. was determined from charcoal roots in a tree mold formed by lava from Little Belknap, in the southern part of the field. Charred roots from another tree mold in the area were used to date lava from South Belknap cone*; its age is 2,635±50 ^{14}C yr B.P. (J.M. Licciardi, unpub. data, 1999). This South Belknap tree mold is the same site for charcoal collected in the 1960s by Taylor, who obtained an age of 1,775±400 ^{14}C yr B.P. (E.M. Taylor, in Champion, 1980). The older age (2,635) is preferred on the basis of high concentrations of cosmogenic ^{3}He that indicate a greater surface exposure age than the 1,775-yr age permits (J.M. Licciardi, written commun., 1999). The stratigraphic relations between Little Belknap and adjacent Belknap Crater are discussed more fully as part of the next group of ages.

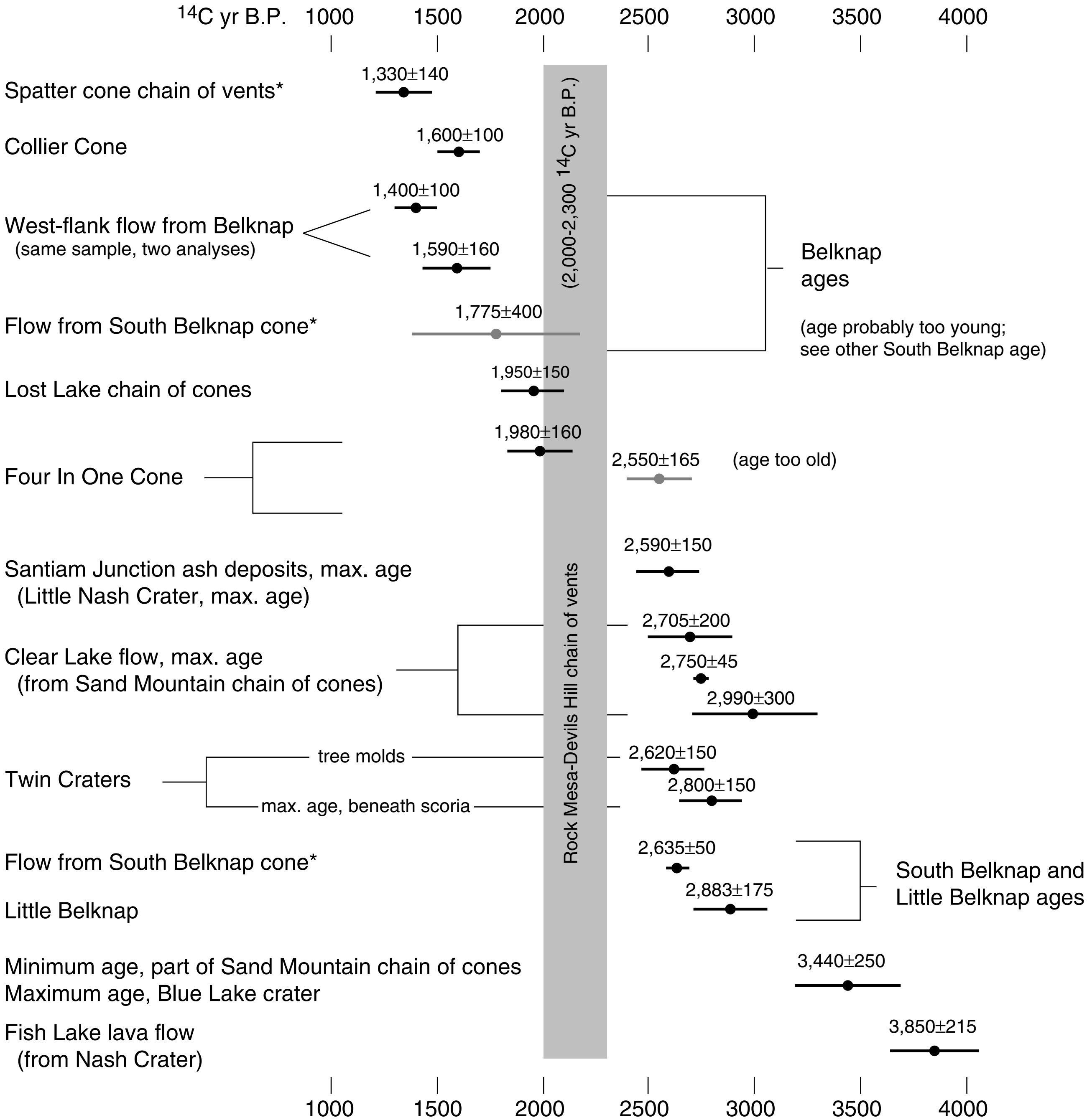
Ages younger than 2,000 ^{14}C yr B.P. are also scattered across the lava field and define the youngest group (3). At the north end of the field, the Lost Lake chain of cones was active about 1,950±150 ^{14}C yr B.P. (Taylor, 1968; Chatters, 1968). Four In One Cone at the southerly limit of the lava field has an age of about 1,980±160 ^{14}C yr B.P. The charcoal from beneath the Four In One tephra overlies a thin, fine white silicic tephra thought to have been erupted from Rock Mesa or Devils Hill chain of vents between about 2,000 and 2,300 years ago (W.E. Scott, unpub. data). An older age of 2,550±165 ^{14}C yr B.P. from the Four In One tephra (Taylor, 1968; Chatters, 1968) is from the core of a tree already of substantial girth by the time of the Four In One eruption (older age shown in gray on fig. 6).

Stratigraphic relations of tephra and lava flows indicate the following relative ages for four units in the southern part of the field: Little Belknap (oldest), then Yapoah Crater, then Four In One Cone, then Collier Cone (youngest). Collier Cone has an age of 1,600±100 ^{14}C yr B.P. and the preferred age for Four In One Cone is 1,980±160 ^{14}C yr B.P.

Belknap Crater's age is perhaps the most difficult to define precisely, and the Belknap shield has probably grown through repeated eruptions. As mentioned previously, South Belknap cone* is considered to be about 2,635 ^{14}C yr B.P. Charcoal from beneath a flow that traveled down the west flank of Belknap Crater yielded two ages: 1,590±160 and 1,400±100 ^{14}C yr B.P.; this lava emanated from Belknap's northerly summit vent. These two ages overlap at the level of statistical certainty (fig. 6*A*), allowing them to be interpreted as roughly the same age or ages that differ by as much as eight centuries. An additional age criterion is provided by the relation between Belknap Crater and Little Belknap: early Belknap lava flows were already emplaced before construction of the Little Belknap volcano. The ages indicate that vents have been active near or at the site of Belknap Crater intermittently through an interval of at least 1,200 years.

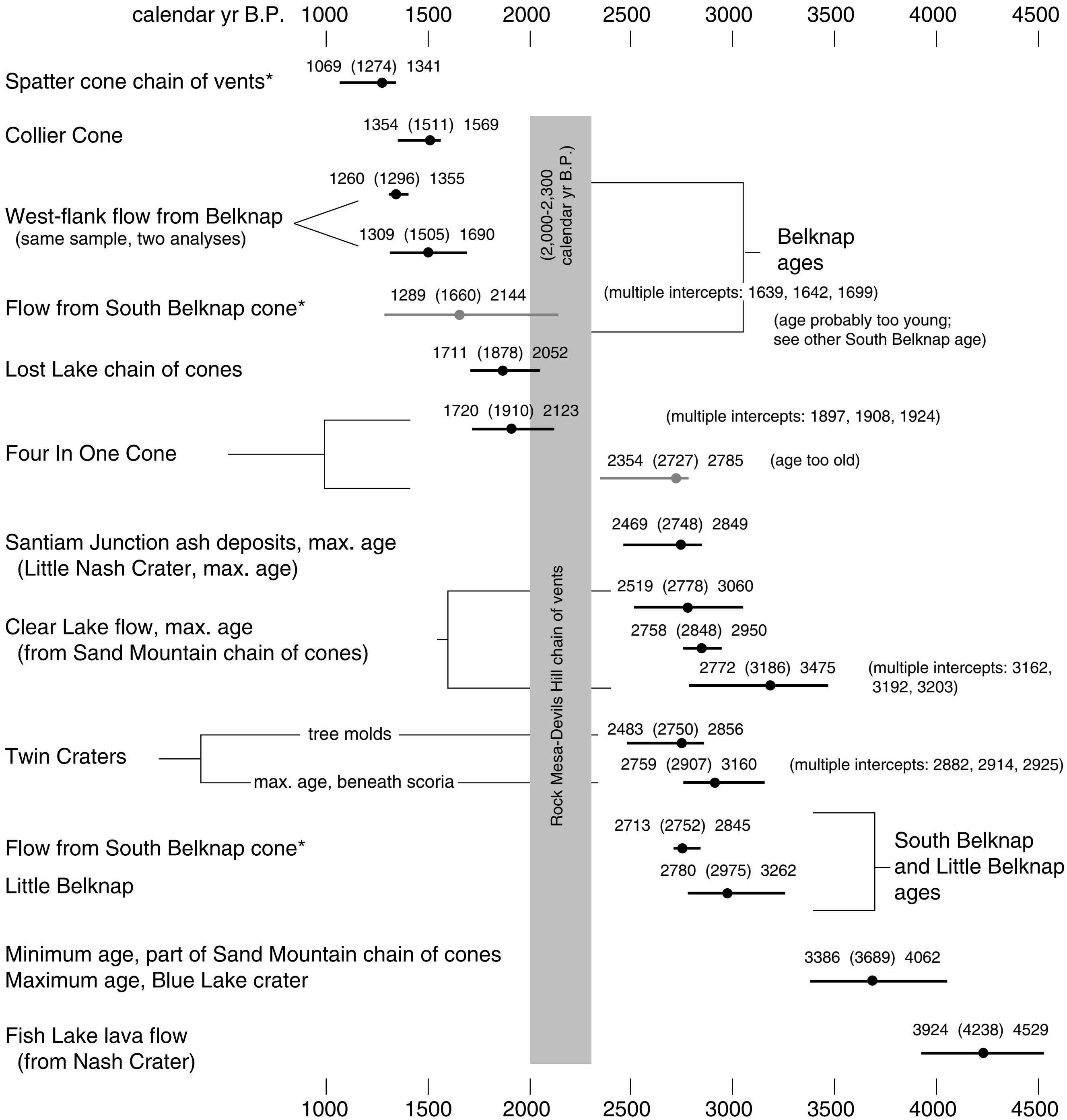
Blue Lake crater and a chain of spatter cones between Blue Lake and Mount Washington may be the youngest volcanic features in the Santiam and McKenzie Passes region. Neither vent fed lava flows. An age of 1,330±140 ^{14}C yr B.P. was obtained from charred forest litter collected beneath the spatter-cone cinders (table 1). The chain of spatter cones trends N. 18° E., on line with Blue Lake, 6 km distant. Tephra from Blue Lake crater is petrographically similar to that from the chain of spatter cones—moderately porphyritic with 10–15 percent plagioclase phenocrysts as large as 3 mm and about 1 percent olivine phenocrysts, 1 mm across. The alignment of the spatter cone chain of vents with Blue Lake crater and the petrographic similarity of their tephra lead us to suggest that these vents were active during a single eruptive episode about 1,330 ^{14}C years ago. An age of 3,440±250 ^{14}C yr B.P. had been previously assigned to Blue Lake crater (Taylor, 1968, 1981), but the tree limb dated lay at the interface between tephra from Blue Lake crater and underlying ash of Sand Mountain. We think it likely that the limb was part of a tree killed by the Sand Mountain eruptions and subsequently buried by younger Blue Lake deposits—and not a casualty of the Blue Lake eruptions. Thus, the 3,440-yr age may provide only a maximum limiting age for the tephra from Blue Lake crater but a useful age for the ash of Sand Mountain. We failed to find additional organic material suitable for dating the tephra from Blue Lake crater.

Blue Lake crater erupted a tephra plume of coarse blocks and lapilli that blanket the Suttle Lake trough. Isopach lines on the map show that the tephra plume was deflected by gentle winds blowing to the east-northeast. The plume is thicker than 2 m along the southwestern shore of Suttle Lake. Blue Lake itself is surrounded by a modest cone of cinder and agglutinate.



*Informal geographic name

Figure 6A. Carbon-14 ages from Santiam and McKenzie Passes: 6*A*, noncalibrated, in ^{14}C yr B.P.; 6*B*, calibrated yr B.P. Carbon-14 ages in the 2,000-2,300-yr range are little affected by calibration, so the stratigraphic horizon occupied by tephra from the Rock Mesa-Devils Hill chain of vents is shown in the same position on figures 6*A* and 6*B*.



*Informal geographic name

Figure 6B. Carbon-14 ages from Santiam and McKenzie Passes: 6*A*, noncalibrated, in ^{14}C yr B.P.; 6*B*, calibrated yr B.P. Carbon-14 ages in the 2,000-2,300-yr range are little affected by calibration, so the stratigraphic horizon occupied by tephra from the Rock Mesa-Devils Hill chain of vents is shown in the same position on figures 6*A* and 6*B*.

SISTERS FAULT ZONE AND TUMALO FAULT

The Sisters fault zone comprises nearly 50 mapped faults extending from Black Butte southeastward through Sisters and beyond Bend (Lawrence, 1976; Pezzopane and Weldon, 1993, their fig. 2). Total length of the zone is 60 km; width ranges from 5 to 15 km. The Tumalo fault, longest single fault strand in the zone, can be traced nearly continuously for 47 km, reaching from 3 km south of the map area to 4 km north of Sisters. Shorter faults range in length from 0.5 to 20 km.

Sense of slip is unknown for any of the faults. Dip separation is apparent, but some slip may be oblique. Displacement of a lobate flow of basaltic andesite that crosses the Tumalo fault suggests a small component of right-lateral separation (Mimura, 1992), but even the evidence for that example is arguable. Dip separation is as great as 60–70 m near Tumalo Dam on the basis of topographic escarpments underlain by Pliocene lava flows of the Deschutes Formation. Quaternary lava flows younger than 0.78 Ma in the same area have escarpments of only 6–10 m.

Lava flows in the suburbs southeast of Bend have escarpments as high as 15 m. A K-Ar age of 2.7±0.3 Ma was reported from a lava flow in one of these escarpments (table 2, Sample No. 86–3), but we suspect the age is too old. That lava flow (in unit Qbn) was erupted from a vent on the north flank of Newberry volcano, possesses normal-polarity magnetization, and is likely younger than 0.78 Ma. Pilot Butte lava in Bend is offset a minimum of 20 m (downthrown side buried). Pilot Butte and its lava is thought to be younger than 0.78 Ma on the basis of normal-polarity magnetization. A poorly exposed white rhyolitic tephra, of unknown correlation but probably younger than the Bend Pumice, mantles the lower southwest flank of the butte. Little is known of Pilot Butte's age, which is important for estimating the rate of faulting.

The Tumalo fault and a few other strands of the Sisters fault zone near Bend cut the Shevlin Park Tuff, which indicates offset occurring more recently than about 170,000 years ago. A fault-inspection trench dug by M.A. Hemphill-Haley (Univ. of Oregon) north of Tumalo exposed fractured and slightly faulted alluvial deposits overlain by undeformed alluvium (field evidence we viewed with Hemphill-Haley in October 1994). The undeformed alluvium has been in place since 25,000–50,000 yr B.P., an age crudely estimated by us on basis of soil weathering profiles. Thus, we tentatively accept about 25,000 yr as the youngest possible age of recent faulting at that location. Corroborative field investigations are lacking elsewhere along the zone but should be undertaken prior to siting critical facilities near or along faults in the Sisters fault zone. We remain skeptical that any of the faults have been active in the past 10,000 yr, although it has been suggested that the Mazama ash bed (age 6,845±50 ^{14}C yr) is displaced near Bend (Fisk and others, 1993). By all accounts, the Sisters fault zone or faults along it are considered potentially active (U.S. Army Corps of Engineers, 1983a, 1983b; L.R. Squier Associates, 1984; Hawkins and others, 1988; Geomatrix Consultants, 1995).

Earliest age of offset is unknown. The Deschutes Formation, oldest stratigraphic unit exposed along the fault zone west of Redmond, shows only rare examples of faulting during deposition (Stensland, 1970; Smith, 1986; our mapping), but the Sisters fault zone is located mostly southwest of the main outcrop belt of the Deschutes Formation.

Early views held that the Sisters fault zone is the along-strike extension of the Brothers fault zone (Lawrence, 1976; Peterson and others, 1976), which is generally viewed as containing discontinuous normal faults developed along a right-lateral transverse fault zone that extends southeast of the map area across eastern Oregon. More recent opinion accepts the Sisters and Brothers fault zones as distinct structural zones (Hawkins and others, 1988, 1989; MacLeod and Sherrod, 1988; Pezzopane and Weldon, 1993), although the gross structural styles may be similar. The Brothers fault zone is buried by Pleistocene lava flows from Newberry volcano (unit Qbn) in the area where it terminates, merges, or steps westward into the Sisters fault zone.

An interesting interpretation by Hawkins and others (1988) tries to reconcile recency of faulting and the trend of distinct fault zones where they nearly overlap. By that interpretation, the Brothers fault zone terminates roughly where the Sisters fault zone begins (a 5- to 7-km gap separates the fault zones), and an even more westerly zone extends from the northwest rift system of Newberry volcano through the west side of Bend to Black Butte (Metolius fault zone of Hawkins and others, 1988). We see little point in subdividing the Sisters fault zone into western and eastern parts, given the limited knowledge of fault history in the area.

GREEN RIDGE AND THE HIGH CASCADES GRABEN

The escarpment of Green Ridge (cross section *A–A*') marks the east side of a major north-trending graben (Taylor, 1981; Smith and Taylor, 1983). The graben is 30 km wide and 50 km long, reaching from south of Mount Jefferson to nearly the Three Sisters (fig. 7). The western graben-bounding faults form the Horse Creek fault zone. A strand of the Horse Creek fault system lies in the southwest corner of the map area (cross section *B–B*').

Displacement on the Green Ridge and Horse Creek fault zones took place in late Miocene and early Pliocene time. Motion along the Green Ridge fault zone isolated the Deschutes basin from now-buried volcanic centers in the High Cascades beginning about 5.4 Ma (Smith and others, 1987a). Rocks as young as about 5 Ma are exposed at the top of the 650-m escarpment of Green Ridge (Armstrong and others, 1975), whereas the downthrown block is mantled by Pliocene and Quaternary sedimentary deposits. Displacement is at least 1 km, on the basis of an age of 1.81 Ma from the base of drill hole SP 77–24 at Santiam Pass (cross section *A–A*') (Hill and Priest, 1992).

The Horse Creek fault zone displaces 5- to 6-Ma strata as much as 670 m down along a fault north of the McKenzie

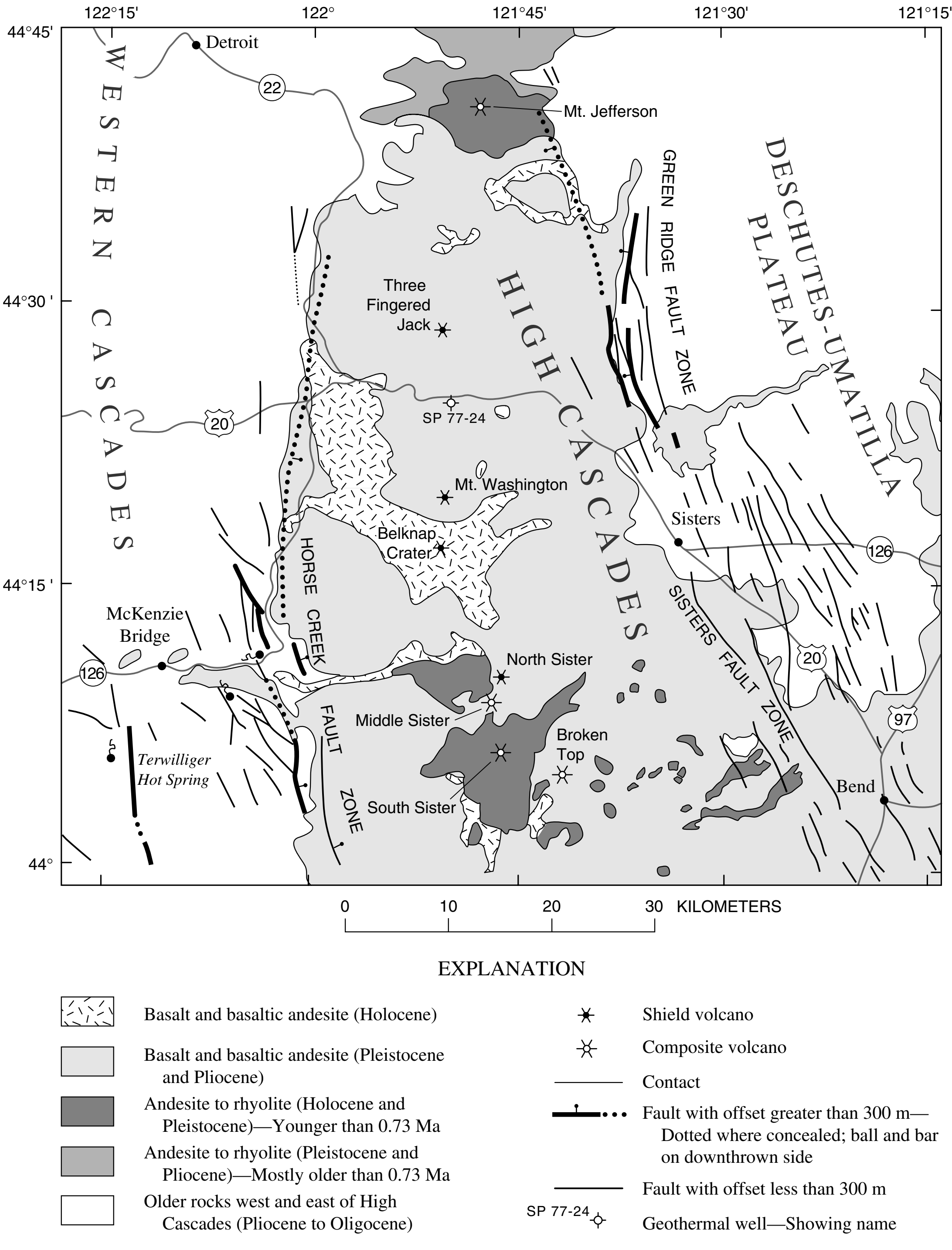


Figure 7. Map showing area of High Cascades and bounding faults on east and west sides. Generalized from Sherrod and Smith (2000) and this map.

River (Brown and others, 1980b); cumulative mapped offset is as much as 850 m south of the McKenzie River (Priest and others, 1988). An additional 400 m of offset may be indicated by a steep unconformity perhaps resulting from lava buttressing a fault escarpment in the vicinity of Scott Creek (Priest and others, 1988). Thus, demonstrable graben subsidence is on the order of about 1.3 km. Headward erosion by the McKenzie River breached the escarpment by late Pliocene time. About 1.7 Ma, the basalt of Roney Creek flowed from a source in the High Cascades westward across the fault trace and along the McKenzie River valley (Priest and others, 1988). The fault has been inactive since the emplacement of the basalt of Roney Creek.

Seismic reflection experiments along a line that traversed the Cascade Range between lat 44°10' and 44°15' had high noise-to-signal ratios and failed to establish the magnitude of offset on the Horse Creek fault zone (Keach and others, 1989). The line ends near the town of Sisters, where offset on the Green Ridge fault zone may have decreased to less than 100 m; no escarpment was imaged by the seismic reflection profiling. The conclusion drawn from the seismic data was that the Green Ridge fault zone has diminishing structural relief southward toward the town of Sisters (Keach and others, 1989).

A magnetotelluric profile that trends roughly east-west through the Middle Sister approached the Sisters fault zone near Three Creek Butte, 16 km south of the town of Sisters (fig. 7; line *C–C'* in Livelybrooks and others, 1989). This profile showed a shallow conductive layer thickening abruptly from 0.3 to 1.8 km as it passes westward near Three Creek Butte. The conductive layer is overlain by an 0.7-km-thick resistive layer of unvarying thickness. The interpretation offered was the existence of a major fault buried by Quaternary deposits (Livelybrooks and others, 1989). The profile's geometry suggests that such a fault would project to the surface about 4 km east of Three Creek Butte, in line with the on-strike projection of a fault in the Sisters fault zone shown on our geologic map (at about station No. 10 shown on fig. 5).

Despite its magnitude of offset, the fault interpreted by Livelybrooks and others (1989) from the magnetotelluric data lacks expression on Bouguer gravity maps (Pitts and Couch, 1978; Couch and others, 1981). But gravity data rarely demarcate well-known examples of some other prominent Cascade Range graben-bounding faults, such as the Horse Creek fault. These failures probably result from insufficient density contrasts across the fault zones.

To summarize the east-side graben-bounding faults located on the Bend geologic map, we are left with an image of faults that vary substantially in offset along their length. The Green Ridge fault zone merges south-southeastward into the Sisters fault zone, judging from the structural interpretation provided by the magnetotelluric profiling. Offset of 1–2 km characterizes some parts of the Green Ridge and Sisters fault zones. Many faults in the zone show only minor offset. The major faults lie toward the west limit of the fault zones; any faults farther west are buried by Quaternary lava flows and pyroclastic rocks of the Cascade Range and lack geophysical expression.

ACKNOWLEDGMENTS

Access to many parts of the map area has been possible only through permission granted willingly by numerous property owners. We acknowledge the work by Donald E. Stensland (deceased), whose mapping in the late 1960s has proven exceptionally thorough and accurate. Much of his work is incorporated here with little or no modification.

Our collaboration with colleagues Marshall Gannett (U.S. Geological Survey) and Ken Lite, Jr., Sarah Gates, and Karl Wozniak (Oregon Department of Water Resources) has sharpened our thinking about the hydrology of the Deschutes basin. We also have benefited from field studies of the Sisters fault zone by Mark Hemphill-Haley (University of Oregon). Joe Licciardi (Oregon State University) shared his newly obtained radiocarbon ages and allowed us to incorporate them into our tables, figures, and discussion. Marvin Lanphere (U.S. Geological Survey) provided $^{40}Ar/^{39}Ar$ ages for two buttes in the Deschutes basin whose ages have puzzled geologists since the 1930s. As is true of most geologists working in central Oregon, we turned periodically to Larry Chitwood and Bob Jensen (both of the U.S. Forest Service, Deschutes National Forest) to share in their knowledge of the area.

The manuscript was reviewed by Marshall Gannett, Bob Christiansen, Jan Zigler (all of U.S. Geological Survey), and Britt Hill (Southwest Research Institute), who graciously provided suggestions leading to an enriched publication.

DESCRIPTION OF MAP UNITS

SURFICIAL DEPOSITS

m **Man-modified land (Holocene)**—Chiefly waste piles of diatomite and sand from strip mining along Deschutes River 9 km west of Terrebonne. Main period of mining was from 1936 to 1961 (Peterson and others, 1976)

Qal **Alluvium (Holocene and Pleistocene)**—Unconsolidated deposits of sand and gravel along streams and in valley bottoms

Qe **Eolian deposits (Holocene and Pleistocene)**—Wind-blown sand and silt. Fills depressions in lava flows in eastern part of map area; mapped only where forms extensive deposits. Includes reworked ash of Mazama ash bed in upper part. Thickness ranges from 3 to 6 m in quarried exposures where base is exposed

Qls **Landslide deposits (Holocene and Pleistocene)**—Slumped blocks of sedimentary rocks, tuff, and basalt along valley walls of Deschutes and Crooked Rivers and a few scattered chaotic deposits elsewhere in map area. Those adjacent to basalt of Katsuk and Talapus Buttes in High Cascades formed after late Pleistocene glaciers melted, removing lateral support that buttressed the lava plateaus adjacent to these buttes

Qt **Talus and colluvium (Holocene and Pleistocene)**—Chiefly blocky deposits that blanket steep slopes at higher elevation in map area. Probably deposited during or after last major glacial advance

Till (Holocene and Pleistocene)—Very poorly sorted, angular to sub-rounded pebbles, cobbles, and boulders in silty sand matrix. Chiefly forms ground and lateral moraines in map area. Includes minor alluvium where reworked by streams. Divided into:

Qgn **Till of Neoglacial age (Holocene)**—Forms steep, sharp-crested, barren or sparsely vegetated moraines close to existing glaciers and perennial snowfields. In map area, found on North, Middle, and South Sisters, Broken Top, and Three Fingered Jack; includes deposits of early and late Neoglacial age as shown on more detailed maps (Taylor, 1978; Wozniak, 1982; Scott and Gardner, 1992). Younger than Mazama ash bed. Early Neoglacial deposits are locally overlain by tephra from Rock Mesa and Devils Hill chain of vents (Qrrm) and therefore are older than approximately 2,000 ^{14}C yr B.P., whereas late Neoglacial deposits are younger. Age determinations from elsewhere in the Cascade Range suggest early Neoglaciation lasted from about 3,500 to 2,300 yr B.P. and late Neoglaciation (occasionally referred to as the "Little Ice Age") occurred during the past several centuries (see discussion and references in Scott and Gardner, 1992)

Qgc **Till of Canyon Creek advance (of Cabot Creek glaciation of Scott, 1977) (Pleistocene)**—Forms moraines in cirques or just downslope from cirques; moraines lie chiefly within 2 km downslope of terminal moraines of Neoglacial age. Degree of weathering is similar to that on till of Suttle Lake advance, which suggests that Canyon Creek advance occurred during waning phase of last major glaciation. Overlain by Mazama ash bed and locally derived scoria deposits; oldest dated of these has minimum limiting radiocarbon age of 9,520 ^{14}C yr B.P. On basis of correlation to moraines of similar position in Washington Cascade Range, more closely limiting minimum age is 11,250 ^{14}C yr B.P. (Heine, 1996)

Qgs **Till of Suttle Lake advance (of Cabot Creek glaciation of Scott, 1977) (Pleistocene)**—Forms belts of moraines that mark maximum extent of glaciers during last major ice age, which on basis of regional correlations probably culminated about 20,000 yr B.P. Cambic B horizons typically 30–45 cm thick; weathering rinds on basaltic clasts less than 0.2 mm thick. Total depth of oxidation of soil profiles chiefly less than 1 m

Qgj **Till of Jack Creek glaciation of Scott (1977) (Pleistocene)**—Forms extensive moraine belt east of Three Fingered Jack that predates formation of that volcano (Scott and others, 1996). Characterized by reddish-brown argillic B horizons; basaltic clasts bear weathering rinds that average about 0.5 mm thick. Total depth of soil oxidation about 1.5 to 2 m. Map pattern east of Three Fingered Jack mimics that of moraines of Suttle Lake age near Suttle Lake, which suggests that, during Jack Creek glaciation, ice from broad upland area under what is now Three Fingered Jack formed a large east-flowing outlet glacier. Subsequent growth of Three Fingered Jack restricted glaciers of Suttle Lake advance to adjacent valleys (of First and Canyon Creeks) at margins of former outlet valley. Age of Jack Creek glaciation is probably either about 75 or 150 ka (Scott, 1977). Map-unit label shown queried for deposits of uncertain age but thought to predate the Cabot Creek glaciation; these deposits located on west side of High Cascades south of Bunchgrass Ridge

Outwash (Holocene and Pleistocene)—Moderately rounded to well-rounded cobbles and pebbles in sandy matrix. Forms stratified gravel deposits. Confined to valley floors at higher elevations but widens into broad outwash fans at middle elevations. Chiefly Pleistocene in age; most was deposited during Suttle Lake advance by meltwater streams from glaciers that deposited till of that advance (unit Qgs). Outwash of Canyon Creek advance mapped as alluvium (Qal) because it rarely forms deposits with distinct geomorphic form or located far from active stream courses. Minor outwash resulting from Neoglacial epochs (in past 3,500 yr) is found on upper flanks of the Middle and South Sisters and Broken Top. Deposits have been divided, on basis of weathering characteristics similar to till units, into:

Qon **Outwash of Neoglacial age (Holocene)**

Qos **Outwash of Suttle Lake advance (Pleistocene)**

Qoj **Outwash of Jack Creek glaciation (Pleistocene)**

Qs **Sand and gravel (Pleistocene)**—Alluvium deposited throughout middle and late Pleistocene time. Locally, older and younger parts of sequence may be recognizable by geomorphic form such as nested terraces. Deposits along Deschutes River are sand and gravel younger than Tumalo Tuff (Qtt) and both older and younger than basalt of Newberry volcano (Qbn). Near O'Neil, deposits form high-standing terraces adjacent to flood plain of Crooked River. Those terraces probably deposited when lava flows from Newberry volcano (Qbn) dammed the Crooked River, forming a higher base level for deposition of sand and gravel. Includes catastrophic flood deposits on plains southwest and north of Tumalo. These latter deposits, which contain boulders as large as 3 m across, may have resulted from glacial outburst floods originating in Cascade Range. Deposits near Alfalfa are commonly about 8 m thick and have been locally quarried; clasts are chiefly basaltic lava but include about five percent rhyolitic lava. Those deposits may have formed by increased runoff during pluvial periods and outflow from a lake southeast of map area near Millican, with provenance for the rhyolite most likely being Pine Mountain but possibly any of several domes in the Dry River drainage as far east as Hampton Buttes

Qf **Alluvial fan deposits (Pleistocene)**—Poorly sorted silt, sand, and subangular gravel. Found chiefly in broad fans surrounding Miocene and older rocks in eastern part of map area but includes some small fans scattered throughout area

Qsd **Diatomite (Pleistocene)**—Poorly indurated, earthy white diatomite with interbedded sand. As noted by Moore (1937), the deposit originally lay under a cover of sand, appearing as brilliant white outcrops in the bluffs of the Deschutes River near Lower Bridge. Once as thick as 20 m; little of the original deposit remains, however, and the site is now mostly occupied by irregularly heaped overburden and waste from strip mining. Dominant diatom species are *Stephanodiscus niagarae* (K.E. Lohman in Moore, 1937) and *S. excentricus* (Smith and others, 1987b), indicating a late Pliocene or Pleistocene age (Krebs and others, 1989). Volcanic ash bedded within the deposit has been tentatively correlated with the Loleta ash bed (distal-fallout equivalent of Bend Pumice) (Smith and others, 1987b; A. Sarna-Wojcicki, oral commun., 1995), which is thought to be about 0.3–0.4 Ma in age. Alternative correlation with 1.9-Ma ash bed found in drill core from a well near Tulelake, Calif. (T–749, 191 m depth; Rieck and others, 1992), is nearly as satisfactory on basis of statistical comparison coefficients (A. Sarna-Wojcicki, oral commun., 1995). Age of main mass probably middle Pleistocene on basis of a geomorphic analysis; the deposit fills valley floor whose elevation is only slightly higher than the surface later mantled by basalt of Newberry volcano (unit Qbn). Presumably the pre-diatomite erosional stage is only slightly older than the basalt. Overlain by basalt of Newberry volcano (Qbn) in roadcuts east of Lower Bridge, but earlier lava flows from same unit may have dammed ancestral river courses to create the lake in which diatomite was deposited (Smith, 1986). Small scattered areas shown east of Deschutes River are pond diatomite that fills topographically low areas on surface of basalt of Newberry volcano. These pond diatomite deposits are middle Pleistocene in age

QTs **Sedimentary rocks and deposits (Pleistocene and Pliocene)**—Poorly indurated sandstone and pumice-fall deposits. Exposed chiefly in canyons cut through overlying alluvial fan deposits (Qf) on southwest flank of Powell Buttes. At this location unit is lithologically similar to upper part of Deschutes Formation, but overlies basalt of Dry River (Tbdr) and therefore is younger; underlies east edge of basalt of Newberry volcano (Qbn). Exposure near Juniper Butte includes some moderately consolidated deposits whose lower part may be correlative with Deschutes Formation. Includes few small areas at west edge of map area corresponding to lacustrine and fluviatile sedimentary rocks deposited in late Pliocene and Pleistocene time at west edge of High Cascades. In northwest corner of map area these deposits include strata equivalent to Parkette Creek sedimentary rocks of Black and others (1987). In southwest corner of map area, deposits are conglomerate poorly exposed in south canyon wall of Separation Creek

VOLCANIC ROCKS AND DEPOSITS OF THE CASCADE RANGE AND NEWBERRY VOLCANO

[Arranged generally by composition, although first twelve units are compositionally diverse and have been grouped separately owing to their overlapping geographic setting and brief period of eruptive activity. These twelve units and one additional unit discussed later, the rhyolite of Rock Mesa and Devils Hill chain of vents (Qrrm), are younger than the Mazama ash bed, a widespread tephra deposit erupted during climactic eruptions of Mount Mazama (Crater Lake National Park), 120 km south of map area]

Young volcanic rocks of Santiam and McKenzie Passes

Young lava flows (Holocene)—Youthful lava flows that form the Sand Mountain volcanic field, Belknap Crater, and other young volcanic features in area of Santiam and McKenzie Passes. Includes ropy pahoehoe, clinkery aa, and blocky lava. Possesses sparsely vegetated flow surfaces with well-preserved pressure ridges, tumuli, and levees. Erupted from cinder cones (unit Qyc) and lava shields (vents indicated by red asterisk). Chiefly basaltic andesite, but includes basalt, minor andesite, and rare dacite. Emplaced between about 7,000 and 1,300 years ago. Radiocarbon ages summarized in table 1 and shown in figure 5. Divided by composition and eruptive source into:

Qybc **Basaltic andesite and andesite of Collier Cone**—Lava ranges in composition from basaltic andesite to andesite, with rare dacite; SiO_2 ranges from 56 to 65 percent. Phenocryst abundance ranges widely too, with andesite typically more porphyritic than basaltic andesite or dacite. Comprises multiple emplacement units, each of which ranges in composition (Schick, 1994). Age 1,600±100 ^{14}C yr B.P. on basis of charcoal beneath tephra from cone (Scott, 1990). Cone mantled on southwest side by till deposited during late Neoglaciation. Stipple shows a small cinder deposit on a lava flow from Collier Cone (3 km northwest of North Sister) and another deposit on a lava flow 14 km northeast of North Sister. This latter deposit was considered part of Shevlin Park Tuff by Taylor and Ferns (1995) but is reinterpreted herein as a rafted cinder deposit

Qya **Andesite of Four In One Cone**—Erupted from chain of cones built above fissure trending N. 10° E. Northern four cones contiguous (hence the name), and two cones farther south (in unit Qyc) are surrounded and isolated by lava from Collier Cone (Qybc). Early-erupted lava (found in flow levees) are sparsely porphyritic basaltic andesite (SiO_2 about 56 percent), whereas later flows (found chiefly in gutters) are porphyritic andesite (SiO_2 about 58-59 percent). Radiocarbon age of 1,980±160 ^{14}C yr B.P. obtained from charred needles and twigs in lower 20 cm of tephra that mantles broad area east of fissure (Scott, 1990); this age most closely approximates age of eruption. An older age of 2,550±165 ^{14}C yr B.P. (Chatters, 1968; Taylor, 1968) was obtained from the center of a large charred tree standing in fused cinders

Qyby **Basaltic andesite of Yapoah Crater**—Moderately porphyritic lava flows. Composition ranges from 54.8 to 56.9 percent SiO_2. Emplaced before eruption of Collier Cone and Four In One Cone on basis of ash-lava relations in upland area near vents. Younger than Little Belknap (Qyblk)

Qybk **Basalt and basaltic andesite of Belknap Crater**—Numerous lava flows erupted from unforested shield volcano surmounted by Belknap Crater. Typically contains small plagioclase and olivine phenocrysts about 1 mm across; sparse glomerocrysts reach 7 mm. Duration of eruptive activity likely spans a lengthy period. Charcoal encased in lava on west flank yielded ages of 1,400±100 and 1,590±160 ^{14}C yr B.P. (Taylor, 1965; Chatters, 1968; E.M. Taylor, in Champion, 1980). Eruptions at cone on south flank (South Belknap cone*) occurred about 2,635±50 ^{14}C yr B.P. on basis of radiocarbon age from charred roots in tree mold about 5 km southwest of McKenzie Pass (J.M. Licciardi, unpub. data, 1999). An earlier reported age from charcoal collected at this same site—1,775±400 ^{14}C yr B.P. (E.M. Taylor, in Champion, 1980; Taylor, 1990)—is thought too young because the concentration of cosmogenic ^{3}He in olivine phenocrysts in the lava indicates a surface-exposure age in excess of 2,000 yr B.P. (J.M. Licciardi, written commun., 1999). Early eruptive history obscure but partly predates volcano at Little Belknap

Qyt **Young tephra**—Thick blanket of ash and minor lapilli originating from cinder vents along Cascade Range crest. Composition ranges from basalt to andesite. Widely distributed across Santiam Pass and locally near McKenzie Pass but shown only where drifted to substantial thickness and masking underlying units. Erupted chiefly from Sand Mountain chain of vents and Belknap Crater. Less extensive areas also shown downwind from their source vents at Four In One Cone, Collier Cone, and Lost Lake chain of cones. Younger than Mazama ash bed; radiocarbon ages range from 3,440±250 to 1,600 ^{14}C yr B.P. for most deposits or lava from source vents

Qyblk **Basaltic andesite of Little Belknap**—Erupted from shield volcano located east of Belknap Crater. Radiocarbon age of 2,883±175 ^{14}C yr B.P. from roots within tree mold near Pacific Crest National Scenic Trail (Chatters, 1968; Taylor, 1968, 1990)

[Following four units form Sand Mountain volcanic field]

Qybln **Basaltic andesite of Little Nash Crater**—Contains abundant small plagioclase and sparse olivine phenocrysts. Composition about 56.8 percent SiO_2. Age known only to be younger than 2,590±150 ^{14}C yr B.P. on basis of charcoal from soil developed on till that underlies cinder deposits of vent (table 1, No. W–6018)

Qybll **Basalt of Lost Lake chain of cones**—Slightly porphyritic, with 2–3 percent olivine phenocrysts 1–2-mm across. Radiocarbon age is 1,950±150 ^{14}C yr B.P.

Qybn **Basaltic andesite of Nash Crater**—Lava flows with sparse small olivine phenocrysts. Contains about 53.5 percent SiO_2

Qybsm **Basalt of Sand Mountain chain of cones**—Lava flows. Composition ranges from basalt to basaltic andesite (51.6–53.2 percent SiO_2); the basalt contains sparse phenocrysts of plagioclase and olivine, whereas basaltic andesite has only olivine phenocrysts. Includes flows younger than about 2,750 ^{14}C yr B.P. (Clear Lake flows; J.M. Licciardi, unpub. data, 1999) and flows as old as 3,850±215 ^{14}C yr B.P. (Fish Lake flow; Chatters, 1968; Taylor, 1968)

Qybt **Basaltic andesite of Twin Craters**—Lava flows with olivine and sparse plagioclase phenocrysts. Contains about 53.6 percent SiO_2. Predates Belknap eruptions. Maximum age is 2,800±150 ^{14}C yr B.P. on basis of charcoal in soil beneath Twin Craters scoria (table 1)

Qybic **Basalt of Inaccessible cone**—Nearly aphyric lava flows form alignment of cinder cones, most southerly of which is Inaccessible cone* (Taylor, 1965). Predates some or all Sand Mountain flows and all Belknap eruptions; two cinder cones of alignment were almost completely buried by basalt and basaltic andesite of Belknap Crater (Qybk). Younger than Mazama ash

Basalt of the Cascade Range and Newberry volcano

Qb **Basalt (Holocene? and Pleistocene)**—Moderately porphyritic to aphyric, light- to dark-gray lava flows and flow breccia found throughout Cascade Range and areas to east. Chiefly 50–52 percent SiO_2 but includes rocks with as little as 48 percent SiO_2, especially east of Cascade Range. Phenocrysts commonly olivine and plagioclase; clinopyroxene is uncommon. Age chiefly Pleistocene, but first three units may be Holocene. Divided locally into:

Qbsb **Basalt of Sims Butte (Holocene or Pleistocene)**—Erupted between 7,600 and 20,000 yr ago, because Mazama ash lies upon lava, and cinders from cone lie upon till of Suttle Lake age. The till has only about 8 cm of oxidation, suggesting that Sims Butte cinders and ash were deposited soon after glacial retreat—closer to 20 ka than 7.6 ka (W.E. Scott, unpub. data, 1987); therefore age is most likely latest Pleistocene

Qbcy **Basalt of Cayuse Crater (Holocene or Pleistocene)**—Moderately porphyritic lava flows erupted from Cayuse Crater and two smaller cinder cones to northwest (Taylor, 1978). Olivine phenocrysts to 2 mm, 10–12 percent (Taylor, 1978). Silica content ranges from 49.7 to 51.8 percent on basis of 12 analyses. Older than Mazama ash bed. Age between about 12,500 and 9,500 yr B.P., because scoria locally overlies till of Canyon Creek advance, which generally is regarded to be about 11,000–12,500 yr in age. A radiocarbon age of organic-rich sediment from beneath the scoria is 9,520±100 ^{14}C yr B.P. (Scott and Gardner, 1992), but this carbon sample contains dispersed organic debris, could not be pretreated, and could be contaminated by younger material. Therefore the 9,520-yr age is considered a minimum age

Qbec **Basalt of Egan cone (Holocene or Pleistocene)**—Aphyric to slightly porphyritic lava flows erupted from informally named cinder cone at north base of Mount Bachelor, which lies just south of map area. Includes some basaltic andesite; proximal lava and scoria approximately 50.6–53 percent SiO_2, whereas distal, presumably early-erupted lava has approximately 53–54.5 percent SiO_2 (Scott and Gardner, 1992; Gardner, 1994). Older than Mazama ash bed (older than about 7,650 calibrated yr B.P.). Age considered closer to Mazama time (perhaps only 1,000 yr older) on basis of minimal weathering prior to eruption of Mazama ash, although paleomagnetic field directions suggest that distal lava may be closer in age to summit cone of Mount Bachelor, about 11,000–12,500 yr (Scott and Gardner, 1992)

Qbkt **Basalt of Katsuk and Talapus Buttes (Pleistocene)**—Porphyritic and glomeroporphyritic basalt erupted from 2.5-km-long alignment of vents west of Sparks Lake. Lava flows form steep-sided plateau with ice-contact features suggesting lava encountered and was buttressed by glacial ice. Slumping of lava has occurred in places along east and west plateau margin since deglaciation (Scott and Gardner, 1992)

Qbn **Basalt of Newberry volcano (Pleistocene)**—Open-textured vesicular lava flows. Contains about 49–50 percent SiO_2 (McDannel, 1989; Linneman, 1990). Erupted from vents on north flank of Newberry volcano (south of map area) and flowed north across broad plain extending to Redmond. Beyond Redmond, the basalt flowed into Deschutes and Crooked River canyons and, via the Deschutes canyon, reached Lake Billy Chinook, 5 km north of map area. Unit possesses normal-polarity magnetization and is younger than 0.78 Ma. Overlies Tumalo Tuff along west margin near Bend; therefore younger than about 0.4 Ma in that area. An age of 2.7±0.3 Ma (K-Ar, whole rock) was reported from lava flows exposed in fault blocks in southeast part of city of Bend (Hawkins and others, 1988). This age is discordant with geologic setting and probably is too old. Potassium-argon age of 5.96±2.08 Ma (Evans and Brown, 1981) is meaningless. Lava in eastern part of unit divided on basis of mineralogy into:

Qbn_1 **Basalt of Badlands**—Surface extremely irregular, displaying numerous features characteristic of inflated pahoehoe lava flows such as pressure ridges, pressure plateaus, tumuli, and residual depressions (Chitwood, 1994). More extensive south of map area, including Badlands Roadless Area (Bergquist and others, 1990). Vent area is matter of debate: unit forms a broad topographic rise that may be the discharge point for lava tubes draining from upslope on Newberry volcano (MacLeod and others, 1995), or alternatively, the rise is a separate volcano (informal “Badlands volcano” of Hawkins and others, 1988). Contains about 50 percent SiO_2 (Linneman, 1990). Isotopic ages of 0.7±0.1 and 2.9±0.3 Ma (K-Ar, whole rock) were reported from this unit south of map area (Hawkins and others, 1989) but are too old on basis of flow morphology. Interpreted to overlie sand and gravel (in unit Qs) near Alfalfa

Qbn_2 **Porphyritic basalt**—Contains olivine phenocrysts 1–3 mm across and 1–3 percent in abundance

Qbn_3 **Highly porphyritic basalt**—Olivine-rich lava flows. Contains 3–5 percent olivine phenocrysts as large as 4 mm across. Forms linear ridges and pressure plateaus. Outcrop pattern suggests unit likely inflated to form a sinuous train of tumuli. Subsequently, porphyritic basalt (Qbn_2) inundated same area and buried all but high-standing masses of highly porphyritic basalt. Contains about 48.5 percent SiO_2 (Linneman, 1990)

Qbn_4 **Large-feldspar basalt**—Contains scant plagioclase phenocrysts as large as 7 mm

Qbn_5 **Basalt near Alfalfa**—Fine-grained basalt, commonly with slight hematitic alteration of olivine and magnetite on weathered surfaces

Qbn_6 **Very fine grained basalt**—Dark-gray to black aphanitic lava flows

Qbsc **Basalt of cones at summit and southeast flank of Cache Mountain (Pleistocene)**—Glaciated lava flows bearing sparse xenocrysts of quartz. Unusual for its lack of plagioclase phenocrysts and abundance of olivine (1–2 mm, 5 percent) and clinopyroxene (1–2 mm, 1 percent). Contains about 50 percent SiO_2 (Hughes and Taylor, 1986)

Qbcb **Basalt of Condon Butte (Pleistocene)**—Glaciated aphyric lava flows. Summit crater remains intact, suggesting relatively youthful age

Qbkm **Basalt of Koosah Mountain (Pleistocene)**—Olivine- and plagioclase-bearing lava. Contains 51.4–52.6 percent SiO_2. Most phenocrysts less than 2 mm long, but typically contains a few outsized olivine crystals as large as 7 mm across. Age may be younger than 100 ka on basis of preserved landforms

Qbbt **Basalt of Burnt Top (Pleistocene)**—Olivine- or olivine- and plagioclase-bearing lava with sparse glomerocrysts. Contains 52 percent SiO_2. Forms shield centered at Burnt Top. Includes a somewhat younger flow erupted from both summits of Burnt Top; that flow is more plagioclase rich than most lava in the shield. Of same general age as basalt of Koosah Mountain (Qbkm) on basis of similar lack of erosion

Qbtb **Basalt of Two Butte (Pleistocene)**—Glaciated lava flows from cones south of Scott Mountain. Contains abundant small olivine phenocrysts

Qbc **Basalt of Craig Lake (Pleistocene)**—Moderately porphyritic lava flows. Contains 3–5 percent of olivine phenocrysts and scant clinopyroxene phenocrysts. Erupted from broad cinder vent west of Craig Lake in Mount Jefferson Wilderness Area

Qbwf **Basalt of Wizard Falls (Pleistocene)**—Vesicular, finely porphyritic lava with about 2 percent olivine phenocrysts smaller than 1 mm. Contains 50 percent SiO_2 (Conrey, 1985). Erupted from cinder cone near base of Green Ridge. Lava displaced Metolius River and flowed 2 km north of quadrangle to form Wizard Falls. Normal-polarity magnetization

Qbg **Basalt of Garrison Butte (Pleistocene)**—Fine-grained, open-textured lava flows. Contains about 50 percent SiO_2. Erupted from cinder cones along chain that includes Garrison Butte. Some lava flowed northeast into Stevens Canyon, reaching nearly to confluence of Deschutes River. Normal-polarity magnetization

Qbh **Basalt of Henkle Butte (Pleistocene)**—Olivine-bearing lava flows

Qbsp **Basalt of Santiam Pass (Pleistocene)**—Porphyritic olivine basalt or basaltic andesite. Commonly contains glomerocrysts of plagioclase and olivine, which makes it petrographically similar to some lava from Three Fingered Jack volcano to the north. Covers broad area of Santiam Pass between U.S. Highway 20 and Big Lake; erupted from cinder cones along Cascade Range crest. Normal-polarity magnetization

Qbbl **Basalt of Booth Lake (Pleistocene)**—Clinopyroxene- and olivine-bearing lava flows. Erupted from vent on ridge south of Three Fingered Jack and flowed south and east from Cascade Range crest

Qblb **Basalt of Little Brother (Pleistocene)**—Lava flows with microphenocrysts of plagioclase and clinopyroxene

Qbpp **Basalt of Plainview (Pleistocene)**—Widespread lava flows exposed on east side of Cascade Range near Sisters and in Deep Canyon. Contains as much as 20 percent plagioclase phenocrysts (Taylor and Ferns, 1995). Vent buried by younger flows in upslope area of Cascade Range south of Sisters town. Normal-polarity magnetization; overlies Desert Spring Tuff and therefore is younger than about 0.6 Ma

Qbti **Basalt of The Island (Pleistocene)**—Open-textured, vesicular lava flows exposed along Crooked River Gorge from Crooked River Ranch north to edge of map area. Extends northward downcanyon beyond quadrangle for 17 km to Round Butte. Forms The Island, a prominent mesa in vicinity of Cove Palisade State Park, 7 km north of quadrangle (Smith, 1986). Possesses reversed-polarity magnetization but otherwise is indistinguishable from normal-polarity basalt of Newberry volcano, which overlies it near Crooked River Ranch, or from basalt of Opal Springs, which underlies it along much of Crooked River Gorge in map area. Isotopic age is 1.19±0.08 Ma ($^{40}Ar/^{39}Ar$, whole rock; Smith, 1986) from sample near Crooked River Ranch. Reputedly erupted from Newberry volcano (for example, Peterson and others, 1976; Smith, 1986; Dill, 1992), but unit cannot be traced farther south than Crooked River Ranch. Thus, the upstream pathway for the reversed-polarity basalt must now be overlain entirely by normal-polarity basalt of Newberry volcano (unit Qbn). As a possibly contradictory observation, upper surface of unit lies roughly at 730-m elevation in most locations (Dill, 1992; Ferns and others, 1996b), which seems unlikely if the lava were flowing downstream along entire extent. An alternative explanation, therefore, is that the basalt of The Island was erupted from some yet-to-be-found fissure vent downstream from (north of) Crooked River Ranch and backed up along Crooked River

QTb **Basalt (Pleistocene and Pliocene?)**—Lava flows on west side of High Cascades exposed in canyon walls of White Branch, Separation, Horse, and Eugene Creeks; and on east side near Overturf Butte in Bend city limits. Canyon-wall exposures (north and south of Oregon Highway 242) consist of open-textured lava flows, chiefly basalt, that accumulated at the west margin of the High Cascades during latest Pliocene(?) and Pleistocene time; these correspond to the basalt of Roney Creek as mapped farther west by Priest and others (1988). Chiefly reversed-polarity magnetization. Overturf Butte deposits are lava flows and cinders unrelated to the west-side lava and possessing normal-polarity magnetization

Tb **Basalt (Pliocene)**—Lava flows on west side of High Cascades exposed in canyon walls of Horse and Eugene Creeks. Chiefly open-textured basalt lava flows but includes minor basaltic andesite, thin beds of unwelded ash-flow tuff, sandstone, and conglomerate. Most lava possesses normal-polarity magnetization, corresponding to eruption during Gauss Normal-Polarity Chron (2.60–3.55 Ma). Lowest part, however, may include lower Pliocene strata

Basaltic andesite of the Cascade Range

Qba **Basaltic andesite (Holocene? and Pleistocene)**—Slightly porphyritic to aphyric, light- to dark-gray lava flows and flow breccia. Forms much of High Cascades throughout map area. Chiefly Pleistocene, but youngest unit may be Holocene in age, and second youngest unit may be partly Holocene. Possesses normal-polarity magnetization; age younger than 0.78 Ma. Oldest isotopic age is 0.63±0.09 Ma (whole rock, K-Ar) from scoria in associated cinder cone (Qc, part) 1.5 km west of Triangle Hill (Hill, 1992a), but unit was emplaced as numerous lava flows from multiple vents that span a broad time period. Divided locally into:

Qbal **Basaltic andesite of Le Conte Crater (Holocene or Pleistocene)**—Porphyritic lava flows. Younger than last major glaciation but older than Mazama ash bed (emplaced sometime between about 20,000 and 7,650 years ago)

Qbam **Basaltic andesite of Mount Bachelor (Holocene? and Pleistocene)**—Includes lava flows younger and some older than Canyon Creek advance (of Cabot Creek glaciation). Older than Mazama ash bed

Basaltic andesite of South Sister (Pleistocene)—Clinopyroxene- and olivine-bearing lava flows. Contains 56–58 percent SiO_2 (Wozniak, 1982). Divided on basis of intervening andesite ($Qass_1$) into younger and older parts:

$Qbass_1$ **Basaltic andesite of summit cone**—Scoria and oxidized lava flows

$Qbass_2$ **Basaltic andesite of upper flanks**

Qbah **Basaltic andesite of Hoodoo Butte (Pleistocene)**—Nearly aphyric lava flows with less than 1 percent olivine and clinopyroxene as microphenocrysts. Contains about 55 percent SiO_2 (Black and others, 1987). Summit crater of cinder cone is relatively well preserved but lava has been glaciated, so unit is older than about 20,000 yr

Qbamx **Basaltic andesite of Maxwell Butte (Pleistocene)**—Nearly aphyric basaltic andesite. Contains 55–56 percent SiO_2 (R.M. Conrey, unpub. data, 1990). Erupted from vent at Maxwell Butte. Forms thick, medium-grained, light-gray glaciated lava flows on slopes surrounding Maxwell Butte, whereas at lower elevations to west beyond glacial limits, forms relatively youthful-looking, dark-gray to black lava flows with rugged primary flow features preserved locally

Qbasm **Basaltic andesite of Scott Mountain (Pleistocene)**—Lava flows at lower elevations not glaciated; may be about same age as basaltic andesite of Maxwell Butte

Qbatm **Basaltic andesite of Tumalo Mountain (Pleistocene)**—Lava flows and cinder-cone deposits, some of which are hyaloclastite. Forms shield volcano of Tumalo Mountain (north of Mount Bachelor) and scoria cones trending south and northwest from summit (Taylor, 1978; Scott and Gardner, 1992). Phenocrysts of plagioclase (as much as 2 mm across, 25 percent of rock), clinopyroxene (as much as 1 mm across, 5 percent), olivine (as much as 0.5 mm across, 1 percent), and rare orthopyroxene; phenocrysts commonly found as glomerocrysts as large as 6 mm in diameter, 3–7 percent of rock (Taylor, 1978). Age between about 18,000 and 150,000 years; glaciated during Suttle Lake advance (of Cabot Creek glaciation, 18,000–22,000 yr ago), and unit overlies an older till thought to be about 150,000 years old (Scott and Gardner, 1992)

Basaltic andesite of Sixmile Butte lava field (Pleistocene)—Erupted from ten cinder cones in area between Black Butte and Black Crater. Emplaced prior to Suttle Lake glacial advance (pre-latest Pleistocene). Divided into:

$Qbasx_1$ **Basaltic andesite of Bluegrass Butte**—Aphyric

$Qbasx_2$ **Basaltic andesite of Graham Butte**—Small plagioclase and olivine grains, about 1 mm across and about 2–3 percent in combined abundance (more olivine than plagioclase), commonly forming microglomerocrysts

$Qbasx_3$ **Basaltic andesite of Fivemile Butte**—Scant plagioclase phenocrysts less than 1 mm long, about 1 percent of rock; olivine as large as 1 mm across, 1 percent

$Qbasx_4$ **Basaltic andesite of Fourmile Butte**—Aphyric to sparsely porphyritic

$Qbasx_5$ **Basaltic andesite of Sixmile Butte**—Plagioclase phenocrysts seriate to 2 mm long, 10 percent of rock; olivine phenocrysts to 1 mm across, 1 percent

Qbacs **Basaltic andesite of Cold Spring (Pleistocene)**—Nearly aphyric lava, with less than 1 percent small phenocrysts of plagioclase, clinopyroxene, and olivine. Contains 56–57 percent SiO_2 (Taylor, 1987). Issued from unnamed cinder cone 2.6 km southwest of Millican Crater. Flow surface is extensively glaciated above 1,160-m elevation but covered with fresh scoria and blocks at lower elevation beyond reach of Pleistocene glaciers

Qbamc **Basaltic andesite of Millican Crater (Pleistocene)**—Porphyritic lava with glomerocrysts of plagioclase and olivine. Contains 53–54 percent SiO_2 (Taylor, 1987). Younger than basaltic andesite of Black Crater

Qbabc **Basaltic andesite of Black Crater (Pleistocene)**—Sparsely porphyritic lava with scant plagioclase and even less abundant clinopyroxene. Contains 55–57 percent SiO_2 (Taylor, 1987)

Qbarh **Basaltic andesite of Red Hill (Pleistocene)**—Olivine- and plagioclase-bearing lava erupted from small vent near south edge of map. Contains 55.2 percent SiO_2. Characterized by thick, steep-sided lava flows, commonly with glassy or palagonitized margins. These features suggest eruption during intraglacial period. Overlies basalt of Koosah Mountain (Qbkm). Age probably younger than 100 ka

Qbams **Basaltic andesite of Middle Sister (Pleistocene)**—Moderately to highly porphyritic lava flows. Commonly contains abundant plagioclase phenocrysts 2–4 mm across, as much as 50 percent in some flows, and olivine up to 3 mm across, 5 percent in most flows. Contains 52–53 percent SiO_2 (Taylor, 1987). Younger than Shevlin Park Tuff (younger than about 0.17 Ma); isotopic age of 0.4±0.2 Ma has large analytical error (Hill, 1992a)

Qbans **Basaltic andesite of North Sister (Pleistocene)**—Vesicular lava flows with abundant plagioclase microphenocrysts and glomerocrysts of plagioclase and olivine. Contains 54–55 percent SiO_2 (Taylor, 1987). Oldest of the Three Sisters volcanoes. Vent deposits of central pyroclastic cone (in unit Qmv) include substantial palagonitic tuff on east flank, possibly the result of subglacial eruption during initial cone growth

Qbatf **Basaltic andesite of Three Fingered Jack (Pleistocene)**—Slightly to moderately porphyritic lava flows with phenocrysts and microphenocrysts of plagioclase and olivine. Many lava flows contain glomerocrysts of plagioclase and olivine, chiefly those in the middle and upper flanks of the volcano. Outlying lava flows on lower east flank have primary flow surfaces unmodified by glaciation, lie upslope of terminal moraines deposited during Jack Creek glaciation, and are overlain upslope by moraines of Suttle Lake age, indicating an age between Jack Creek and Suttle Lake glaciations (Scott and others, 1996)

Qbabp **Basaltic andesite of Black Pine Spring (Pleistocene)**—Nearly aphyric lava, with less than 1 percent small phenocrysts of plagioclase. Contains 54–55 percent SiO_2 (Taylor, 1987). Erupted from cinder cone 1 km southwest of Black Pine Spring campground. Displaced near its terminus by segment of Sisters fault zone. Overlain by Shevlin Park Tuff. Normal-polarity magnetization and younger than 0.78 Ma

Qbat **Basaltic andesite of Trout Creek Butte (Pleistocene)**—Vesicular lava flows with sparse plagioclase phenocrysts and glomerocrysts of plagioclase and olivine. Contains 56–57 percent SiO_2 (Taylor, 1987). Normal-polarity magnetization and younger than 0.78 Ma

Qbaw **Basaltic andesite of Mount Washington (Pleistocene)**—Plagioclase- and olivine-bearing lava flows and breccia. Vent deposits of central pyroclastic cone (in unit Qmv) include substantial palagonitic tuff on northeast flank, possibly the result of subglacial eruption during initial cone growth

Qbasp **Basaltic andesite of Substitute Point (Pleistocene)**—Olivine-bearing lava; contains 53.6–56.2 percent SiO_2. Erupted from north-northwest-trending sequence of three vents and their conduit-filling plugs (shown separately as units Qmv and Qi). Normal-polarity magnetization and younger than 0.78 Ma

Qbapb **Basaltic andesite of Pilot Butte (Pleistocene)**—Highly porphyritic lava; contains 10–15 percent of blocky plagioclase phenocrysts as large as 5 mm across. Contains about 53.5 percent SiO_2 and 20 percent Al_2O_3. Erupted from cinder cone that forms Pilot Butte in city of Bend. Thought to be younger than 0.78 Ma on basis of normal-polarity magnetization. Predates many flows assigned to basalt of Newberry volcano (Qbn). Cinder cone is mantled by a rhyolitic tephra fall on its southwest side. This tephra is chemically similar to tephra exposed on south rim of Tumalo Creek at 1,728-m elevation and likely younger than Bend Pumice (see appendix 1, locality Nos. 12 and 13). Stratigraphic relation of the Pilot Butte lava to Bend Pumice unknown; that tephra deposit should be thicker than 2 m in Pilot Butte area, but none is reported to overlie lava flows from Pilot Butte. However, Bend Pumice is commonly eroded except where protected by overlying deposits and is absent on many features that predate it in the Bend area

Qoba **Older basaltic andesite (Pleistocene)**—Older than 0.78 Ma; possesses reversed-polarity magnetization or known to underlie reversely polarized strata. Includes slightly to moderately porphyritic lava flows of Black Butte, a mildly eroded, steep-sided lava cone whose pyroclastic core remains unexposed. Black Butte lava contains 5–10 percent of plagioclase phenocrysts 1–2 mm long and 3–5 percent of olivine phenocrysts 1 mm across. Potassium-argon age for Black Butte is 1.43±0.33 Ma (whole rock) (Hill and Priest, 1992; recalculated); earlier age determinations of about 0.4 Ma were known to be too young owing to reversed-polarity magnetization of the lava (Armstrong and others, 1975). Black Butte sits astride a small graben-bounding fault, and its lava has been slightly offset by a fault on the northwest flank. Map-unit symbol shown queried for older basaltic andesite at Cache Mountain, where lava possesses normal-polarity magnetization; sample from Cache Mountain has K-Ar age of 0.90±0.05 Ma (Armstrong and others, 1975). If age is correct, then Cache Mountain strata were likely erupted during the Jaramillo Normal-Polarity subchron of the Matuyama Reversed-Polarity chron, 0.98–1.04 Ma (time scale from Cande and Kent, 1992)

Andesite of the Cascade Range

Qa **Andesite (Pleistocene)**—Chiefly porphyritic lava flows, all with normal-polarity magnetization. Commonly contains phenocrysts of plagioclase, orthopyroxene, and clinopyroxene. May contain olivine phenocrysts. Divided locally into:

Qass **Andesite of South Sister**—Porphyritic, platy to massive lava flows and breccia. Isotopic age from early-erupted silicic andesite on northeast flank is 93±11 ka (Hill, 1992a). Divided at summit into:

$Qass_1$ **Andesite of summit**

$Qass_2$ **Andesite of east flank**

Qah **Andesite of Hogg Rock and Hayrick Butte**—Prominent flat-topped buttes in area of Santiam Pass; their shape and locally glassy margins suggest they may have erupted into glacial ice. Slightly porphyritic, with plagioclase, orthopyroxene, and trace amounts of olivine phenocrysts. Silica content about 59 percent (Davie, 1980; Hughes, 1983; Hill, 1992b). Potassium-argon age from Hogg Rock is 80±20 ka (Hill and Priest, 1992; age recalculated)

Qams **Andesite of Middle Sister**—Typically medium-gray, slightly porphyritic lava with black, glassy margins and base. Possesses pervasive platy fracturing throughout its extent. Fills broad canyon on west side of Middle Sister

Qoad **Andesite and dacite of First Creek (Pleistocene)**—Aphyric andesite and dacite lava and dacitic(?) pumiceous ash-flow tuff. Exposed in First Creek valley on southeast flank of Three Fingered Jack. Possesses reversed-polarity magnetization; older than 0.78 Ma

Dacite, rhyodacite, and rhyolite of the Cascade Range

Qd **Dacite (Pleistocene)**—Generally porphyritic lava with 5–10 percent plagioclase phenocrysts and lesser amounts of clinopyroxene and orthopyroxene phenocrysts. Possesses normal-polarity magnetization. Divided locally into:

Qdss **Dacite of South Sister**

Qdms **Dacite of Middle Sister**

Qdlp **Dacite of Lane Plateau**—Contains about 65 percent SiO_2 (Hughes, 1983; Hill, 1992a)

Qdt **Dacite of Todd Lake**—Porphyritic lava flows west and north of Todd Lake. Includes interbedded ejecta and central plug (not mapped separately), which together form the Todd Lake volcano of Taylor (1978) or Hill (1992a). Normal polarity magnetization. Potassium-argon age is 0.460±0.030 Ma (whole rock; Hill, 1992a)

Qrd **Rhyodacite (Pleistocene)**—Lava flows and domes. Possesses normal-polarity magnetization. Divided locally into:

Qrdt **Rhyodacite of Tam McArthur Rim**—Glassy to holocrystalline, slightly porphyritic lava. Consists of two flows, near-vent pumiceous deposits, and east-striking dikes (Taylor, 1978). Interbedded with basaltic andesite lava flows from Broken Top. Potassium-argon age is 213±9 ka (Hill, 1992a)

Qr **Rhyolite (Holocene and Pleistocene)**—Lava flows and domes. Found southeast of Condon Butte, on northwest and southeast sides of Middle Sister, south of South Sister, and interlayered in cone of South Sister. Also forms isolated domes in area near Melvin and Three Creek Buttes and a dome complex near Triangle Hill east of Broken Top. Normal-polarity magnetization; younger than 0.78 Ma. Isotopic ages from unit (all K-Ar from whole rock) include 95±10 ka from rhyolitic obsidian at Obsidian Cliffs (Hill, 1992a), 0.4±0.4 Ma from Melvin Butte dome (Armstrong and others, 1975), and 0.2±0.9 Ma from Three Creek Butte dome (Armstrong and others, 1975); latter two ages are rendered meaningless by the large standard deviation. An age of 1.63±1.1 Ma was obtained from dome at Bearwallow Butte (Fiebelkorn and others, 1983). This dome possesses normal-polarity magnetization and is probably younger than 0.78 Ma, within the range of the reported age. Youngest rhyolite shown separately as:

Qrrm **Rhyolite of Rock Mesa and Devils Hill chain of vents (Holocene)**—Dense to pumiceous, porphyritic rhyolite. Chiefly thick lava flows and domes; shown stippled are fragmental deposits, including tephra-fall, pyroclastic-flow, pyroclastic-surge, and laharic deposits. Fragmental deposits drape and are cut by cracked ground or gaping fractures. Erupted between 2,000 and 2,300 ^{14}C yr B.P. on basis of several radiocarbon ages from charcoal beneath associated tephra (Scott, 1987). Dormant interval of at least 100 yr separates older Rock Mesa from younger Devils Hill chain of vents (Scott, 1987). [Geographic note: Devils Hill proper is an older rhyolite lava flow of unit Qr]

Trd **Rhyodacite or dacite (Pliocene or Miocene)**—Lava flow, probably a dome, exposed in floor of Eugene Creek on west side of Cascade Range, southwest corner of map area. Likely correlative with a unit of andesite and dacite mapped west of map area by Priest and others (1988, their unit Tmpa)

Pyroclastic flow and fall deposits

[Rock Mesa-Devils Hill ash bed (Holocene). *Distribution shown only by isopachs*. Surficial deposit comprising two beds of white rhyolitic lapilli and ash found mostly south and east of the South Sister. Deposits are as thick as 2 m near vent and extend 30–40 km downwind. Derived from eruptions at Rock Mesa (older) and Devils Hill chain of vents (younger) during two brief episodes between 2,300 and 2,000 ^{14}C yr B.P. (Scott, 1987); waning stages of these eruptions produced rhyolitic lava flows (Qrrm).]

[Mazama ash of Powers and Wilcox (1964) (Holocene). *Not shown on map*. Surficial deposit (herein referred to as the Mazama ash bed) that forms important stratigraphic horizon. Derived from climactic eruption of Mount Mazama (Crater Lake National Park), 135 km south-southwest of Bend (fig. 1); grain size and thickness decrease northward and eastward. Age about 6,845±50 ^{14}C yr B.P. (Bacon, 1983), which corresponds to about 7,650 calibrated yr B.P.]

Qp **Pumice-fall deposits (Pleistocene)**—Coarse- to medium-grained, light-gray to white pumiceous lapilli, locally reworked. Chiefly rhyodacite and rhyolite in composition but includes minor dacite and rarely andesite (andesitic scoria black to brownish).

Consists of several unrelated deposits, including Bend Pumice (fallout tephra preceding emplacement of Tumalo Tuff), pumice of Columbia Canal (stratigraphically between Shevlin Park and Tumalo Tuffs; see text), and tephra from eruptions near Middle Sister, South Sister, and Broken Top. Forms mappable unit along Bottle Creek 4 km west of Bearwallow Butte in south-central part of map area (pumice of Bottle Creek); exposures there are at least 20 m thick resulting from a single tephra shower, and base is not exposed. Most occurrences, however, range in thickness from 10 cm to 2–3 m and are marked on map by "x" owing to restricted exposure; several of these are discussed more fully in appendix 1. None of the deposits is thought to predate Bend Pumice, which is approximately 0.3–0.4 Ma in age

Qsp **Shevlin Park Tuff (Pleistocene)**—Dark-gray to black, fresh pyroclastic-flow deposits. Pumice lapilli are mostly porphyritic andesite with phenocrysts of plagioclase, hypersthene, augite, and opaque oxides (Mimura, 1992), but some lapilli are rhyodacite. Whole-pumice and glass analyses range chiefly from 57 to 62 percent SiO_2 (Hill and Taylor, 1989; Sarna-Wojcicki and others, 1989; Mimura, 1992), with a few analyses as high as 67.5 percent SiO_2 (our unpub. data). Deposit contains lithic fragments of basalt, andesite, and rhyolite. Forms single cooling unit that originated as two pyroclastic flows. Lower pyroclastic-flow deposit is rich in fine ash; upper deposit is pumice rich. Dense welding in lower part and vapor-phase crystallization in upper part are ubiquitous in thicker parts of unit. Imbrication, which is well developed in lower part of each pyroclastic-flow deposit, indicates that unit was erupted west of map area, perhaps from now-buried vent in highlands near Broken Top volcano, 15 to 25 km west of Bend (Mimura and MacLeod, 1978; Mimura, 1984; Hill and Taylor, 1990). Distribution varies from surface mantling to valley filling. Maximum thickness 45 m. Normal-polarity magnetization. Age slightly younger than 0.17 Ma on basis of stratigraphic position occupied by distal fallout tephra in ancient lakebeds of the northern Great Basin (see explanatory text)

Qcd **Century Drive Tuff (Pleistocene)**—Moderately porphyritic pyroclastic-flow deposits that range from nonwelded to moderately welded. Contains both rhyodacitic and andesitic pumice lapilli (Hill and Taylor, 1990; Hill, 1992a), in contrast to chiefly andesitic Shevlin Park Tuff; but phenocryst mineralogy is otherwise similar. Also similar in age to Shevlin Park Tuff, which overlies it in exposures along Tumalo Creek, and the two units may be products of same eruptive episode. Three-km-long main deposit in Tumalo Creek is densely welded and 8 m thick but cannot be shown separately from Shevlin Park Tuff at scale of map. Map-unit label shown queried for deposits of uncertain correlation

Qrt **Rhyodacite tuff (Pleistocene)**—Densely welded, moderately porphyritic, stony welded tuff. Collapsed pumice contains about 67 percent SiO_2; whole-rock analyses range from 66 to 68 percent (Hill, 1992a; our unpub. data). Found only in Tumalo Creek valley and in south wall above Tumalo Lake. Western exposure once formed the floor of an ancestral Tumalo Creek valley but subsequently has been incised and now forms a ridge that projects into the valley. Probably similar in age to Shevlin Park and Century Drive Tuffs on basis of topographically similar canyon settings

Qtt **Tumalo Tuff (Pleistocene)**—As mapped, consists chiefly of pink pyroclastic-flow deposits (Tumalo Tuff, aggregate thickness 24 m) but locally includes thick underlying pumiceous fallout deposit (Bend Pumice, maximum thickness 11 m). Stippled where Bend Pumice is exposed over large areas owing to open-pit quarrying. Tephra fallout and pyroclastic flow resulted from single eruptive episode at vent west of Bend; pumiceous lapilli of the two deposits are mineralogically similar, containing phenocrysts of plagioclase, orthopyroxene, and minor amphibole, titanomagnetite, apatite, and zircon (Hill and Taylor, 1990). Silica content ranges from 73.1 to 75.7 percent (Mimura, 1992; Hill, 1985, 1992a). Well-developed imbrication in lower part and locally in upper part of Tumalo Tuff indicates that pyroclastic debris flowed northeastward into Bend area (Mimura and MacLeod, 1978; Mimura, 1984). Flows, thought to have erupted from uplands east of Broken Top volcano, have been channeled by northeast-trending drainages (Hill, 1985; Hill and Taylor, 1990). Normal-polarity magnetization in ash-flow tuff; age about 0.3–0.4 Ma on basis of several K-Ar ages (Sarna-Wojcicki and others, 1989)

Qds **Desert Spring Tuff (Pleistocene)**—Rhyodacitic ash-flow tuff. Ashy matrix is brownish orange, purple, or dark gray. Dark-gray pumiceous lapilli commonly contain phenocrysts of plagioclase, hypersthene, augite, and opaque minerals. Diagnostic characteristic is abundant apatite needles enclosed within most phenocryst phases. Contains 68–69 percent SiO_2 (Mimura, 1992). Commonly contains basaltic lithic fragments. Thickness ranges from 5 to 11 m; lower part of unit is partially welded and columnar jointed. Imbrication indicates that direction of flow was from southwest to northeast (Mimura and MacLeod, 1978; Mimura, 1984). Normal-polarity magnetization. Age between 0.6 and 0.7 Ma on basis of correlation with distal tephra (see explanatory text)

VOLCANIC AND SEDIMENTARY ROCKS IN THE DESCHUTES BASIN

Tbal **Basaltic andesite of Little Squaw Back (Pliocene)**—Slightly porphyritic, light-gray lava flows that form shield volcano of Little Squaw Back. Contains phenocrysts of hypersthene, plagioclase, and olivine. Age uncertain but not older than late Pliocene. The volcano lacks exposures suitable for directly testing its magnetization. A computer analysis was used by R.J. Blakely (U.S. Geological Survey) to calculate the magnetic anomalies that would be expected over the volcano for various magnetization directions. A comparison of these calculations with observed magnetic anomalies suggests that the volcano has dominantly reversed-polarity magnetization. The analysis also indicates certain complexities in magnetization, explainable by either a transitional polarity direction or some anomalous aspect of the volcano's structure (R.J. Blakely, written commun., 1995)

Tbas **Basaltic andesite of Squaw Back Ridge (Pliocene)**—Slightly porphyritic lava flows that form shield volcano of Squaw Back Ridge. Olivine phenocrysts form 2–3 percent of rock. In some samples, glomerocrysts of plagioclase and olivine are present. Contains 54.4–56.0 percent SiO_2 (Conrey, 1985). Normal-polarity magnetization. Age is 2.9±0.2 Ma (Armstrong and others, 1975)

Tam **Andesite of McKinney Butte (Pliocene)**—Aphyric high-iron andesite lava, also with unusually high concentration of Na; average of four analyses indicates about 60 percent SiO_2, 11 percent FeO, and 6 percent Na_2O (E.M. Taylor, unpub. data). Brick-red weathering. Magnetic polarity uncertain; total of ten fluxgate magnetometer measurements at different localities produced mixed results, all with low magnetic intensity. Potassium-argon age is 3.3±0.2 Ma (whole rock; Armstrong and others, 1975)

Tbdr **Basalt of Dry River (Pliocene)**—Fine-grained olivine basalt, commonly open-textured. Forms rimrock of Crooked River east of O'Neil and broad plain farther south nearly to Alfalfa; also found west as far as Redmond. Erupted from vents southeast and north of Powell Buttes (outside of map area). Reversed-polarity magnetization; probably about same age as basalt of Redmond (Tbr). Map-unit symbol shown queried south of Alfalfa for basalt of uncertain polarity (field measurements inconclusive)

Tbr **Basalt of Redmond (Pliocene)**—Slightly porphyritic, open-textured basalt that caps plateau between Redmond and Terrebonne. Once included as Deschutes-equivalent stratum (Robinson and Stensland, 1979, their "Redmond flow" of the Madras Formation) but now considered a separate, overlying unit (Smith, 1986). Isotopic age is 3.56±0.30 Ma ($^{40}Ar/^{39}Ar$, whole rock) from sample near Terrebonne (Smith, 1986). Normal-polarity magnetization, but otherwise similar to basalt of Dry River (Tbdr), which occupies a similar geomorphic setting. Outcrops exposing the stratigraphic relation between these two units have not been found

Deschutes Formation (Pliocene and Miocene)—Sequence of interbedded volcanic and subaerial sedimentary strata. Divided into:

Tds **Sedimentary rocks and deposits**—Chiefly volcaniclastic sandstone, conglomerate, and breccia, which formed by fluvial processes. Commonly includes minor primary volcanic deposits of fine vitric tuff, lapilli tuff, and volcanic breccia. Much of this tuff formed as fallout and pyroclastic flows; pyroclastic-flow deposits (ash-flow tuff) mapped separately where well exposed (unit Tdt and its divisions)

Tdb **Basalt**—Medium- to dark-gray, fine- to medium-grained, open-textured to compact olivine basalt, chiefly forming lava flows. Erupted from small to moderate-sized cinder cones (unit Tdc). Includes basaltic andesite and andesite not mapped separately. Basaltic andesite may form as much as 30 percent of unit, but we have too few chemical analyses and flow-by-flow mapping to define the compositional proportions more thoroughly. Basaltic andesite may predominate at Green Ridge, along north-central edge of map. Andesite is probably less than 5 percent throughout area. Queried for lava of uncertain stratigraphic assignment south of Sisters. Colored line shows extent of deposits where exposed within Deschutes Formation sedimentary strata (unit Tds) along canyon walls of Deschutes River and its tributaries. Locally divided into:

Tdbp **Porphyritic basalt**—Contains abundant plagioclase phenocrysts. Comprises several occurrences derived from multiple vents

Tdbl **Basalt of Long Butte**—Moderately to highly porphyritic lava flows that form shield volcano of Long Butte. Contains blocky phenocrysts of plagioclase (3–4 mm long) and less abundant olivine (1–2 mm across)

Tdbt **Basalt of Tetherow Butte (Tetherow Butte member of Smith, 1986)**—Consists of two lava flows and scattered cinder deposits. Unusually low Al_2O_3 (13–14 percent) compared to other basalt in Cascade Range or Deschutes basin. Contains scattered glomerocrysts of plagioclase and iron-rich augite (Smith, 1986). Lava flows have been named informally by Smith (1986): Agency Plains flow and overlying Crooked River flow (coincides with Crooked River flow as named by Robinson and Stensland, 1979). Contact between the two may be seen in cliffy exposures along Crooked River. Crooked River flow terminates at about the north edge of map area (approximately lat 44°30' N.), but Agency Plains flow extends north of map area for nearly 40 km to South Junction (Smith, 1986). Normal-polarity magnetization. Isotopic age is 5.31±0.05 Ma from sample collected 5 km north of map area ($^{40}Ar/^{39}Ar$, whole rock; Smith, 1986), but unit likely is younger than 5.04 Ma if magnetization is to match the currently accepted paleomagnetic time scale (see fig. 4). Includes many small deposits of cinders and scoria that probably were rafted by lava flowing away from vent area; these deposits shown stippled

Tdbld **Basalt of Lower Desert (Lower Desert basalt member of Smith, 1986)**—Open-textured olivine basalt. Comprises Fly Lake and Canadian Bench flows as defined by Smith (1986). Both possess normal-polarity magnetization, and the slightly older Canadian Bench flow, dated north of the map area, has isotopic ages of 5.0±0.5 Ma (K-Ar, whole rock; Armstrong and others, 1975) and 5.43±0.05 Ma ($^{40}Ar/^{39}Ar$, whole rock; Smith, 1986). (Unit likely is younger than 5.04 Ma if the magnetization is to match the currently accepted paleomagnetic time scale; see fig. 4.) Contact between flows shown on map by dashed-line internal contact (from Smith, 1986), and age relation indicated by Y (younger) and O (older)

Tdbc **Basalt of Cline Falls**—Moderately porphyritic lava flow, with 15 percent phenocrysts of plagioclase as large as 6 mm. Contains 50.5 percent SiO_2. Reversed-polarity magnetization

Tdbo **Basalt of Opal Springs**—Open-textured, vesicular lava flows. Normal-polarity magnetization. Isotopic age is 5.77±0.07 Ma (Smith, 1986)

Tdba **Basaltic andesite**—Aphyric to slightly porphyritic lava. Shown where sufficient chemical analyses to specify composition. Locally divided into:

Tdbal **Basaltic andesite of Laidlaw Butte**—Sparsely porphyritic, containing millimeter-size phenocrysts of plagioclase, augite, and rare olivine (McDannel, 1989). Normal-polarity magnetization

Tdbas **Basaltic andesite of Steamboat Rock**—Lithologically diverse unit of lava flows, lapilli tuff, and breccia; many of the pyroclastic beds are hydromagmatic in origin (Smith, 1986). Dikes that fed unit are shown separately as intrusions of unit Tbi. Nearly aphyric, fine-grained basaltic andesite with scant plagioclase phenocrysts less than or equal to 1 mm in length. Reversed-polarity magnetization. Forms prominent shelves and isolated mesas owing to relatively resistant lava that has withstood regional denudation of surrounding Deschutes plain. Exhumed conduits filled with lapilli tuff form pinnacles on east canyon wall of Deschutes River 1.4 km north of Steelhead Falls. Isotopic age is 5.06±0.03 ($^{40}Ar/^{39}Ar$, whole rock) from mesa south of Steamboat Rock (Smith, 1986). Stipple indicates area of tuff and tuff breccia that form two large cones

Tdbaof **Basaltic andesite of Odin Falls**—Augite-bearing porphyritic lava flows. Contains about 56 percent SiO_2. May have erupted from low lava mound in southwest corner of sec. 35, T. 14 S., R. 12 E.; vent symbol there shown queried because near-vent cinders and scoria are lacking and evidence is limited to topographic expression. Reversed-polarity magnetization. Older than basaltic andesite of Steamboat Rock (older than 5.06±0.03 Ma), although the two units are nowhere in direct stratigraphic succession. Instead, thick fallout tephra beds beneath the Steamboat Rock unit can be traced southward in west canyon wall of Deschutes River to a position above the Odin Falls unit

Tda **Andesite**—Lava flows. Shown near Bull Spring in south-central part of map area, near Thorn Spring at north-central edge, and along southeast wall of Deep Canyon in east-central part. Bull Spring exposure includes some interbedded dacite and capping basaltic andesite, and its magnetostratigraphy varies from reversed polarity at base to normal polarity at top, with an intervening sequence of reversed-polarity olivine basalt mapped separately (in unit Tdb). Capping basaltic andesite flow in Bull Spring area has K-Ar age of 4.7±0.1 Ma (whole rock; Hill, 1992a). Elsewhere in map area, sparse andesite in Deschutes Formation is included in unit Tdb

Tdd **Dacite**—Lava of eroded dome north of Sisters

Tdt **Ash-flow tuff**—Partially to moderately welded pyroclastic-flow deposits. Most contain scoria and pumiceous lapilli and bombs ranging in composition from andesite to rhyolite. Colored line shows extent of deposits where exposed within Deschutes Formation sedimentary strata (unit Tds) along canyon walls of Deschutes River and its tributaries. Locally divided into:

Tdtd **Tuff of Deep Canyon**—Brownish- to olive-gray ash-flow tuff. Moderately welded in basal part of some exposures, but generally only weakly sintered or nonwelded. Characterized by abundant large black dacitic pumiceous lapilli (analyses in Smith, 1986; Hill, 1992a; R.M. Conrey, unpub. data, 1992). Reversed-polarity magnetization. Equivalent to Deep Canyon ignimbrite member of Smith (1986). Colored line shows extent of deposits where exposed within Deschutes Formation sedimentary strata (unit Tds) along canyon walls of Deschutes River and its tributaries

Tdtf **Tuff of Fremont Canyon**—Moderately to densely welded dark-brown to grayish-red ash-flow tuff. Commonly platy weathering. Contains phenocrysts of plagioclase and hypersthene. Reversed-polarity magnetization. Colored line shows extent of deposits where exposed within Deschutes Formation sedimentary strata (unit Tds) along canyon walls of Deschutes River and its tributaries

Tdtp **Tuff of The Peninsula**—Sintered to very slightly welded ash-flow tuff. Contains pumiceous lapilli ranging from andesite to dacite to rhyolite in composition and from black to gray to white in color (Smith, 1986). Reversed-polarity magnetization. Equivalent to Peninsula ignimbrite member of Smith (1986). Colored line shows extent of deposits where exposed within Deschutes Formation sedimentary strata (unit Tds) along canyon walls of Deschutes River and its tributaries

Tdtm **Tuff of McKenzie Canyon**—Slightly porphyritic ash-flow tuff comprising three or four pyroclastic-flow deposits. Forms single cooling unit. Lower parts generally light-colored and poorly welded or nonwelded. Most distinctive and characteristic, however, is compositionally distinct upper part, an extensive reddish-orange or brownish-orange welded tuff that forms low outcrops and bold cliffs with crude columnar jointing. Upper part varies from white basal nonwelded zone about 1 m thick into moderately welded, highly oxidized reddish-brown tuff. Welding and oxidation increase upward, suggesting that an upper nonwelded part may have been stripped by erosion during deposition of the Deschutes Formation.

Pumice lapilli in lower parts are generally white, whereas in upper part they include white, black, and banded (black and white) lapilli. Banded dense pumice is diagnostic of the unit. Phenocrysts are small (approximately 1 mm across) and consist of 2–5 percent feldspar and less than or about 1 percent ferromagnesian minerals (hypersthene, augite); olivine (rare) occurs in black pumiceous lapilli from upper part of unit (Stensland, 1970; Cannon, 1985). Reversed-polarity magnetization. Equivalent to McKenzie Canyon ignimbrite member of Smith (1986). Colored line shows extent of deposits where exposed within Deschutes Formation sedimentary strata (unit Tds) along canyon walls of Deschutes River and its tributaries

Tdtl **Tuff of Lower Bridge**—Slightly porphyritic ash-flow tuff comprising two pyroclastic-flow deposits. Forms single cooling unit. Grayish-brown to grayish-purple weathering; grayish-pink where fresh. Nonwelded to weakly sintered; forms rounded slopes. Contains 10–15 percent white pumiceous lapilli and 1–5 percent volcanic lithic clasts as large as 2 cm. Phenocrysts are small (approximately 1 mm across) and consist of 10–15 percent plagioclase and 5–7 percent ferromagnesian minerals, chiefly augite with minor hypersthene and pargasitic amphibole (Cannon, 1985). Biotite occurs in trace amounts (Stensland, 1970; Smith, 1986). Unit includes 0.5–1.7 m of muddy, poorly sorted pumiceous lapilli and accretionary lapilli, probably the initial fallout deposits associated with Lower Bridge eruptions. Reversed-polarity magnetization. Equivalent to Lower Bridge ignimbrite member of Smith (1986). Colored line shows extent of deposits where exposed within Deschutes Formation sedimentary strata (unit Tds) along canyon walls of Deschutes River and its tributaries

Tddf **Debris-flow deposits**—Poorly sorted volcaniclastic deposits. Includes small area 5 km north of Cline Buttes, where deposits are rich with clasts as much as 2 m across of tuff of Fremont Canyon (Tdtf). The abundant float of tuff led Stensland (1970) to map the area as bedrock exposure of densely welded tuff, but other rock types are found, too, and the tuff blocks are set in odd positions compared to the originally horizontal orientation expected in a primary deposit. Most widespread deposits, however, extend from Forked Horn Butte to areas north and northwest that comprise unsorted angular debris (so-called Tetherow mudflow deposits of Stensland, 1970). Clasts characteristic of Deschutes Formation units are common in these deposits. Also common are prominent blocks of brownish-gray rhyodacite. Several exposures have features characteristic of debris-avalanche deposits. As mapped, includes Forked Horn Butte, a poorly exposed low hill. Roadcuts and trenchwork in new housing developments there expose only debris-flow deposits, many with dark-gray, porphyritic rhyodacite clasts as large as 2 m across. The butte was mapped previously as a Miocene, Oligocene, or perhaps Eocene silicic dome (Stearns, 1931; Williams, 1957; Stensland, 1970; Robinson and Stensland, 1979; Smith, 1986)

Tdrcb **Rhyolite of Cline Buttes (Miocene)**—Sparsely porphyritic, sugary (white) to stony (light-gray) rhyolite. Contains 1 to 2 percent of oligoclase phenocrysts (McDannel, 1989). Most of unit is devitrified, but flow-banded obsidian is exposed low on northeast flank of buttes in rock quarry. Normal-polarity magnetization. Isotopic age is 6.14±0.06 Ma ($^{40}Ar/^{39}Ar$; M.A. Lanphere, written commun., 1999)

Tdrsf **Rhyodacite southwest of Steelhead Falls (Miocene)**—Brownish-gray to black, flow-banded, moderately porphyritic lava. Forms sprawling mass thicker than 180 m (base not exposed). Normal-polarity magnetization. Isotopic age is 6.74±0.20 Ma ($^{40}Ar/^{39}Ar$; M.A. Lanphere, written commun., 1998). Relatively permeable and unaltered (Ferns and others, 1996a), which is consistent with its late Miocene isotopic age because early Miocene and older units in area tend to be altered and have low permeability

[Next two units are not part of the Deschutes Formation as presently defined. They are either of uncertain age relative to Deschutes Formation or relatively isolated from the Deschutes basin]

Tbab **Basalt of Awbrey Butte (Pliocene or Miocene)**—Lava flows of moderately to very porphyritic olivine basalt. Awbrey Butte is a small shield volcano of normal-polarity magnetization. It is deeply weathered, overlain by reversed-polarity basaltic andesite assigned to the Deschutes Formation, and likely older than 4 Ma

Tbw **Basalt of Willow Creek (Miocene)**—Olivine-bearing lava flows. Contains about 51 percent SiO_2 (Thormahlen, 1984). Exposed in northeast corner of map area but more extensive to north and northeast. Erupted from vent 4 km northeast of map area and flowed west and then northerly along Willow Creek drainage mostly north of map area (Peck, 1964; Swanson, 1969; Robinson, 1975). Isotopic age from sample collected north of map area is 6.30±0.09 Ma ($^{40}Ar/^{39}Ar$; Smith, 1986)

Unconformity to disconformity

Tp **Prineville Basalt (Miocene)**—Fine-grained aphanitic lava flows. Includes rocks with both normal- and reversed-polarity magnetization (Hooper and others, 1993); the unit is thought to have erupted during a short time period about 15.8 Ma when Earth's magnetic field was changing polarity from reversed to normal. Has been considered a chemical type within the Grande Ronde Basalt of the Columbia River Basalt Group (Swanson and others, 1979) or, more recently, a distinct member of the group (Tolan and others, 1989). Other workers have considered it a separate, interfingering stratigraphic unit (Hooper and others, 1993)

John Day Formation (Miocene to Eocene)—Chiefly rhyolitic ash-flow tuff, lava flows ranging from basalt to rhyolite, tuffaceous sedimentary rocks, and vent deposits. Most renowned exposure in map area forms Smith Rock, a sequence of rhyolitic welded tuff and volcaniclastic beds on west flank of Gray Butte in northeast corner of map area (unit Tjts). Lowest part of unit in map area (Tjl) is undated but may be late Eocene in age. John Day Formation is as old as late Eocene to east of map area in Blue Mountains (Bestland and others, 1993). Divided into:

Tjt **Tuff and tuffaceous sedimentary rocks (Miocene and Oligocene)**—White to very pale orange silicified tuff and lapilli tuff. Includes ash-flow tuff, fallout tuff, and tuffaceous sedimentary deposits. Age is early Miocene and late Oligocene on basis of stratigraphic position beneath Prineville Basalt (Tp) and above rhyolite of Gray Butte (in unit Tjr)

Tjh **Ignimbrite of member H (Oligocene)**—Fine-grained, welded and nonwelded rhyolitic tuff. Light green, white, or orange where fresh, and typically weathers orange or reddish brown. Mostly devitrified, with abundant lithophysae; dark-greenish-gray, perlitic vitrophyre exposed locally at base. Generally contains less than 5 percent pumice lapilli up to 1 cm across, less than 1 percent rock fragments, and less than 1 percent crystals of quartz, sanidine, and plagioclase. This welded tuff forms the base of member H as defined by Peck (1964) or Robinson (1975), but much of member H in map area has been stripped away by erosion. Isotopic age of 27.62±0.63 Ma ($^{40}Ar/^{39}Ar$, sanidine) was obtained from sample collected at west end of Haystack Reservoir (Smith and others, 1998)

Tjts **Tuff of Smith Rock (Oligocene)**—Thick-bedded to very thickly bedded pumiceous lapilli tuff (pyroclastic-flow deposits), medium-bedded pumice-lithic lapillistone (probably near-vent fallout deposits), and sandstone. Pumiceous lapilli generally aphyric. Bedding becomes more pronounced and the rocks finer grained upsection in Smith Rock area as volcaniclastic sandstone increases in abundance

Tjr **Rhyolite (Oligocene)**—Chiefly lava flows and domes, most prominently Juniper Butte, Powell Buttes, and Gray Butte. Age of 28.3±1.0 (K-Ar, whole rock) was obtained from Powell Buttes dome (Evans and Brown, 1981). Age of 28.82±0.23 Ma ($^{40}Ar/^{39}Ar$, anorthoclase) was obtained from rhyolite at Gray Butte (Smith and others, 1998)

Tjd **Dacite (Oligocene)**—Lava flows and domes. Part of Powell Buttes dome field

Tjtw **Welded tuff (Oligocene)**—Found near rhyolite dome at Juniper Butte (Tjr) and thought to be derived from that vent on basis of similar phenocryst mineralogy (Robinson and Stensland, 1979)

Tjth **Tuff of Haystack Reservoir (Oligocene)**—Light-green, gray, and light-purple tuff and lapilli tuff. Includes dark-reddish-brown welded tuff near top of unit at Haystack Reservoir. Slightly porphyritic; commonly contains 1–5 percent total phenocrysts of plagioclase, quartz, and sanidine. Nonwelded part of unit consists of planebedded and crossbedded, accretionary lapilli-bearing, hydromagmatic pyroclastic surge deposits and locally interbedded, massive lapilli tuff of probable pyroclastic-flow origin. Thickness increases northward from 75 m to at least 100 m near Haystack Reservoir. Probably erupted from a vent now plugged by rhyolite at Juniper Butte (in unit Tjr), on basis of thickness variations, restriction of welded tuff to Haystack Reservoir area, flow directions determined from surge crossbedding, and mineral content similar to the rhyolite. Best exposures are along north and west sides of Haystack Reservoir. Sanidine $^{40}Ar/^{39}Ar$ ages are 29.53±0.09 Ma from hydromagmatic tuff and 29.57±0.17 Ma from capping welded tuff; both samples from west end of Haystack Reservoir (Smith and others, 1998). These ages suggest correlation with member G of John Day Formation. The capping welded tuff was mapped as welded tuff possibly derived from Juniper Butte (Robinson and Stensland, 1979, their unit Tjw)

Tjs **Tuffaceous sedimentary rocks and tuff (Oligocene)**—Tuffaceous sandstone, laminated tuff, and locally conglomerate. Coarser-grained strata composed primarily of basaltic and rhyolitic detritus. Locally includes lapillistone of fallout origin and minor ash-flow tuff. Correlative with members E(?), F, and G of John Day Formation as defined elsewhere in region (see explanatory text). Outcrops near Gray Butte include a lapilli-fall deposit, the tuff of Rodman Spring of Smith and others (1998). These Gray Butte-area outcrops also include overlying strata thought to correlate with lower part of member G. The tuff of Rodman Spring has been correlated to a deposit near the base of member F, 25 km northeast of map area; it has a $^{40}Ar/^{39}Ar$ sanidine age of 32.49±0.30 Ma from a sample collected near Rodman Spring (Smith and others, 1998). Outcrops in area from Haystack Reservoir to Haystack Butte contain the member-F tuff of Rodman Spring but also include underlying brown tuffaceous sandstone and conglomerate that probably correlate, at least in part, to member E

Tjb **Basalt and tuffaceous sedimentary rocks (Oligocene)**—Lava flows are chiefly dark-gray, medium-grained aphyric alkali basalt with groundmass characterized by plagioclase, olivine, and interstitial to subophitic titaniferous clinopyroxene. Interbedded with tan and green tuffaceous sandstone and tan shale; shale is host to Trail Crossing flora (Ashwill, 1990). Sandstone contains abundant, once-glassy basaltic ash and scoria now altered to iron-rich smectite and zeolite. Unit is 75 percent lava, 25 percent sedimentary rocks. Lava petrographically and compositionally similar to alkali basalt found in members E, F, and G of John Day Formation, but flows near Gray Butte underlie a member-F fallout deposit and are therefore correlated with member E

Tjba **Basaltic andesite and tuffaceous sedimentary rocks (Oligocene)**—In Gray Butte area comprises chiefly black, fine-grained, aphyric lava flows containing microlites of plagioclase and clinopyroxene in a variably altered glassy mesostasis. Petrographically and compositionally similar to trachyandesite that defines member B, 20 km northeast of map area near Ashwood (Peck, 1964; Robinson, 1969, 1975). Interbedded sedimentary rocks are brown sandstone, siltstone, and shale containing fragments of rhyolite, basalt, and basaltic andesite. Shale is locally carbonaceous and contains abundant leaf impressions, including the Canal and Nichols Spring flora (Ashwill, 1983) of Oligocene age. Petrified wood is rarely present. Unit is about 50 percent lava, 50 percent sedimentary strata. Beds of accretionary lapilli-bearing, hydromagmatic basaltic andesite tuff are present locally. Also includes a light-green, slightly welded, highly altered rhyolitic welded tuff exposed near middle of unit. This tuff, which is 5–10 m thick, contains 1–3 percent phenocrysts of quartz, plagioclase, and altered anorthoclase. In Powell Buttes area, consists of small exposure of porphyritic, clinopyroxene-bearing basaltic andesite lava

Tjl **Lower John Day Formation (Oligocene and Eocene?)**—Diverse sequence of strata comprising brown to green, well-cemented sandstone, siltstone, and shale; yellow-brown altered rhyolitic welded tuff; white ash-fall tuff; and porphyritic basaltic andesite lava flows. Siltstone and shale host the Kings Gap and Sumner Spring flora (Ashwill, 1983) of Oligocene age; sandstone in this part of the sequence consists almost entirely of rhyolitic and basaltic andesite detritus. Two welded tuffs form about 30–50 percent of lowest 100 m of stratigraphic section. Lower of the two is nonwelded to densely welded rhyolitic tuff, roughly 20 m thick, containing 5–10 percent phenocrysts of quartz and highly altered anorthoclase and plagioclase. Also contains small metasedimentary rock fragments. Upper welded tuff, at least 15 m thick, is nonwelded to slightly welded, devitrified, and silicified; it locally contains layers of lithophysal cavities. Phenocrysts of quartz and highly altered plagioclase and alkali feldspar form 1-2 percent of rock. The welded tuffs, which are tentatively correlated with welded tuff of member A elsewhere in the region, are overlain by 500 m of strata, of which medium-gray porphyritic basaltic andesite lava forms about 20 percent. Lava contains approximately 15 percent phenocrysts of plagioclase, olivine, and scant clinopyroxene. Although once mapped as part of Eocene Clarno Formation (Robinson and Stensland, 1979), unit is now correlated with lower John Day Formation for these reasons: (1) lack of andesite and dacite lava flows that characterize the nearest exposures of Clarno Formation 20 km east (Thormahlen, 1984); (2) lack of andesitic detritus and abundance of rhyolitic and basaltic andesite detritus in sandstone; (3) lack of a lateritic paleosol, which typifies the contact between John Day and Clarno Formations; and (4) tentative correlation of the rhyolitic welded tuffs to those found in latest Eocene member A of the John Day Formation (Robinson and others, 1990)

VENT DEPOSITS AND INTRUSIONS

Qyc **Younger cinder deposits (Holocene and Pleistocene?)**—Basaltic and basaltic andesite scoria and minor lava flows forming relatively pristine cinder cones. Marks vents for basaltic andesite of Le Conte Crater (Qbal), basalt of Cayuse Crater (Qbcy), basalt of Egan cone* (Qbec), and numerous lava flows near McKenzie and Santiam Passes. Hachured lines indicate crater rims. Age is Holocene except for the Sims Butte, Cayuse Crater, and Egan cone* deposits, which may be latest Pleistocene. Age of specific vents is discussed with descriptions for erupted lava (for example, see basalt of Belknap Crater, unit Qybk). Two vents, however, erupted no lava flows: Blue Lake vent (west of Suttle Lake) and an informally named Spatter cone chain of vents*, scoria and agglutinate (northeast of Mount Washington). Both are younger than 3,440±250 ^{14}C yr B.P. because their tephra overlies fine ash associated with eruptions from Sand Mountain chain (Taylor, 1965, 1981; Chatters, 1968). An age of 1,330±140 ^{14}C yr B.P. was obtained from charcoal beneath tephra of the northernmost of the three fissure deposits of the Spatter cone chain of vents* (table 1). Southern and middle fissure deposits of Spatter cone chain of vents* are nearly connected by linear furrows mantled by nonmagmatic lithic tephra (Fractured ground in Map Explanation)

Qc **Cinder deposits (Pleistocene)**—Basaltic, basaltic andesite, and minor andesite scoria and lava forming slightly to moderately weathered deposits in cinder cones throughout map area. Extent of erosion varies depending on elevation, age, and position of deposits relative to Cascade Range crest, which forms a precipitation barrier or rain shadow. Most cones lack summit craters; hachured lines indicate crater rims on relatively young cones. Deposits mark vents for numerous units of basalt and basaltic andesite. Younger than 0.78 Ma on basis of normal-polarity magnetization in related lava flows

Qmv **Mafic vent deposits (Pleistocene)**—Moderately bedded, near-vent ejecta forming cores of large, steep-sided shield volcanoes such as Mount Washington, North Sister, or Three Fingered Jack; commonly laced with dikes. Parts of some vents hyaloclastic, suggesting that rising magma interacted with snow and ice, shallow ground water, or surface water. Ranges in composition from basalt to basaltic andesite

Qsv **Silicic vent deposits (Pleistocene)**—Three occurrences of near-vent tephra-fall and surge deposits: (a) palagonitic tephra of rhyodacitic composition in upper North Fork of Tumalo Creek; (b) near-vent pumice cones(?) exposed in escarpment of Triangle Hill; (c) pumiceous rhyodacitic tephra beneath rhyodacite near Three Creek Lake

Qi **Intrusions (Pleistocene)**—Plugs and thick dikes chiefly of basaltic andesite but including basalt and andesite. Fills conduits that fed large mafic vents such as Three Fingered Jack or Mount Washington. Not shown are many thin dikes that lace the pyroclastic cones of several Cascade Range shield and composite volcanoes such as Three Fingered Jack, Mount Washington, Broken Top, and the Three Sisters. Normal-polarity magnetization; presumably entirely middle or late Pleistocene in age

Qoc **Older cinder deposits (Pleistocene)**—Similar to cinder deposits (unit Qc) but older than 0.78 Ma on basis of reversed-polarity magnetization. Only one occurrence, 1.5 km northwest of Suttle Lake. Other probable deposits largely stripped by glaciation, leaving only remnant conduit-filling plug (unit Qoi, older intrusions)

Qoi **Older intrusions (Pleistocene)**—Similar to intrusions (unit Qi) but older than 0.78 Ma on basis of reversed-polarity magnetization. Consists of two masses in southwest corner of map area and one mass in northwest corner near Round Lake

Tc **Cinder deposits (Pliocene)**—Cinder deposits marking vent for andesite of McKinney Butte (unit Tam), north of Sisters

Tbi **Basaltic intrusions (Pliocene and Miocene?)**—Dikes and sills emplaced into the Deschutes Formation

Tdc **Cinder deposits of Deschutes Formation (Pliocene and Miocene)**—Basalt and basaltic andesite scoria and lava, forming cones and irregular accumulation of cinders. Marks vents for lava flows in Deschutes Formation. Major cinder cones for one Deschutes Formation lava sequence, the basalt of Tetherow Butte, are shown with labels Tdc and (Tdbt)

Tri **Rhyolitic intrusions (Miocene or Oligocene)**—Dikes and plugs of very fine grained rhyolite emplaced into the John Day Formation near Smith Rock State Park. Dikes west of Gray Butte are porphyritic rhyolite

Tjbi **Basalt and basaltic andesite intrusions of John Day age (Oligocene)**—Dikes and sills north of Gray Butte. Petrographically and compositionally similar to, and probably of same age as, nearby John Day lava flows (in units Tjb and Tjba). An isotopic age of 30.8±0.5 Ma (K-Ar, whole-rock) was reported from this unit 2 km northeast of Gray Butte (Fiebelkorn and others, 1983)

Tjmv **Mafic vent deposits of John Day age (Oligocene)**—One occurrence, which forms poorly exposed, altered scoria and agglutinate northwest of Gray Butte. May mark upper part of conduit that erupted scoria and spatter found in adjacent outcrops of basaltic andesite (unit Tjba)

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APPENDIX 1. DESCRIPTION OF OCCURRENCES FOR ISOLATED PUMICE DEPOSITS.

[Numbered by locality and keyed to simplified location map (fig. 8). Quadrangles are U.S. Geological Survey 7.5' topographic quadrangles. Whole-pumice chemical analyses from tephra and some comparative whole-rock analyses from rhyolite domes are listed separately (table 3)]

Locality No.	Quadrangle	Chemical analysis (Sample No., table 3)	Description
1	North Sister	Unanalyzed	On west ridge of Little Brother; single, thick silicic tephra fall deposits. Age and correlation uncertain; may have resulted from precursory eruptions leading to emplacement of rhyolite of Obsidian Cliffs.
2	Trout Creek Butte	830920-5	Tephra deposit mantling cinder cone at Pole Creek cinder pit, 3.3 km south of Trout Creek Butte.
3	Three Creek Butte	RC95-178	Tephra-fall deposit beneath Shevlin Park Tuff, roadcut. The roadcut has sloughed and requires excavation to expose the deposit. Thickness greater than 1.5 m; base not reached by shoveling. Probably pumice of Columbia Canal on basis of stratigraphic position and chemical similarity to lapilli from Columbia Canal type section (Locality No. 10).
4	Three Creek Butte	830920-6	Scattered pumiceous lapilli along Forest Road 16 where it surmounts a thick basaltic andesite lava flow near 3823' benchmark, 5.5 km north-northeast of Melvin Butte.
5	Three Creek Butte	3S086	Pumice south-southwest of Three Creek Butte; tephra-fall deposits exposed along logging road. At least 1.5 m thick; base not reached by auguring. Multiple emplacement units indicated by marked bedding, changes in grain size, and varying proportion of lithic clasts. Pumiceous lapilli to 2 cm. Deposit predates Suttle Lake glaciation and lies at edge of lateral moraine. The lapilli chemically resemble rhyolite at Obsidian Cliffs (in unit Qr), 18 km to the west-northwest (B.E. Hill, written commun.); those analyses are Sample Nos. TS-690 and 3S139 (table 3).
6	Three Creek Butte	Unanalyzed	Small gravel pit; tephra-fall deposit overlies gravel. Gravel has carbonate stains and weathering rinds as thick as 0.5 mm and therefore predates the Suttle Lake advance of Cabot Creek glaciation (Evans Creek stade of Fraser glaciation). No thickness noted.
7	Tumalo Dam	Unanalyzed	Tephra-fall deposit lying beneath Shevlin Park Tuff and above Tumalo Tuff. Stratigraphic position suggests it may be pumice of Columbia Canal (Locality No. 10, below).
8	Tumalo Falls	3S018	Pumice of Bottle Creek, from tephra-fall deposit on flank of cinder cone north of Bearwallow Butte. Thickness roughly 50 cm. Lapilli to 6 cm in upper part; ash increases in lower part, with finer grain size overall. Chemically similar to Locality No. 11, along Bottle Creek.
9	Shevlin Park	3S001	Tephra-fall deposit that mantles Deschutes-age strata near Bull Spring. Coarse lapilli exposed in root throw. Thickness unknown. Chemically similar to Bend Pumice but hydrated (Hill, 1992a).
10	Shevlin Park	3S079	Pumice of Columbia Canal, at Columbia Canal waterfall exposure. Was named pumice of Columbia Canyon by Hill and Taylor (1990), but title modified here to more closely match a named geographic feature. Underlies Shevlin Park Tuff; overlies Tumalo Tuff. Chemically similar to analyses from Locality Nos. 2, 3, and 4. Glass shards have composition similar to Summer Lake ash bed NN (Sarna-Wojcicki and others, 1989). Ash bed NN lies 4.5 m beneath ash bed JJ (Shevlin Park Tuff distal fallout) at the Summer Lake reference locality (fig. 4 in Davis, 1985).
11	Tumalo Falls	3S024 and 830920-1 (same location)	Pumice of Bottle Creek, along Bottle Creek. Two exposures, one lying 0.9 km northwest of road and the other extending 250 m downcreek from road in south bank. Thickness substantial; at least 20 m thick northwest of road and at least 5 m thick east of road, but base not exposed in either locality. Samples collected east of road crossing (table 3) are chemically similar to Locality No. 8, pumice that mantles cinder cone 5 km to northeast.
12	Tumalo Falls	830803-6 (from white lapillli)	Pumice of Pilot Butte, collected 19 km west-southwest of Pilot Butte at East Tumalo quarry, from tephra-fall deposit on flank of cinder cone (quarry). Thickness at least 2 m; base not exposed. Contains chiefly white pumiceous lapilli to 7 cm, with about 5 percent of dark lapilli. White lapilli are slightly porphyritic, with phenocrysts of plagioclase and clinopyroxene, 1-2 mm, ≤1 percent. Dark lapilli (andesitic scoria?) are mostly aphyric. Chemically similar to Locality No. 13.
13	Bend	3S007	Pumice of Pilot Butte, from tephra-fall deposit mantling southwest flank of Pilot Butte cinder cone. Chemically similar to Locality No. 12.

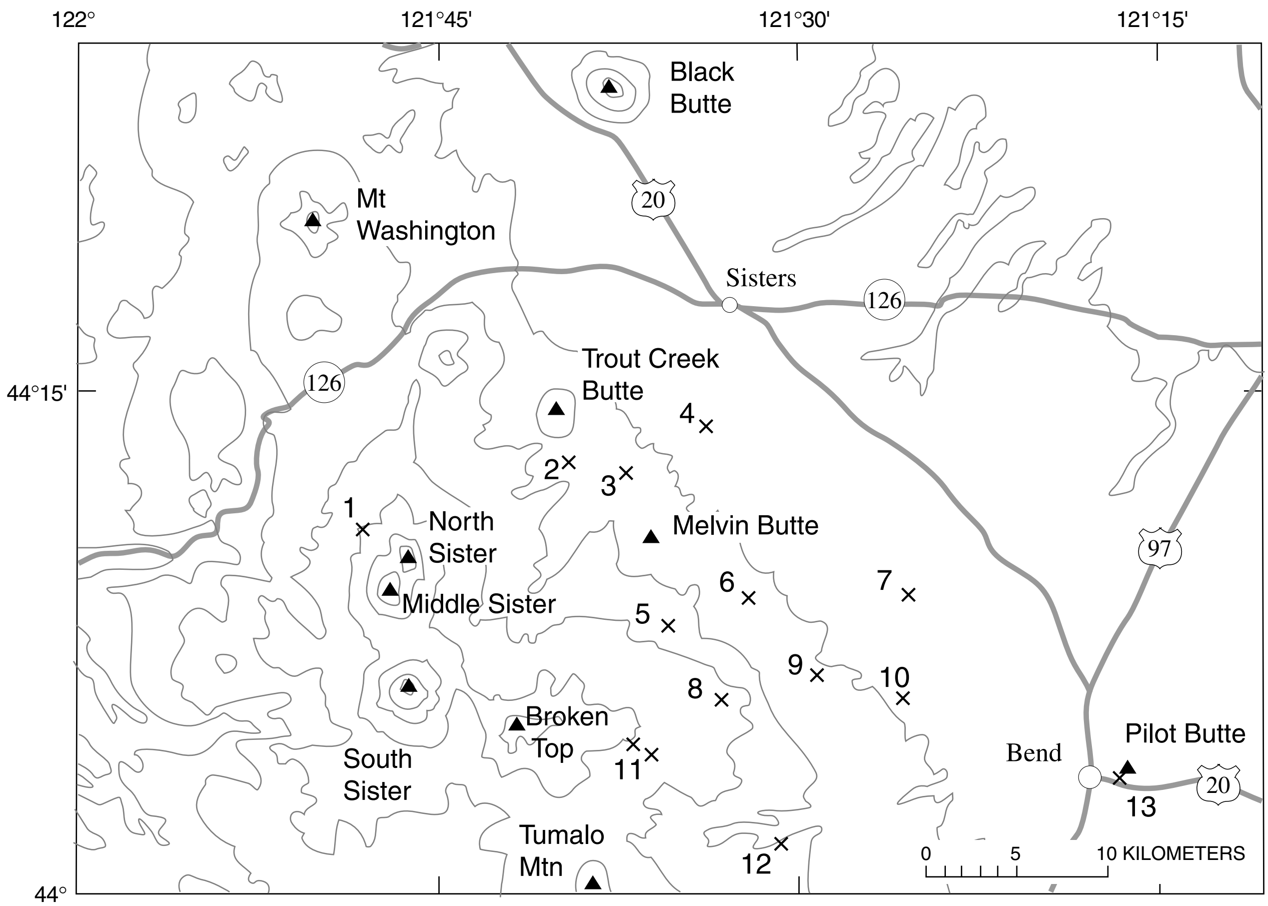

Figure 8. Location of isolated pumice deposits younger than Bend Pumice or of uncertain correlation. Numbers correspond to localities described in appendix 1. Occurrences also shown on geologic map (labeled Qp). Chemical analyses listed in table 3 by Location No. Base from U.S. Geological Survey, Bend quadrangle, 1971; contour interval 1,000 ft.

Table 1. *Radiocarbon ages for Holocene volcanic rocks at Santiam and McKenzie Passes, Oregon*

[All ages are calculated using half-life of 5,568 years and reported as ^{14}C year B.P. Description of material dated may vary somewhat from earlier reported descriptions, several of which were incorrect. Column labeled "Reported variants" is included for thoroughness, in the event that ages reported casually elsewhere in the geologic literature create the impression of additional radiocarbon results not reported here]

Lab No.	Field No.	Age	Description of material dated	Map unit	References	Reported variants
GAK-1922	TFJ-269	1,330±140	Charred forest litter from base of Spatter cone chain of vents*	Qyc (part)	E.M. Taylor, unpub. data	
WSU-370+	TFJ-60A	1,400±100	Charcoal excavated from radial system of large roots in buried soil at base of a tree mold in west Belknap lava flow	Qybk (part)	E.M. Taylor, in Champion, 1980	"1,495 ^{14}C yr B.P." (Taylor, 1990) "about 1,500 yr ago" (Taylor, 1981)
WSU-292	TFJ-60	1,590±160	Second analysis on same sample of charcoal as WSU-370 (above)	Qybk (part)	Taylor, 1965; Chatters, 1968	see above
W-5705	850909-2	1,600±100	Charcoal from beneath tephra plume of Collier Cone	Qybc	Scott, 1990	
WSU-450	TS-381	1,775±400	Charred roots in tree mold 1.3 km west of benchmark 5036, McKenzie Pass Highway, collected in 1964. Probably too young; see Lab No. AA30523, below	Qybk (part)	E.M. Taylor, in Champion, 1980; Taylor, 1990	"1,800 yr ago" (Taylor, 1981)
WSU-371	TFJ-204	1,950±150	Charred wood beneath coarse cinders from cone at southwest base of Potato Hill; collected along Jack Pine road south of U.S. Highway 20	Qybll	Chatters, 1968; Taylor, 1968	"2,000 yr" (Taylor, 1968)
W-6017	870725-1	1,980±160	Charred needles and twigs in lower 20 cm of tephra from Four In One Cone, ~300 m east of vents. The dated andesitic tephra overlies a thin fine white tephra, which is thought to be from Rock Mesa or Devils Hill chain of vents (Qrrm)	Qya	Scott, 1990	
WSU-365	TS-374	2,550±165	Charcoal from core of 0.4-m-diameter upright stump enclosed in fused cinders 200 m east of Four In One Cone. Age too old; preferred age is 1,980±160 yr B.P. (see W-6017, above)	Qya	Chatters, 1968; Taylor, 1968	"2,600 yr B.P." (Taylor, 1981)
W-6018	870804-1	2,590±150	Charcoal on contact where soil developed on till is overlain by 1.8 m of scoriaceous ash from Nash Crater and north part of Sand Mountain chain of vents. That ash is overlain by 2 m of scoria from Little Nash Crater. Interpreted as maximum age for volcanic activity near Santiam Junction	Maximum age for Qybln	W.E. Scott, unpub. data	
GAK-1921	TFJ-230	2,620±150	Charcoal from small limbs buried by coarse lapilli tephra about 650 m west of the central point of Twin Crater's south crater	Qybt	E.M. Taylor, unpub. data	"2,600 yr ago" (Taylor, 1981)

Table 1. *Radiocarbon ages for Holocene volcanic rocks at Santiam and McKenzie Passes, Oregon—Continued*

Lab No.	Field No.	Age	Description of material dated	Map unit	References	Reported variants
AA30523	SB1998	2,635±50	Charred roots in tree mold 1.3 km west of benchmark 5036, McKenzie Pass Highway; collected in 1998. Dates flows from vents close to South Belknap	Qybk (part)	J.M. Licciardi, unpub. data, 1999	
not reported[§]	not reported[§]	2,705±200 (outer wood); 3,200±220 (inner wood)	Inner and outer layers from 0.3-m-diameter submerged stump in Clear Lake; younger age is maximum age for lava flows from south end of Sand Mountain chain of vents	Qybsm	Benson, 1965; Taylor, 1965	"approximately 2,950 yr B.P." (Taylor, 1965); "3,000 ^{14}C yr B.P." (Taylor, 1981); "2,950 ^{14}C yr B.P." (Taylor, 1990)
AA30522	CL1964	2,750±45	Wood from center of 0.3-m-diameter rooted snag submerged in Clear Lake, a new analysis using sample material collected in 1964 by E.M. Taylor. Dates part of eruptive activity at Sand Mountain chain of vents	Qybsm	J.M. Licciardi, unpub. data, 1999	
W-6021	870728-4	2,800±150	Charcoal fragments from upper 1 cm of soil in till and Mazama ash that is buried by 3 m of scoria from Twin Craters; places maximum age for Twin Craters. (See age of 2620±150 from tree molds in GAK-1921, above)	Qybt	W.E. Scott, unpub. data	
WSU-364	TFJ-207	2,883±175	Charred roots in tree mold along margin of Little Belknap lava, near Skyline trail. Age appears too old, as Little Belknap Crater largely postdates Belknap Crater	Qyblk	Chatters, 1968; Taylor, 1968, 1990	"2,900 yr ago" (Taylor, 1981)
WSU-449	TFJ-213	2,990±300	Charred roots under lava, east shore Clear Lake. Dates part of eruptive activity at Sand Mountain chain of vents	Qybsm	E.M. Taylor, in Champion, 1980; Taylor, 1990	"3,000 yr ago" (Taylor, 1968, 1981)
WSU-291	S-16	3,440±250	Long, delicate charred limb at interface between tephra of Blue Lake (above) and ash of Sand Mountain (beneath), from large cut in logging road on south side of Suttle Lake. Interpreted here as tree killed by ash of Sand Mountain and later blanketed by tephra of Blue Lake	Qyt	Taylor, 1965, 1990; Chatters, 1968	Blue Lake crater was assigned an age of 3,500 yr on basis of this age (Taylor, 1968, 1981)
WSU-372	TFJ-205	3,850±215	Charred root bark mixed with soil and rootlets near Old Santiam Wagon Road. Dates Fish Lake lava flow of Taylor (1968) or Hackleman Creek flow of Champion (1980, p. 177)	Qybsm	Chatters, 1968; Taylor, 1968, 1990	"3,800 yr ago" (Taylor, 1981)

* Informal geographic name
\+ Laboratory number incorrectly reported as WSU-270 by Champion (1980)
§ Neither laboratory nor field numbers were reported by Benson (1965). Samples were analyzed by Isotopes, Inc.

Table 2. *Potassium-argon and $^{40}Ar/^{39}Ar$ isotopic ages from map area. See figure 3 for sample location map*

[Grouped by stratigraphic unit and generally arranged from youngest to oldest. All ages are K-Ar except those shown by *, which are $^{40}Ar/^{39}Ar$. The K-Ar ages are recalculated where necessary to conform with currently accepted constants for radioactive decay and abundance of ^{40}K (Steiger and Jäger, 1977). Symbols indicating "quality" show usefulness of age in stratigraphic interpretations: +, age thought meaningful; o, age probably meaningful but accuracy may be far poorer than indicated by the reported precison; -, age meaningless (owing to large analytical error) or incorrect (on basis of our knowledge obtained by all ages and regional stratigraphic relationships). Lithologically, material dated is lava except where noted]

Map No.	Strat. unit	Age (Ma)	Quality	Sample No.	Geologic unit or geographic location	Quadrangle (1:24,000 scale)	Lat. N Long. W	Rock type	Material dated	Reference
Volcanic rocks of High Cascades or lava flows erupted from north flank of Newberry volcano										
1	Qah	0.08±0.02[a]	+	TFJ-2	Hogg Rock	Three Fingered Jack	44°25.53' 121°52.11'	Andesite	Whole rock	Hill and Priest, 1992
2	Qass	0.093±0.011	+	3S162	South Sister, early-erupted lava on northeast flank	Trout Creek Butte	44°08.29' 121°43.20'	Dacite	Whole rock	Hill and Duncan, 1990; Hill, 1992a (table 3.1, p. 19)
3	Qbams	0.4±0.2	-	3S159	Middle Sister	North Sister	44°07.89' 121°45.95'	Basaltic andesite	Whole rock	Hill, 1992a (table 3.1, p. 19)
4	Qr	0.095±0.010	+	3S139	Obsidian Cliffs	North Sister	44°10.64' 121°48.98'	Rhyolite	Whole rock	Hill, 1992a (table 3.1, p. 19)
5	Qsp	2.6±2.2	-	BD-2	Shevlin Park Tuff	Bend	44°03.71' 121°20.18'	Andesitic pumice	Plagioclase	Fiebelkorn and others, 1983
6	Qrdt	0.213±0.009	+	3S046	Tam McArthur Rim	Broken Top	44°05.57' 121°38.54'	Rhyodacite	Whole rock	Hill and Duncan, 1990; Hill, 1992a (table 3.1, p. 19)
7	Qc	0.340±0.020	o	3S010	Triangle Hill	Tumalo Falls	44°05.93' 121°32.41'	Andesite bomb	Whole rock	Hill and Duncan, 1990; Hill, 1992a (table 3.1, p. 19)
8	Qba	0.63±0.09	o	3S015	Lava 1.5 km west of Triangle Hill	Tumalo Falls	44°06.22' 121°33.36'	Basaltic andesite	Plagioclase	Hill, 1992a (table 3.1, p. 19)
9	Qtt	0.83±1.5[a]	-	B-4	Tumalo Tuff	Tumalo Dam	44°08.10' 121°22.65'	Dacitic pumice	Whole rock	Armstrong and others, 1975
10	Qtt	3.98±1.9	-	M5-41	Tumalo Tuff	Bend	44°03.80' 121°21.61'	Ash-flow tuff	Plagioclase	Fiebelkorn and others, 1983
11	Qtt	2.50±2.0	-	M5-40	Bend Pumice (fallout tephra)	Bend	44°03.70' 121°21.51'	Ash flow	Plagioclase	Fiebelkorn and others, 1983
12	Qbn	2.7±0.3	-	86-3	Lava from North flank of Newberry volcano	Bend Airport	44°00.49' 121°14.39'	Basalt	Whole rock	Hawkins and others, 1988, 1989
13	Qbn	5.96±2.08	-	Pb-2; UT-210	Quaternary lava west of Powell Butte	O'Neil	44°15.73' 121°04.82'	Basalt	Whole rock	Brown and others, 1980a; Evans and Brown, 1981
14	Qba	0.12±0.3[a]	o	TS-137	Husband volcano	South Sister	44°07.29' 121°51.27'	Basaltic andesite	Whole rock	Armstrong and others, 1975
15	Qba	0.44±0.12	+	TFJ-321	Potato Hill road	Santiam Junction	44°25.57'[w] 121°55.49'	Basaltic andesite	Whole rock	Armstrong and others, 1975
16	Qdt	0.460±0.030	+	3S067	Todd Lake volcano	Broken Top	44°01.35' 121°43.28'	Dacite	Whole rock	Hill and Duncan, 1990; Hill, 1992a (table 3.1, p. 19)
17	Qr	0.4±0.4	-	BT-31	Melvin Butte dome	Three Creek Butte	44°10.61' 121°36.16'	Dacite	Whole rock	Armstrong and others, 1975
18	Qr	0.2±0.9	-	BT-72	Three Creek Butte dome	Three Creek Butte	44°09.06' 121°34.54'	Dacite	Whole rock	Armstrong and others, 1975
19	Qr	1.63±1.1	-	M6-45	Bearwallow Butte dome	Tumalo Falls	44°04.70' 121°33.20'	Rhyodacite	Plagioclase	Fiebelkorn and others, 1983
20	Qoba	0.56±0.14	-	TFJ-427	U.S. 20 roadcut N. of Blue Lake, reversed-polarity TRM	Three Fingered Jack	44°25.17' 121°46.32'	Basaltic andesite	Whole rock	Armstrong and others, 1975

Table 2. *Potassium-argon and $^{40}Ar/^{39}Ar$ isotopic ages from map area. See figure 3 for sample location map—Continued*

Map No.	Strat. unit	Age (Ma)	Quality	Sample No.	Geologic unit or geographic location	Quadrangle (1:24,000 scale)	Lat. N Long. W	Rock type	Material dated	Reference
21	Qoba	0.72±0.19	+	81/108	Highway 20, 0.5 km north of Blue Lake	Three Fingered Jack	44°25.16' 121°46.22'	Basaltic andesite	Whole rock	Hill and Priest, 1992
22	Qoba	0.90±0.05	+	TFJ-363	Cache Mountain, older part	Three Fingered Jack	44°23.25' 121°46.03'	Basaltic andesite	Whole rock	Armstrong and others, 1975
23	Qoba	0.46±0.30	-	S-80	Black Butte volcano, reversed-polarity TRM	Black Butte	44°24.41' 121°37.53'	Basaltic andesite	Whole rock	Armstrong and others, 1975
24	Qoba	0.48±0.2[a]	-	S-23	Black Butte volcano, reversed-polarity TRM	Black Butte	44°24.41' 121°37.53'	Basaltic andesite	Whole rock	Armstrong and others, 1975
25	Qoba	1.43±0.33	+	81/110	Black Butte, 1 km northeast of summit	Little Squaw Back	44°24.41' 121°37.53'	Basaltic andesite	Whole rock	Hill and Priest, 1992
26	Qbti	*1.19±0.08	+	D4	Intracanyon lava, Crooked River, reversed-polarity TRM	Opal City	44°25.96' 121°14.48'	Basalt	Whole rock	Smith, 1986
27	Qoba	1.6±0.3	+	TFJ-431	State Hwy 126, 0.6 mi SE of Carmen Reservoir	Clear Lake	44°19.75' 121°59.61'	Basaltic andesite	Whole rock	Armstrong and others, 1975
28	Qoba	1.1±0.2	+	TFJ-256	State Hwy 126, 0.6 mi SE of Carmen Reservoir	Clear Lake	44°19.75' 121°59.61'	Basaltic andesite	Whole rock	Armstrong and others, 1975
					Drill core from High Cascades: Quaternary rocks					
29	Qoba	1.00±0.03	o	SP 77-24, 502 m	Drill hole, east side of Santiam Pass (502 m depth)	Three Fingered Jack	44°25.46' 121°50.40'	Basalt	Whole rock	Hill,1992b
30	Qoba	0.91±0.06	o	SP 77-24, 698 m	Drill hole, east side of Santiam Pass (698 m depth)	Three Fingered Jack	44°25.46' 121°50.40'	Basaltic andesite	Whole rock	Hill,1992b
31	Qoba	1.81±0.05	o	SP 77-24, 928 m	Drill hole, east side of Santiam Pass (928 m depth)	Three Fingered Jack	44°25.46' 121°50.40'	Basaltic andesite	Whole rock	Hill,1992b
					Drill core from High Cascades: probably Quaternary but units not determined					
32	not known	0.15±0.05	-	88-2-1819	Devils Lake drill hole 83-2, core at 1819-ft depth	South Sister	44°02.01' 121°45.84'	Basalt	Plagioclase	Priest, 1990; G.R. Priest, unpub. data
33	not known	0.073±0.034	-	88-4-810	Trout Creek drill hole 82-4, core at 810-ft depth	Trout Creek Butte	44°13.06' 121°39.71'	Basalt	Plagioclase	Priest, 1990; G.R. Priest, unpub. data
					Pliocene basalt and basaltic andesite					
34	Tbas	2.9±0.2	+	B-22	Summit, Squaw Back Ridge shield volcano	Squaw Back Ridge	44°28.70' 121°28.59'	Basaltic andesite	Whole rock	Armstrong and others, 1975
35	Tbdr	8.83±1.36	-	Pb-1; UT-216	Pliocene lava west of Powell Butte	O'Neil	44°15.02' 121°03.20'	Basalt	Plagioclase	Brown and others, 1980a; Evans and Brown, 1981
36	Tam	3.3±0.2	+	S-84	Slope above Camp Polk site north of Sisters	Sisters	44°19.18' 121°31.07'	Andesite	Whole rock	Armstrong and others, 1975
37	Tbr	*3.56±0.30	+	D3a	Plateau-forming flow near Redmond	Opal City	44°23.20' 121°13.02'	Basalt	Whole rock	Smith, 1986
					Deschutes Formation					
38	Tda	4.7±0.1	+	3S002	Deschutes Formation lava, near Bull Spring	Shevlin Park	44°06.63' 121°29.22'	Basaltic andesite	Whole rock	Hill, 1992a (table 3.1, p. 19)
39	Tdb	4.9±0.4	+	HB-7	Lava flow at top of Deep Canyon grade (Oreg. Hwy 126)	Henkle Butte	44°17.38' 121°24.80'	Basaltic andesite	Whole rock	Armstrong and others, 1975
40	Tdbas	*5.06±0.03	+	D1a	Basaltic andesite of Steamboat Rock, Deschutes Formation	Cline Falls	44°21.45' 121°16.03'	Basaltic andesite	Whole rock	Smith, 1986; Smith and others, 1987a
41	Tdb	5.1±0.2	+	S-74	Green Ridge summit, south end	Little Squaw Back	44°25.61' 121°36.00'	Basaltic andesite	Whole rock	Armstrong and others, 1975
42	Tdbo	*5.77±0.07	+	D5	Basalt of Opal Springs, Deschutes Formation	Opal City	44°26.11' 121°14.50'	Basalt	Whole rock	Smith, 1986; Smith and others, 1987a
43	Tdrcb	*6.14±0.06	+	S94-B78	Rhyolite of Cline Buttes, Deschutes Formation	Cline Falls	44°15.89' 121°17.50'	Rhyolite	Plagioclase	M.A. Lanphere, written commun., 1999

Table 2. *Potassium-argon and $^{40}Ar/^{39}Ar$ isotopic ages from map area. See figure 3 for sample location map—Continued*

Map No.	Strat. unit	Age (Ma)	Quality	Sample No.	Geologic unit or geographic location	Quadrangle (1:24,000 scale)	Lat. N Long. W	Rock type	Material dated	Reference
44	Tdrsf	*6.74±0.20	+	S94-B100	Rhyodacite southwest of Steelhead Falls, Deschutes Fm.	Steelhead Falls	44°23.21' 121°22.44'	Rhyodacite	Plagioclase	M.A. Lanphere, written commun., 1998
					John Day Formation					
45	Tjr	10.05±0.45	-	SR-G-1	Gray Butte rhyolite, Smith Rock area	Gray Butte	44°25.1'[?] 121°05.8'[?]	Vitrophyre	--	Obermiller, 1987
46	Tjr	17.76±0.44	-	SR-RH-4	Gray Butte rhyolite	Gray Butte	44°24.0'[?] 121°07.2'[?]	Rhyolite	--	Obermiller, 1987
47	Tjr	*28.82±0.23	+	GSO95-41	Gray Butte rhyolite, basal vitrophyre	Gray Butte	44°24.30' 121°06.79'	Rhyolite	Anorthoclase	Smith and others, 1998
48	Tjr[†]	28.3±1.0	+	PB-5; AH-34	Powell Buttes dome	Powell Buttes[†]	44°11.86'[†] 120°58.03'[†]	Rhyolite	Anorthoclase	Evans and Brown, 1981
49	Tjh	*27.62±0.63	+	GSO95-134	West end of Haystack Reservoir, quarry	Opal City	44°29.87' 121°09.37'	Welded tuff	Sanidine	Smith and others, 1998
50	Tjts	15.39±0.29	-	SR-T-5	Tuff of Smith Rock, Smith Rock area	Gray Butte	44°23.5'[?] 121°05.7[?]	Rhyolitic tuff	--	Obermiller, 1987
51	Tjth	*29.57±0.17	+	GSO95-132	West end of Haystack Reservoir, quarry	Opal City	44°29.76' 121°09.36'	Welded tuff	Sanidine	Smith and others, 1998
52	Tjth	*29.53±0.09	+	GSO95-133	West end of Haystack Reservoir, quarry	Opal City	44°29.85' 121°09.28'	Hydromagmatic tuff	Sanidine	Smith and others, 1998
53	Tjbi[¥]	30.8±0.5	+	10-6-78-2	Northeast of Gray Butte	Gray Butte	44°26.10' 121°05.40'	Basalt (intrusion)[¥]	Whole rock	Fiebelkorn and others, 1983
54	Tjs	*32.49±0.30	+	GSO95-130	Tuff of Rodman Spring, at Rodman Spring	Gray Butte	44°27.83' 121°06.91'	Fallout lapilli tuff	Sanidine	Smith and others, 1998
55	Tjb	17.54±0.98	-	SR-B-1	West of Gray Butte	Gray Butte	44°25.3'[?] 121°07.2'[?]	Basaltic andesite	--	Obermiller, 1987
56	Tjb	18.85±0.51	-	24	Canal flora area	Opal City	44°24.0'[?] 121°09.4'[?]	Basalt	--	Obermiller, 1987
					Drill core sample in or beneath John Day Formation strata in Bend quadrangle					
57	Tjb?[§]	1.53±0.77	-	DOGMI-Bas81-1	Powell Buttes, subsurface(?)	Powell Butte	44°11.63' 121°03.04'	--	Whole rock	Evans and Brown, 1981
58	Tjb?[§§]	30.1±1.1	+	DOGMI-Bas81-2	Powell Buttes, subsurface(?)	Powell Butte	44°11.63' 121°03.04'	--	Whole rock	Evans and Brown, 1981

--, no data reported

[a]Recalculated age varies more than 5 percent from published age

[w]Latitude originally reported is too far north

* $^{40}Ar/^{39}Ar$ age determination

[?]Location accurate only to nearest one-quarter section; positional error may be as great as ±500 m

[†]East of map area. Location measured after plotting sample location from photocopy of original field sheet (provided courtesy of G.R. Priest, Oregon Department of Geology and Mineral Industries, 1995)

[¥]Recognized as intrusion on this map

[§]May be from drill core. Records lost for sample description and material sampled (G.R. Priest, Oregon Department of Geology and Mineral Industries, written commun., 1995)

[§§]Probably from drill core, corresponding to sample from Powell Buttes 1 geothermal well, 310-320 m depth, as described by Brown and others (1980a, p. 5)

Table 3. *Chemical analyses from some Pleistocene tephra and rhyolite domes in map area*

[Major element analyses normalized to 100 percent with all iron as Fe^{2+}. Also shown are oxide totals from original analysis. Dashes indicate elements not analyzed. Location numbers are keyed to appendix 1 and figure 8; dashes indicate sample localities not shown on figure 8]

Bend Pumice									
Location No.	--	9	--	--	--	--	--	--	--
Sample No.	3SXBP	3S001	BD16-5	BD16-6	BD16-7	BD16-8	BD16-9	BD23-2	BD23-1
References	1	1	2	2	2	2	2	2	2
Major-element analyses, normalized water-free (weight percent)									
SiO_2	74.72	72.52	74.73	74.66	74.89	74.39	74.28	73.80	72.88
Al_2O_3	14.30	16.54	13.66	13.74	13.54	13.79	14.35	14.74	15.59
FeO	1.83	2.35	1.82	1.83	1.80	1.90	1.89	1.92	2.15
MgO	0.08	0.12	0.12	0.17	0.13	0.27	0.16	0.28	0.26
CaO	0.82	0.83	0.89	0.87	0.94	0.93	0.87	0.89	0.90
Na_2O	4.49	3.76	4.97	5.03	4.92	5.04	4.92	4.60	4.63
K_2O	3.49	3.52	3.52	3.46	3.49	3.40	3.25	3.45	3.26
TiO_2	0.16	0.21	0.13	0.14	0.13	0.14	0.15	0.17	0.18
P_2O_5	0.03	0.04	0.08	0.08	0.08	0.08	0.08	0.09	0.09
MnO	0.07	0.10	0.06	0.02	0.06	0.06	0.05	0.06	0.05
Original oxide total	99.30	99.14	100.02	98.76	100.83	100.90	99.35	99.00	100.46
Trace-element analyses (parts per million)									
Ni	11	18	--	--	--	--	--	--	--
Cr	1	4	--	--	--	--	--	--	--
Sc	4.3	6.3	--	--	--	--	--	--	--
V	0	0	--	--	--	--	--	--	--
Ba	794	986	--	--	--	--	--	--	--
Rb	84	77	--	--	--	--	--	--	--
Sr	65	68	--	--	--	--	--	--	--
Zr	231	264	--	--	--	--	--	--	--
Co	0.5	4.9	--	--	--	--	--	--	--
Zn	105	69	--	--	--	--	--	--	--
La	28.7	27.4	--	--	--	--	--	--	--
Ce	59.7	62.7	--	--	--	--	--	--	--
Nd	26.5	26.1	--	--	--	--	--	--	--
Sm	5.95	5.69	--	--	--	--	--	--	--
Eu	0.83	0.75	--	--	--	--	--	--	--
Tb	0.94	0.85	--	--	--	--	--	--	--
Yb	4.2	4	--	--	--	--	--	--	--
Lu	0.58	0.56	--	--	--	--	--	--	--
Cs	3.1	2.7	--	--	--	--	--	--	--
Hf	6.7	7.1	--	--	--	--	--	--	--
Ga	20	23	--	--	--	--	--	--	--
Y	36	37	--	--	--	--	--	--	--
Nb	16.9	20.8	--	--	--	--	--	--	--
Ta	1.2	1.16	--	--	--	--	--	--	--
Th	8.1	7.6	--	--	--	--	--	--	--
U	2.7	2.5	--	--	--	--	--	--	--
Pb	--	--	--	--	--	--	--	--	--

References: 1, Hill (1992a); 2, Mimura (1992); 3, Taylor and Ferns (1995); 4, W.E. Scott, unpub. data; 5, R.M. Conrey and D.R. Sherrod, unpub. data; 6, Hill and Taylor (1989); 7, Hughes (1983).

Sample locations:

3SXBP, from quarry 1.2 km south of Overturf Butte in Bend city limits.

3S001, deposit mantling hillslopes at 4,340 ft elevation, 3 km west of Bull Spring.

BD16-5, 6, 7, 8, 9, exposure 2.4 km west of Overturf Butte; sampled downsection from -5 (near top) to -9 (near base).

BD23-2, 1, quarry along O.B. Riley Road, 450 m southeast of Tumalo State Park; sampled near base (23-2 overlies 23-1).

Table 3. *Chemical analyses from some Pleistocene tephra and rhyolite domes in map area—Continued*

	Rhyolite domes north of Triangle Hill				Three Creek Butte		Melvin Butte	
Location No.	--	--	--	--	--	--	--	--
Sample No.	3S012	S95-B160	3S075	S95-B163	3S032	S-3-CRBT	3S034	S-MELVIN
References	1	5	1	5	1, 3	4	1, 3	4
Major-element analyses, normalized water-free (weight percent)								
SiO_2	74.57	74.59	75.34	75.11	74.81	75.06	74.95	75.12
Al_2O_3	14.11	13.74	13.78	13.51	13.76	13.52	13.75	13.51
FeO	1.68	1.44	1.57	1.52	1.71	1.73	1.58	1.72
MgO	0.17	0.23	0.08	0.00	0.00	0.14	0.02	0.13
CaO	0.71	0.70	0.66	0.66	0.71	0.72	0.72	0.71
Na_2O	5.06	5.57	4.81	5.44	5.28	5.21	5.27	5.16
K_2O	3.46	3.50	3.55	3.56	3.49	3.43	3.47	3.45
TiO_2	0.15	0.14	0.14	0.13	0.15	0.14	0.16	0.14
P_2O_5	0.02	0.02	0.02	0.02	0.02	0.05	0.02	0.05
MnO	0.06	0.06	0.05	0.05	0.06	<0.5	0.06	<0.5
Original oxide total	99.94	101.15	99.95	101.24	99.58	99.12	99.66	99.17
Trace-element analyses (parts per million)								
Ni	12	7	12	6	10	<2	10	<2
Cr	0	0	<4	0	<3	<1	<3	2
Sc	4.1	7	4.3	4	4.3	4	4.3	4
V	0	10	9	2	0	<2	2	<2
Ba	797	766	801	783	796	790	818	780
Rb	82	87	87	87	86	--	82	--
Sr	54	48	42	41	52	49	50	47
Zr	218	224	201	210	222	--	219	--
Co	0.5	--	0.7	--	0.5	1	0.5	1
Zn	88	52	71	46	84	49	64	34
La	23.0	--	19.4	--	25.3	30	24.2	30
Ce	48.1	--	43.4	--	52.6	51	53	49
Nd	20.8	--	17.5	--	20.4	28	21.8	27
Sm	4.26	--	3.84	--	4.77	--	4.71	--
Eu	0.59	--	0.54	--	0.64	--	0.63	--
Tb	0.70	--	0.64	--	0.78	--	0.78	--
Yb	3.1	--	3.1	--	3.7	4	3.5	3
Lu	0.47	--	0.46	--	0.53	--	0.54	--
Cs	0.8	--	1.6	--	1.5	--	1.6	--
Hf	6.1	--	6.1	--	6.5	--	6.5	--
Ga	22	19	22	18	20	18	18	19
Y	29	39	26	28	31	34	32	32
Nb	16.5	16.4	17.4	15.2	17.8	8	18	9
Ta	1.01	--	1.04	--	1	--	1.04	--
Th	7.7	8	8.0	8	7.9	9	7.8	8
U	2.2	--	2.3	--	2.7	--	2.5	--
Pb	--	9	--	12	--	8	--	9

References: 1, Hill (1992a); 2, Mimura (1992); 3, Taylor and Ferns (1995); 4, W.E. Scott, unpub. data; 5, R.M. Conrey and D.R. Sherrod, unpub. data; 6, Hill and Taylor (1989); 7, Hughes (1983).

Sample locations:

3S012, 5,400-ft elevation, 460 m east from summit of hill with spot elevation 5,009 ft (Tumalo Falls quadrangle), 1.3 km north-northeast of Triangle Hill.

S95-B160, similar location as 3S012, but at 5,540-ft elevation, 300 m east-northeast from summit of hill.

3S075, 5,400-ft elevation, upslope from abandoned spur road, 122 m northwest from summit of hill with spot elevation 5,875 ft (Tumalo Falls quadrangle), 1,920 m north-northwest of Triangle Hill.

S95-B163, similar location as 3S075, but at 5,800-ft elevation, 60 m north-northwest from summit of hill.

3S032, near summit of Three Creek Butte.

S-3-CRBT, near summit of Three Creek Butte.

3S034, 4,960-ft elevation, south summit area of Melvin Butte.

S-MELVIN, 4,860-ft elevation, south-southwest flank of Melvin Butte.

Table 3. *Chemical analyses from some Pleistocene tephra and rhyolite domes in map area—Continued*

	Pumice of Columbia Canal				Pumice of Bottle Creek		
					along Bottle Creek		5 km northeast
Location No.	10	3	4	2	11	11	8
Sample No.	3S079	RC95-178	830920-6	830920-5	3S024	S830920-1	3S018
References	1, 6	5	4	4	1	4	1
Major-element analyses, normalized water-free (weight percent)							
SiO_2	67.66	67.60	67.70	67.85	71.91	70.08	72.08
Al_2O_3	17.27	16.53	17.25	16.19	16.32	17.44	16.41
FeO	4.16	3.87	4.04	3.89	2.53	2.81	2.38
MgO	0.84	0.91	0.94	1.03	0.22	0.39	0.22
CaO	2.41	2.35	2.52	2.55	1.17	1.23	1.03
Na_2O	4.37	5.43	4.47	5.09	4.33	4.72	4.47
K_2O	2.18	2.20	1.99	2.26	3.14	2.90	3.07
TiO_2	0.82	0.81	0.81	0.81	0.26	0.28	0.23
P_2O_5	0.16	0.18	0.11	0.12	0.04	0.09	0.04
MnO	0.13	0.12	0.16	0.21	0.08	0.06	0.07
Original oxide total	99.03	99.03	92.17	93.88	99.29	93.46	99.33
Trace-element analyses (parts per million)							
Ni	7	6	3	<2	11	<2	9
Cr	3	6	4	2	2	3	0
Sc	11.1	6	13	12	5.0	6	4.9
V	36	23	12	14	1	3	17
Ba	616	701	620	690	830	900	859
Rb	44	42	--	--	74	--	73
Sr	278	288	280	290	113	140	125
Zr	231	261	--	--	270	--	281
Co	2.1		2	3	1.1	2	0.9
Zn	87	81	77	80	84	68	87
La	19.8	--	27	25	24.3	30	27.9
Ce	39.9	--	60	51	48.2	56	48.2
Nd	22.1	--	37	31	23	32	25.7
Sm	6.06	--	--	--	5.09	--	5.50
Eu	1.37	--	--	--	0.84	--	0.83
Tb	0.87	--	--	--	0.78	--	0.86
Yb	3.4	--	4	4	3.4	4	3.8
Lu	0.5	--	--	--	0.54	--	0.56
Cs	1.6	--	--	--	2.1	--	2.0
Hf	5.5	--	--	--	6.7	--	7.0
Ga	21	20	22	18	23	19	21
Y	36	43	39	36	34	38	38
Nb	14.3	16	<4	15	15.7	18	15.6
Ta	0.66	--	--	--	0.86	--	0.89
Th	3.8	4	<4	<4	6.2	6	6.4
U	1.4	--	--	--	2.2	--	2.3
Pb	--	9	<4	12	--	10	--

References: 1, Hill (1992a); 2, Mimura (1992); 3, Taylor and Ferns (1995); 4, W.E. Scott, unpub. data; 5, R.M. Conrey and D.R. Sherrod, unpub. data; 6, Hill and Taylor (1989); 7, Hughes (1983).

Sample locations:

3S079, exposure in Columbia Canal along its narrow canyon reach, 2.1 km southeast of Bull Spring

RC95-178, roadcut, U.S. Forest Service Road (USFS) 1514, 1.7 km west of junction with Road 16, 10 km south-southwest of Sisters.

830920-6, surface-mantling deposit along USFS Road 16 near benchmark 3823, 7.5 km south-southwest of Sisters

830920-5, cone-mantling deposit in cinder quarry 3.3 km south of Trout Creek Butte.

3S024, creek-bank exposure, south wall of Bottle Creek, 6,600-ft elevation, east side of USFS Road 370, 7.7 km east of Broken Top.

S830920-1, same location as 3S024.

3S018, cone mantling deposit exposed in bulldozer scraping at 6,140-ft elevation along USFS spur road 4602-350. This locality is 5.2 km northeast of 3S024 and S830920-1, which are correlative but in a substantially thicker part of tephra-fall deposit.

Table 3. *Chemical analyses from some Pleistocene tephra and rhyolite domes in map area—Continued*

	Pumice SSW. of Three Creek Butte		Lava of Obsidian Cliffs		Pumice on Pilot Butte	
					at Pilot Butte	East Tumalo quarry
	5	5	--	--	13	12
Sample No.	830920-4	3S086	TS-690	3S139	3S007	830803-6
References	4	1	7	1	1	4
Major-element analyses, normalized water-free (weight percent)						
SiO_2	76.78	75.81	76.02	76.23	72.63	72.13
Al_2O_3	13.52	14.24	12.84	13.42	15.45	15.41
FeO	1.01	1.07	1.10	1.16	2.40	2.43
MgO	0.18	0.09	0.50	0.11	0.47	0.33
CaO	0.79	0.93	0.90	0.97	1.42	1.23
Na_2O	4.07	4.23	4.71	4.47	4.06	4.90
K_2O	3.54	3.41	3.83	3.42	3.17	3.20
TiO_2	0.08	0.13	0.09	0.14	0.25	0.22
P_2O_5	0.03	0.04	--	0.04	0.05	0.07
MnO	<0.5	0.04	--	0.04	0.08	0.06
Original oxide total	94.68	99.72	99.71	99.83	99.00	93.44
Trace-element analyses (parts per million)						
Ni	<2	11	9	<10	13	<2
Cr	2	4	2	1	2	2
Sc	<2	2.0	3.1	1.6	4.9	5
V	<2	0	--	9	0	<2
Ba	930	861	880	876	776	780
Rb	--	74	115	79	67	--
Sr	100	115	160	119	130	110
Zr	--	97	130	96	253	--
Co	<1	0.9	0.9	0.6	1.5	1
Zn	29	58	--	64	69	57
La	22	20.0	21	20	21.8	27
Ce	40	43.5	71.5	44.6	44.9	50
Nd	15	16.3	18.0	14.9	20.7	27
Sm	--	2.77	2.83	2.63	4.71	--
Eu	--	0.44	0.85	0.42	0.78	--
Tb	--	0.41	0.46	0.39	0.71	--
Yb	2	1.5	1.7	1.5	3.1	4
Lu	--	0.26	0.29	0.24	0.48	--
Cs	--	1.8	4.16	1.94	1.7	--
Hf	--	3.3	5.1	3.2	6.1	--
Ga	16	17	--	15	19	18
Y	14	16	--	15	32	33
Nb	<4	10.9	--	10	14.8	15
Ta	--	0.69	1.54	0.74	0.75	--
Th	5	7.3	12.2	7.3	5.5	8
U	--	4.5	2.9	2.6	1.8	--
Pb	<4	--	--	--	--	14

References: 1, Hill (1992a); 2, Mimura (1992); 3, Taylor and Ferns (1995); 4, W.E. Scott, unpub. data; 5, R.M. Conrey and D.R. Sherrod, unpub. data; 6, Hill and Taylor (1989); 7, Hughes (1983).

Sample locations:

830920-4, roadcut at 5,400-ft elevation along USFS spur road 1628-600, 2.3 km south-southwest of Three Creek Butte

3S086, same location as 830920-4.

TS-690, summit of small hill about 150 m northwest of Sister Spring, 3.6 km west of North Sister.

3S139, near Prouty memorial plaque, about 975 m north of Sister Spring, 3.7 km west of North Sister.

3S007, cone-mantling deposit on west side of Pilot Butte at 3,720-ft elevation upslope from foot of Pilot Butte access road.

830803-6, cone-mantling deposit exposed at west edge of cinder quarry in hill with spot elevation 3,670 ft (Tumalo Falls quadrangle) or 1,728 m (on Bend 30- x 60-minute quadrangle), 2.1 km east of Tumalo Lake.