# GEOLOGIC MAP OF UPPER EOCENE TO HOLOCENE VOLCANIC AND RELATED ROCKS OF THE CASCADE RANGE, OREGON

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## INTRODUCTION

Since 1979, Earth scientists of the Geothermal Research Program of the U.S. Geological Survey have carried out multidisciplinary research in the Cascade Range. The goal of this research is to understand the geology, tectonics, and hydrology of the Cascades in order to characterize and quantify geothermal resource potential. A major goal of the program is compilation of a comprehensive geologic map of the entire Cascade Range that incorporates modern field studies and that has a unified and internally consistent explanation.

This map is one of three in a series that shows Cascade Range geology by fitting published and unpublished mapping into a province-wide scheme of rock units distinguished by composition and age; map sheets of the Cascade Range in Washington (Smith, 1993) and California will complete the series. The complete series forms a guide to exploration and evaluation of the geothermal resources of the Cascade Range and will be useful for studies of volcano hazards, volcanology, and tectonics.

For geothermal reasons, the maps emphasize Quaternary volcanic rocks. Large, igneous-related geothermal systems that have high temperatures are associated with Quaternary volcanic fields, and geothermal potential declines rapidly as age increases (Smith and Shaw, 1975). Most high-grade recoverable geothermal energy is likely to be associated with silicic volcanic systems active in the past 1 million years. Lower grade (= lower temperature) geothermal resources may be associated with somewhat older rocks; however, volcanic rocks emplaced prior to 2 million years ago are unlikely geothermal targets (Smith and Shaw, 1975).

Rocks older than a few million years are included on the maps because they help to unravel geologic puzzles of the present-day Cascade Range. The deeply eroded older volcanoes found in the Western Cascades physiographic subprovince[1] are analogues of today's snow-covered shield and composite volcanoes. The fossil hydrothermal systems in the roots of Eocene to Pliocene vents, now exposed, provide clues to processes active today beneath the Pleistocene and Holocene volcanic peaks along the present-day crest of the Cascade Range. Study of these older rocks aids in developing models of geothermal systems. These rocks also give insight into the origins of volcanic-hosted mineral deposits and even to potential volcanic hazards.

Historically, the regional geology of the Cascade Range in Oregon has been interpreted through reconnaissance studies of large areas (for example, Diller, 1898; Williams, 1916; Callaghan and Buddington, 1938; Williams, 1942, 1957; Peck and others, 1964). Early studies were hampered by limited access, generally poor exposures, and thick forest cover, which flourishes in the 100 to 250 cm of annual precipitation west of the range crest. In addition, age control was scant and limited chiefly to fossil flora. Since then, access has greatly improved via a well-developed network of logging roads, and isotopic ages—mostly potassium-argon (K-Ar)—have gradually solved some major problems concerning timing of volcanism and age of mapped units. Nevertheless, prior to 1980, large parts of the Cascade Range remained unmapped by modern studies.

Geologic knowledge of the Cascade Range has grown rapidly in the last few years. Luedke and Smith (1981, 1982) estimated that, when their maps were made, more than 60 percent of the Cascade Range lacked adequate geologic, geochemical, or geochronologic data for a reliable map at 1:1,000,000 scale. Today only about 20 percent of the Cascade Range is too poorly known to show reliably at the larger 1:500,000 scale of this map. In Oregon the poorly known areas include Oligocene and Miocene rocks in the Western Cascades physiographic subprovince and parts of the Columbia River Gorge.

The present series of maps of the Cascade Range is not merely a reworking of previously published data. Geologic interpretations shown here are based largely on newly published and unpublished geologic maps and isotopic age determinations, including our own, done since 1980. To assign all map units their correct composition and age, we also reevaluated older published maps and incorporated recently determined chemical analyses and isotopic ages.

[1]The Cascade Range in Oregon is customarily divided into two subprovinces: Western Cascades and High Cascades (Dicken, 1965). The Western Cascades subprovince is a deeply eroded terrane of Pliocene to Eocene volcanic and sedimentary rocks. The High Cascades encompasses the little-eroded, active volcanic arc, including the major young volcanoes.

## ONSET OF CASCADE RANGE VOLCANISM

This map shows all rocks that are part of the geographic Cascade Range in Oregon. Adjacent areas are included to show the structural and stratigraphic setting of the range. In Oregon, the Cascade Range is built almost entirely of upper Eocene to Holocene volcanic and volcaniclastic rocks. These rocks formed in an arc setting and presumedly are related to subduction.

Our partly temporal definition is somewhat arbitrary, for no one has established when the Cascade Range became a distinct, calc-alkaline volcanic arc. Nor is there a clear understanding of how pre-upper Eocene calc-alkaline volcanic rocks are related to the younger volcanic rocks of the Cascade Range. In eastern Oregon (east of the Cascade Range), lower and middle Eocene rocks are assigned to the Clarno Formation (for example, Rogers and Novitsky-Evans, 1977; Noblett, 1981) and are perhaps part of a broad volcanic belt that may once have been continuous with the Eocene Challis and Absaroka volcanic fields of Idaho and Wyoming. This suite of calc-alkaline volcanic rocks was termed the “Challis arc” by Armstrong (1978). Isotopic ages suggest that Challis arc volcanism had waned by late Eocene time. In contrast, all volcanic rocks within the geographic boundaries of the Cascade Range in Oregon are of late Eocene age or younger.

In Oregon, the oldest rocks generally considered part of Cascade Range volcanism belong to the upper Eocene Fisher Formation. The Fisher, which interfingers with the marine Eugene Formation from Eugene to Roseburg (see figure 1 for index map) includes locally vented materials. Lithologically, the Fisher Formation is similar to conformably overlying Oligocene volcanic rocks. However, the Fisher Formation is virtually unstudied, and the only isotopic ages are from samples near the top of the formation; these samples range in age from 36 to 40 million years (Lux, 1982).

From Eugene north to Salem (fig. 1), the depositional relations between continental volcanogenic rocks and marine sedimentary rocks are nearly everywhere buried by Quaternary alluvial sediment in the Willamette Valley; the contact passes into the subsurface about 50 km northeast of Eugene. Distal volcaniclastic deposits of the late Eocene and earliest Oligocene arc must have interfingered with marine sediment, however, because marine(?) tuff-breccia is interbedded with chiefly marine sandstone in a few wildcat oil wells in the Willamette Valley (Newton, 1969). Unfortunately, few isotopic or paleontologic ages have been published from the drill core or cuttings, so age control is poor. For rocks exposed on the surface, isotopic ages are mostly younger than about 35 million years (m.y.). Lux (1982) reported an age of 41.5±0.9 m.y. for a sample collected near Lebanon. However, Walker and Duncan (1988) resampled this site and obtained an age of 31.7±0.4 m.y., which corresponds more closely with ages between about 32 and 34 m.y. from other nearby sample sites in the same stratigraphic sequence.

In the southwestern part of the state, geologic mapping and K-Ar ages suggest that Cascade Range volcanism was widespread by about 35 m.y. ago. This time corresponds to the age of the tuff of Bond Creek (fig. 1), a rhyolitic ash-flow tuff exposed extensively along the west edge of the Cascade Range in the south half of the state (Hausen, 1951; Peck and others, 1964; Smith and others, 1980, 1982; N.S. MacLeod, unpublished mapping, 1983-84). The tuff of Bond Creek lies directly on Mesozoic crystalline rocks 40 km southeast of Canyonville at about latitude 42°50' N. North and south of this latitude, the tuff of Bond Creek concordantly overlies as much as 350 m of upper Eocene subaerial volcanic conglomerate, sandstone, tuff-breccia, and ash-flow tuff that unconformably buried Mesozoic crystalline rocks. These volcaniclastic rocks do not necessarily date the onset of Cascade Range volcanism. Instead, they mark the slightly later time when distal epiclastic or primary pyroclastic material that was being shed from a growing chain of volcanoes located to the east finally reached the present outcrop area.

Southward from the Rogue River, Tertiary volcanic rocks that form the base of the Cascade Range are progressively younger than 35 m.y. The age of the base of the Tertiary volcanic section is about 30 m.y. from the Medford-Ashland area south to Siskiyou Pass (near the Oregon-California border on U.S. Interstate Highway 5). The volcanogenic rocks rest disconformably on poorly dated Eocene(?) fluvial sediment derived from the nearby Klamath Mountains. Continental nonvolcanic and volcanogenic sedimentary rocks are locally interbedded near the top of the Eocene(?) fluvial sequence.

Just south of Siskiyou Pass, basalt and andesite lava flows with K-Ar ages of about 29 m.y. (Fiebelkorn and others, 1983) are part of an extensive and thick accumulation of proximal flows and tuff-breccia that formed around nearby vents. A silicic ash-flow tuff a few meters stratigraphically below the basalt yielded a K-Ar age of about 30 m.y. The base of the volcanic sequence lies a few tens of meters lower than the dated stratum in this area near Siskiyou Pass in Oregon (Smith and others, 1982).

Farther south in California (fig. 1), the Tertiary volcanic section is lithologically similar to that north of the state line; however, it thickens southward. For example, the Tertiary volcanic section older than about 30 m.y. is as much as 200 m thicker along the Klamath River in California than it is in the Siskiyou Pass area of Oregon. In the Colestin basin this thickening represents local accumulation of lahars and ash flows on an alluvial volcaniclastic apron that lay west of the source vents (Bestland, 1987). East of Interstate Highway 5 along the Klamath River, the added section represents a local build-up of mafic lava flows and interbedded andesitic laharic breccias (Vance, 1984). Despite the greater thickness of the Tertiary volcanic section south of Siskiyou Pass, the age of the base of the section remains in the range from 31 to 35 m.y. (Vance, 1984). From Siskiyou Pass south for 30 km to the Shasta Valley, Tertiary volcano-

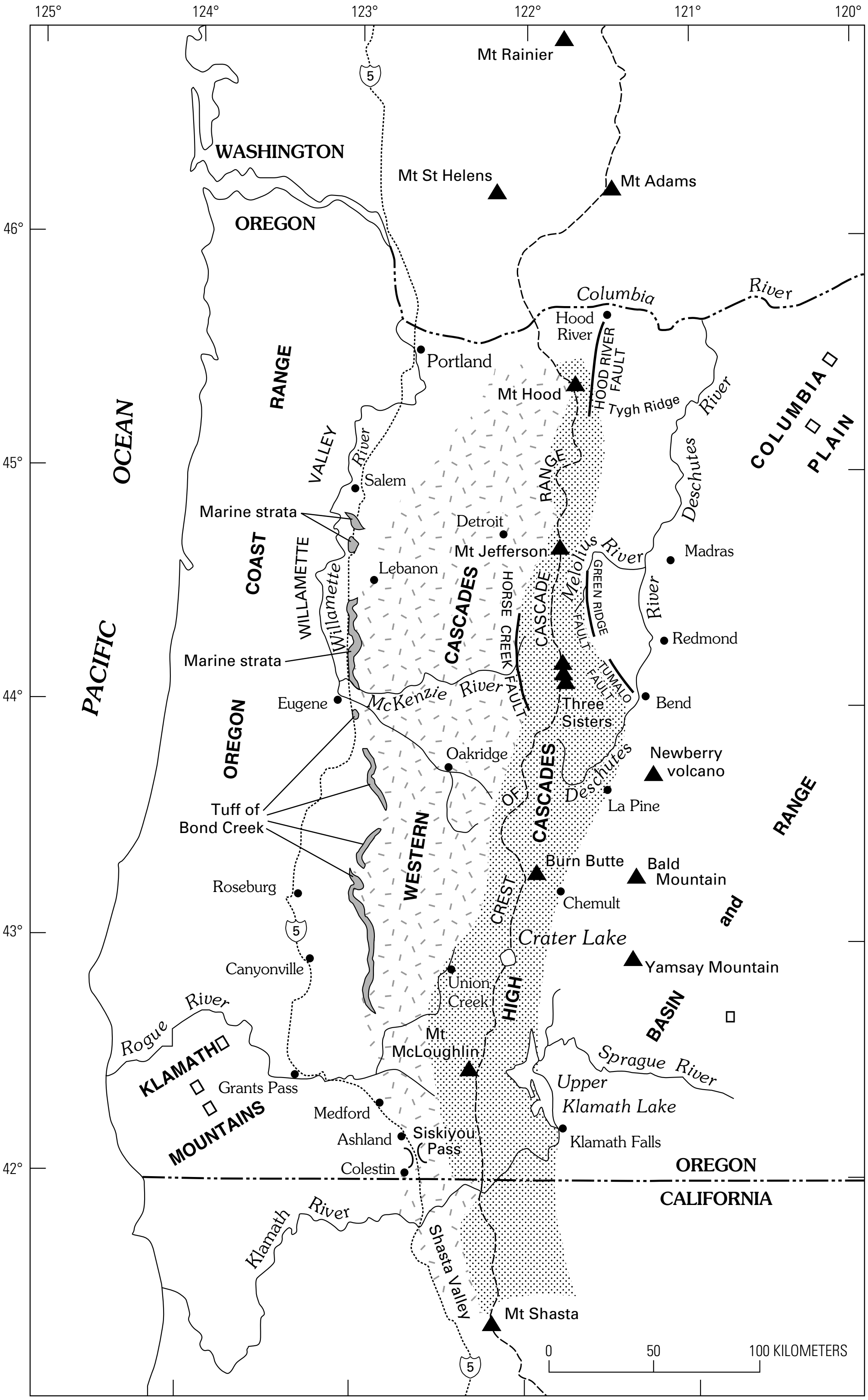


**Figure 1.** Index map showing geographic locations, physiographic provinces and subdivisions, and some faults and lithologic units mentioned in text. Approximate extent of Western and High Cascades (patterned areas) shown for Oregon and northern California. These two subprovince names are not used in Washington or south of Mount Shasta in California, where the Cascade Range lacks a continuous belt of upper Pliocene and Quaternary volcanic rocks.

genic rocks rest unconformably on Upper Cretaceous shallow-water marine rocks. South of Shasta Valley, Tertiary volcanogenic rocks in all but a few small areas are covered by Pliocene and younger volcanic rocks of the High Cascades. Therefore, the original southern extent of Tertiary volcanogenic rocks is unknown.

In the Coast Range of Oregon, onset of Cascade volcanism is recorded in the composition of marine rocks. Sandstone at the base of the middle Eocene Coaledo Formation in southern Oregon shows a marked increase in unmetamorphosed volcanic lithic fragments, which corresponds to a major influx of volcaniclastic debris from the adjacent Cascade volcanic arc about 45 m.y. ago (Heller and Ryberg, 1983). In northern Oregon, onslaught of widespread volcanism in the Cascade arc is recorded by the change in late Eocene time from well-sorted micaceous arkosic sandstone in the Cowlitz Formation to tuffaceous mudstone, siltstone, and volcaniclastic sandstone of the Keasey Formation (Armentrout and Suek, 1983; Kadri and others, 1983). Thus, according to the abundance of volcanic lithic grains in marine sandstone west of the Cascades, Cascade arc volcanism began in the south during the early middle Eocene and progressed northward, reaching Washington by early late Eocene time (Armentrout and Suek, 1983).

In eastern Oregon, the best evidence for the beginning of Cascade Range volcanism is found in the John Day basin, 170 km east of Mount Jefferson. The John Day Formation, which began to accumulate about 39 million years ago, includes a large component of calc-alkaline andesitic to dacitic fine-grained air-fall tuff, lapilli tuff, and tuffaceous claystone. No vents with this calc-alkaline composition are known from the John Day basin. As interpreted by Robinson and others (1984), the John Day basin was the downwind depositional site for voluminous ash that blew in from the west when Cascade volcanoes in northern Oregon first began erupting about 39 million years ago.

## MAP UNITS

The Cascade Range suite of volcanic, volcaniclastic, and nonvolcanic sedimentary rocks is stratigraphically complex compared to miogeoclinal or continental-shelf sedimentary rocks. The complexity results from the intricate way in which volcanic and volcaniclastic rocks were formed, deposited, and reworked in a subaerial arc environment. Hundreds of small overlapping and intertonguing volcanogenic and sedimentary units compose the range; thus, individual lithostratigraphic units are discontinuous and commonly intricately interbedded. In addition, the rocks are poorly exposed in many places, and distinctive widespread marker units are uncommon. Lithologic correlations, even of similar stratigraphic sequences, are unreliable without corroborating isotopic ages or detailed mapping.

To avoid the problems of nomenclature, conventional stratigraphic units were not used for this map. Instead, we interpreted previous studies and our own field observations using a conceptual model of volcanic and sedimentary processes. The model is based chiefly on the models of Smedes and Prostka (1972) and Vessell and Davies (1981); the main criteria for subdivisions are composition, age, and volcanic facies. The result is a more interpretative map than other maps of the Cascade Range, such as Luedke and Smith (1981, 1982) or Walker and MacLeod (1991).

### LITHOLOGY AND MODEL FOR VOLCANIC AND SEDIMENTARY FACIES

A hypothetical cross section (see figure 2 on map sheet 1) illustrates our model of volcanic and sedimentary processes and relations among deposits in the Cascade Range. In this model, volcaniclastic sediment derived from a major volcano laps onto an older eroded volcano and simultaneously interfingers with contemporaneous deposits that were derived from other volcanoes (fig. 2*A*). The resulting suite of volcaniclastic rocks represents many different depositional environments and volcanic sources. Intermittently erupted lava flows, highly mobile ash flows, and large-volume debris flows may travel long distances down valleys. Far downstream these flows become interlayered with fine-grained, thin-bedded volcaniclastic deposits that are characteristic of a low-energy depositional environment. Large andesitic to dacitic volcanoes construct aprons of pyroclastic and epiclastic debris derived from dome growth and eruptions higher on their flanks. Basaltic shield volcanoes overlap and interfinger with one another and with volcaniclastic sediment.

Figure 2*B* shows the facies relations interpreted from the volcanic and sedimentary deposits of figure 2*A*, using the facies terminology of Smedes and Prostka (1972) and Vessell and Davies (1981). The drawing emphasizes the interfingering between rock types that make up the different facies.

Figure 2*C* shows how we grouped lithologic units into volcanic or sedimentary map units and used patterns to show genetic and facies information (see Description of Map Units on map sheet 1 for full explanation of patterns). In table 1, stratigraphic names from the Cascade Range in Oregon are cross referenced to map units and facies used herein. For example, the Deschutes Formation of Smith (1986), which ranges in age from about 7 to 4 m.y. (assigned to time interval $T_1$), contains basalt and basaltic andesite lava flows (unit $Tb_1$ unpatterned); dacitic ash-flow tuff (unit $Td_1$ with ash-flow pattern); sedimentary rocks directly related to volcanism, such as debris flows (unit $Ts_1$ unpatterned); and alluvial fan deposits (unit $Ts_1$ with continental sediment pattern).

### COMPOSITION

The composition of volcanic rocks shown on the map is based on weight percent of $SiO_2$. Where $SiO_2$ content is unknown, we interpreted it from published rock descriptions or our own field studies. The volcanic rocks are divided into the following groups:

(1) rhyolite, more than 70 percent $SiO_2$; (2) dacite, 62 to 70 percent $SiO_2$; (3) andesite, 57 to 62 percent $SiO_2$; (4) basalt and basaltic andesite (mafic andesite or olivine andesite of many workers), less than 57 percent $SiO_2$.

Ideally, it would be better to subdivide the last category into two separate groups, basalt and basaltic andesite. Maps of the major volcanoes now have such detail (see sources of mapping), and many parts of the Quaternary arc (for example, from Mount Jefferson to Columbia River) could be subdivided fairly realistically. In contrast, maps for other extensive areas (including our own early reconnaissance work) lack sufficient detail and supporting chemical analyses. Consequently the entire compositional range of basalt and basaltic andesite is shown as a single unit.

## AGE

Age is another important criterion used to categorize Cascade volcanism. The choices of temporal subdivisions, while somewhat arbitrary, are based on a mixture of traditional chronostratigraphic units and the more or less instantaneous geologic events (such as magnetic reversals) that punctuate Earth's history.

Map-unit ages are based on more than 600 isotopic ages (Cascade Range in Oregon as of December, 1994). We stress, however, that this map shows geology as interpreted from field studies; lithostratigraphic relations take precedent over isotopic determinations. For example, in order to clearly depict lithologic relations with overlying and underlying units, an andesitic sequence (unit $Ta_1$) shown as 7 to 2 m.y. in age might include a few andesite flows whose ages are somewhat outside this interval.

The past 2 million years (defined as the Quaternary period according to Harland and others, 1982) is subdivided into shorter intervals than is the time period from 45 to 2 million years ago because of the important inverse relation between age and geothermal potential (Smith and Shaw, 1975). However, many Quaternary rocks lack isotopic age determinations. Therefore, thermal remanent magnetization and geomorphic features such as depth of erosion, topographic inversion of intracanyon lava flows, and the relative youthfulness of adjacent volcanoes were used to assign undated younger rocks to particular age divisions. Relative geomorphic youth was used effectively to date Quaternary volcanic rocks, because their volcanic landforms are locally well preserved and adjacent volcanoes of different ages may show sharp geomorphic contrasts.

The intervals chosen and reasons for selecting them are discussed below. The subscript used for each interval corresponds to the subscripts used in the Description of Map Units on map sheet 1.

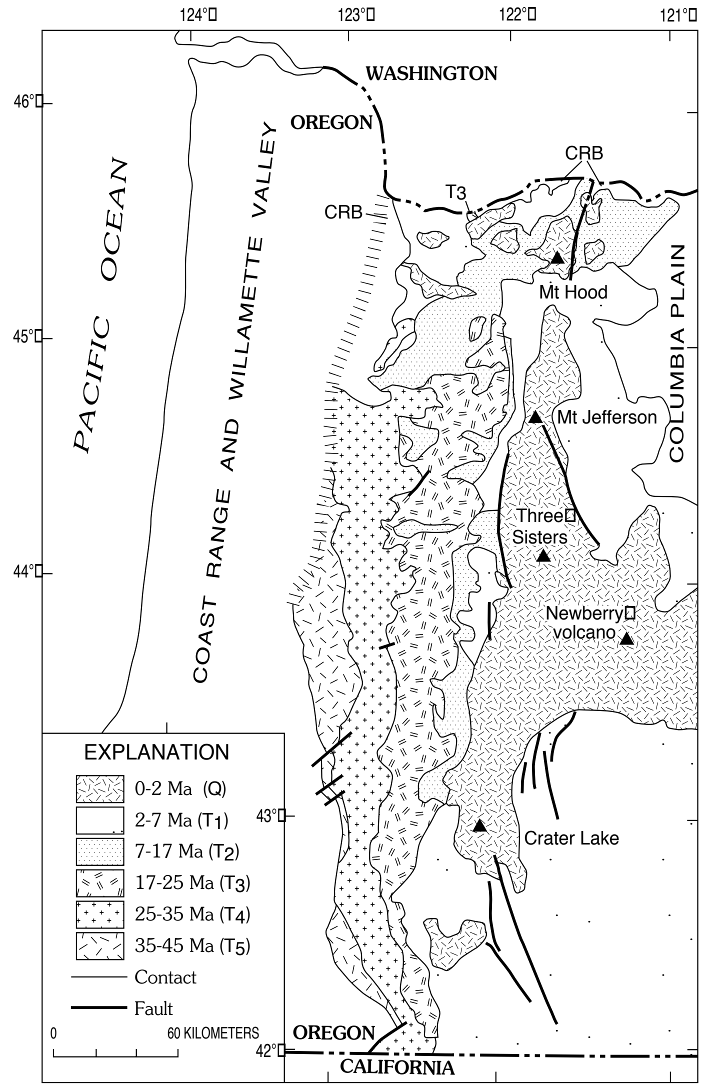


**Figure 3.** Generalized distribution by age of rock in Cascade Range of Oregon. Hachures on northwest side of patterned area shows limit of mapped area on map sheet 1. CRB, Columbia River Basalt Group; Ma million years before present. Symbology (Q, $T_1$, $T_2$, and so on) correspond to broad division of time as discussed in pamphlet.

$Q_1$, **0 to 12,000 years ago:** This interval includes the entire Holocene and extends back into latest Pleistocene time to the end of the last major glaciation in the Cascade Range (Waitt and Thorson, 1983; Porter and others, 1983). Most Cascade researchers relate young volcanic deposits to glacial stratigraphic successions; thus, the 12,000-yr limit for this map unit is useful. Young volcanic deposits dated by the carbon-14 ($^{14}C$) method are readily assigned to this unit.

$Q_2$, **12,000 to 25,000 years ago:** This interval extends from the end of the last major glaciation in the Cascade Range backward to a time for which $^{14}C$ ages are still fairly easily determined (although few radiometric ages in this interval

**Table 1.** Cross reference showing how conventional stratigraphic units were assigned by lithology and facies to pre-Quaternary units used on this map. See Description of Map Units (on map sheet 1) for explanation of unit symbols and patterns.

| | | | | | |
|---|---|---|---|---|---|
| Yonna Formation of former usage | | | | | $Ts_1$ |
| Troutdale Formation | | | | | $Ts_1$ |
| Deschutes Formation | $Tb_1$ | | $Td_1$ | | $Ts_1$ |
| Sandy River Formation | | | | | $Ts_1$ |
| Dalles Formation | | $Ta_2$ | | | $Ts_2$ |
| Rhododendron Formation | | $Ta_2$ | | | |
| Sardine Formation | $Tb_2$ | $Ta_2$ | | | |
| Columbia River Basalt Group | Tcu<br>Tcl | | | | |
| Breitenbush Tuff | $Tb_3$ | $Ta_3$ | | | |
| Colestin Formation | $Tb_4$ | | $Td_4$ | | $Ts_4$ |
| Little Butte Volcanics | $Tb_3$<br>$Tb_4$ | $Ta_3$<br>$Ta_4$ | $Td_3$<br>$Td_4$ | $Tr_3$<br>$Tr_4$ | $Ts_3$<br>$Ts_4$ |
| John Day Formation | | | | $Tr_4$ | $Ts_3$ |
| Eugene Formation | | | | | $Ts_5$ |
| Fisher Formation | $Tb_5$ | $Ta_5$ | | | $Ts_5$ |
| Spencer Formation | | | | | $Ts_5$ |
| Clarno Formation | | $Ta_5$ | | | |

have been obtained from Cascade strata). We distinguish this interval because it highlights a group of young volcanic rocks that are important in making geothermal evaluations. The base of this unit is close to the 24,000-yr boundary suggested by Imbrie and others (1984) as the boundary between oxygen-isotope stages 2 and 3, which is considered by many to separate the middle and late Wisconsin age.

$Q_3$, **25,000 to 120,000 years ago:** This interval extends from beyond the time for which $^{14}C$ ages are readily determined to near the middle Pleistocene-late Pleistocene boundary. Ages are not easily determined by isotopic methods on Cascade rocks in this age range, so some rocks may be incorrectly assigned to the unit. Imbrie and others (1984) suggested an age of 128,000 years for the boundary between the middle and late Pleistocene, whereas Richmond and Fullerton (1986) suggest an age of 132,000 years.

$Q_4$, **120,000 to 780,000 years ago:** The boundary between the Matuyama Reversed-Polarity and Brunhes Normal-Polarity Chrons marks the base of this interval (Shackleton and others, 1990; Baksi and others, 1992). Some recently published geologic maps include the magnetic polarity of stratigraphic units from direct measurements. Magnetic polarity of some shield volcanoes was determined from detailed aeromagnetic maps.

$Q_5$, **0.78 to 2 m.y. ago:** This interval begins at the base of the Pleistocene and ends at the boundary between the Matuyama-Reversed and Brunhes-Normal Polarity Chrons (Harland and others, 1982). Although the age of 2 m.y. does not correspond to any obvious structural or stratigraphic break in the evolution of the Cascade Range, it does mark the maximum age for likely geothermal targets as defined by Smith and Shaw (1975).

$T_1$, **2 to 7 m.y. ago:** In Washington and northern California, the age 7 m.y. marks the approximate onset of renewed volcanism after a period of relatively low volcanic output. In Oregon, most of the rocks exposed along the crest of the Cascade Range are younger than about 7 m.y. Along the subprovince boundary between the High Cascades and the Western Cascades, 7 m.y. approximately corresponds to isotopic ages obtained from the base of a widespread sequence of basalt and basaltic andesite lava flows—

the "basalt of the early High Cascades eruptive episode" of Priest and others (1983), the base of the "volcanic rocks of the High Cascade Range" of Smith and others (1982), or the "ridge-capping basalt" of Sherrod (1991). East of the crest, volcaniclastic sediment derived from the Cascade Range began accumulating about 7 m.y. ago in the upper part of the Deschutes basin and now composes the Deschutes Formation of Smith (1986). Recognizable constructional volcanic landforms predominate in rocks of this age east of the crest and in southern Oregon; west of the crest the landforms are largely obliterated by erosion.

$T_2$, **7 to 17 m.y. ago:** This interval marks the onset of extensive andesitic to basaltic volcanism in northern and central Oregon but seems to be one of diminished volcanic flux in the Cascade Range of Washington, southern Oregon, and northern California. In southern Washington, stratigraphic relations between the Columbia River Basalt Group and Cascade rocks suggest that the Cascade arc was relatively inactive from approximately 17 to 7 m.y. ago. The Columbia River Basalt Group erupted between 17 and 6 m.y. ago (Swanson and others, 1979; McKee and others, 1981), but more than 80 percent of the group erupted between 17 and 15 m.y. ago (Tolan and others, 1989). Cascade-related volcanogenic interbeds are generally thin, composed of air-fall ash, and present only locally. These relations suggest that while the Columbia River Basalt Group vents were active most Cascade vents in northern Oregon were inactive. In southwestern Oregon, no rocks have been mapped with ages between 17 and 7 m.y. (Smith and others, 1982), suggesting that there, too, the interval from 17 to 7 m.y. was a time of relative volcanic quiescence. In northern California, the thickness of the stratigraphic sequence and the ages determined by Vance (1984) and Hammond (1983) indicate that the volume of volcanogenic materials deposited per million years was ten times less during the period from 17 to 7 m.y. ago than during previous or subsequent episodes.

At the present time, the data are insufficient to determine if significant changes in composition or the rate of volcanism took place throughout the Cascade Range between 45 and 17 m.y. ago. Therefore, this lengthy timespan is arbitrarily divided into the following approximately 10-million-year intervals.

$T_3$, **17 to 25 m.y. ago:** Several pyroclastic-flow sequences in the Western Cascades subprovince of Oregon and northern California have K-Ar ages ranging from 25 to 23 m.y. (Smith and others, 1982; Hammond, 1983; Vance, 1984; Verplanck and Duncan, 1987); thus the age 25 m.y., albeit a somewhat arbitrary division, is conveniently close to the Oligocene-Miocene boundary (about 24 m.y. ago) to be useful in classifying rocks that were previously mapped simply as Oligocene or Miocene without corroborating isotopic ages.

$T_4$, **25 to 35 m.y. ago:** The base of this interval generally corresponds to the time when volcanism was widely established in the Cascade Range from southern Oregon northward.

$T_5$, **35 to 45 m.y. ago:** The base of this interval is the approximate age of the base of several isolated, calc-alkaline, presumably arc-related volcanic sequences in Washington and Oregon. Examples are the Tukwila Formation and Goble Volcanics in Washington and the Fisher Formation of west-central Oregon.

## GEOLOGIC HISTORY

The following geologic history briefly summarizes the lithologic and structural development of the Cascade Range in Oregon. It is divided according to the broad periods of time used in the Description of Map Units (sheet 1): 0 to 2 m.y. (Q, Quaternary), 2 to 7 m.y. ($T_1$), 7 to 17 m.y. ($T_2$), 17 to 25 m.y. ($T_3$), 25 to 35 m.y. ($T_4$), and 35 to 45 m.y. ($T_5$). Most of the geographic names mentioned are shown on figure 1.

### 45 TO 35 M.Y. AGO ($T_5$)

Rocks of this age shown on the map are exposed mainly in the area from Eugene to Roseburg and were discussed in an previous section "Onset of Cascade volcanism." Sedimentary rocks include the marine Spencer and Eugene Formations and subaerial volcaniclastic rocks of the Fisher Formation. Volcanic rocks are chiefly basaltic to andesitic lava flows, with relatively minor ash-flow tuff. Few chemical analyses have been obtained from volcanic rocks erupted between 45 and 35 m.y. ago in the Cascade Range.

### 35 TO 17 M.Y. AGO ($T_4$, $T_3$)

Rocks deposited in the Cascade Range in Oregon during the broad interval of time from 35 to 17 m.y. ago are perhaps the least studied strata in the western region of the conterminous United States. Consequently, they are grouped together here and discussed only briefly.

#### Distribution, composition, and lithology

Basalt, basaltic andesite, andesite, and dacite form most of the west half of the Cascade Range, where they are exposed in the foothills and deeply incised central part of the Western Cascades physiographic subprovince. Eruptions of basalt and basaltic andesite were more widespread during the earlier interval (35 to 25 m.y. ago) than the later interval (25 to 17 m.y. ago). Tholeiitic basalt also was more commonly erupted during the earlier interval than during any younger episode of Cascade Range volcanism (for example, White and McBirney, 1978; White, 1980b; Woller and Priest, 1983). Andesite forms near-vent lava and tuff breccia, as well as thick sequences of volcaniclastic rocks. The andesitic volcaniclastic rocks are mainly beds of lapilli tuff that probably formed as debris flows and lithic-rich pyroclastic flows.

Dacite most commonly occurs as ash-flow tuff, but domes and lava flows are locally abundant. The ash-flow tuffs do not form widespread, large-volume, sheet-forming strata typical of epicontinental silicic volcanism. Few Cascade ash-flow tuffs can be traced very far, and most of them probably formed as small-volume valley-filling deposits. Instead, units shown as dacitic ash-flow tuff on the map comprise sequences of strata in which pyroclastic flows make up more than 50 percent of the stratigraphic section.

Rhyolite is relatively uncommon in the map area and is depicted chiefly as a few small dome complexes. Rhyolitic ash-flow tuff may be more widespread than is shown; however, it is included with dacitic tuff owing to the paucity of chemical analyses and adequately detailed maps. Rhyolite does form a regionally extensive ash-flow tuff, the tuff of Bond Creek (Smith and others, 1980, 1982), which was erupted about 35 m.y. ago. The tuff of Bond Creek, exposed from the Medford area north to Eugene, is shown on the map as unit $Tr_4$ and patterned to indicate its origin as a pyroclastic flow. It is the only documented Tertiary rhyolitic ash-flow tuff of sufficient extent to show separately.

The distribution of units deposited between 35 and 17 m.y. ago shows a north-south-trending grain that is well defined south of latitude 44° N. From latitudes 44° to 45° N, the broad areas of volcaniclastic sedimentary rocks and andesite (units $Ts_4$ and $Ta_3$) are far more complex than are shown, and the generalized geologic pattern there indicates less geologic knowledge. Dacite and rhyolite domes are locally abundant, and ash-flow tuff forms some stratigraphically thick sequences that have not been mapped separately (G.W. Walker, U.S. Geological Survey, oral commun., 1986; G.R. Priest, Oregon Department of Geology and Mineral Industries, oral commun., 1988).

### Structure

Faults that strike approximately northeast and northwest are the main structural features in rocks ranging in age from 35 to 17 m.y. Their conjugate pattern, emphasized by differential erosion, has created the topographic grain of northwest- and northeast-trending drainages found in the Western Cascades, as described in several lineament studies (Venkatakrishnan and others, 1980; Brown and others, 1980; Kienle and others, 1981; Knepper, 1985). Fault planes are generally steep to vertical, and slickensides are oriented randomly. The timing of motion is poorly constrained, and many faults were probably active repeatedly during the Cenozoic.

Many of these faults have only small offsets, as indicated by their minor offsetting of map units. A few major faults have been mapped locally (for example, Priest and others, 1987, 1988), and others undoubtedly exist. Their recognition is thwarted by limited exposure, poor stratigraphic control, and insufficient isotopic ages across much of the Western Cascades.

Veins (Diller, 1900) and dikes (Sherrod and Pickthorn, 1989) strike mostly northwest or west-northwest. By inference, the least compressive stress ($\sigma_3$) was oriented northeast to north-northeast (Nakamura, 1977). These stress orientations ignore large-block crustal rotations that have affected at least part of the Western Cascades strata deposited between 35 and 17 m.y. ago (Magill and Cox, 1980). The dike and vein orientations trend approximately east-west if corrected to remove the average clockwise rotation of about 1.4°-1.5° per million years indicated by Magill and Cox (1980, fig. 12).

Eastward tilting of strata by about 5° in much of the Western Cascades of Oregon creates the homoclinal map pattern for units exposed south of latitude 44° N (fig. 3 and map sheet 1). Local minor warping has affected the rocks as well. The age of the tilting and warping is poorly known, but it may have developed after 17 m.y. ago because overlying units deposited between 17 and 11(?) m.y. ago are tilted to the same degree (Sherrod and Pickthorn, 1989). Near Detroit, rocks deposited from 25 to 17 m.y. ago (Breitenbush Tuff or Breitenbush Formation of many workers) now form a broad arch (White, 1980a; Priest and others, 1987). This folding also is younger than 17 m.y. (Sherrod and Conrey, 1988).

## 17 TO 7 M.Y. AGO ($T_2$)

### Distribution, composition, and lithology

Basalt, basaltic andesite, and andesite are the predominant compositions erupted during the time from 17 to 7 m.y. ago. Basalt and basaltic andesite (unit $Tb_2$) form sequences of lava flows and breccia as much as 1 km thick; they crop out in the south-central part of the range from about the latitude of Oakridge south to Crater Lake and in the north-central part of the range near Detroit. Andesite (unit $Ta_2$) forms lava flows and less abundant volcaniclastic strata in the south-central part of the range between Oakridge and Detroit. In contrast, in the northern part of the range from Detroit nearly to the Columbia River, andesitic tuff-breccia (for example, Rhododendron Formation) predominates and lava flows are minor. Volcanism must have died out near the Columbia River, for volcanic rocks of this age have not been identified in southern Washington. Dacite crops out as a few scattered domes. Ash-flow tuff is uncommon.

Volcanic rocks of this age are unknown in the southern part of the Cascade Range in Oregon, south of latitude 43° N (fig. 3 and map sheet 1). However, some basalt assigned to unit $Tb_1$ west of the Rogue River near Union Creek could be 17 to 7 m.y. old. These undated rocks, interpreted as being younger than 8 m.y. by Smith and others (1982), are similar in stratigraphic and topographic setting to 16-m.y.-old rocks located only 20 km north (Verplanck and Duncan, 1987). Nevertheless, the undated rocks are limited in extent, so by any interpretation volcanism was uncommon in the Cascade Range of southern Oregon between 17 and 7 m.y. ago.

There is a limited record of epiclastic sedimentary rocks deposited from 17 to 7 m.y. ago. In the Deschutes basin, strata of this age are preserved beneath plains-forming lava flows (Simtustus Formation of Smith, 1986). Some epiclastic sedimentary rocks may be buried in the Portland area, on the west side of the range. However, most epiclastic material was apparently transported directly to the Pacific Ocean by streams traversing the area now occupied by the Coast Range. At least in the northern Oregon Coast Range, the distribution of the Columbia River Basalt Group indicates that the Coast Range was crossed by broad valleys (Beeson and others, 1985).

An excellent example of the way that volcanic facies change with increasing distance from the volcanic arc can be seen northeast of Mount Hood. Rocks assigned to the interval 17-7 m.y. ago (Dalles Formation, table 1) show a progressive change eastward from andesitic volcaniclastic strata (unit $Ta_2$ with diamicton pattern) to thin debris flows (unit $Ts_2$ with no pattern) to alluvial fan deposits of sandstone and conglomerate (unit $Ts_2$ with continental sediment pattern).

The Columbia River Basalt Group (table 1), though not a part of Cascade Range volcanism, forms an important stratigraphic marker emplaced between 17 and 12 m.y. ago. The lower part (unit Tcl) of this sequence of tholeiitic flood basalt was erupted between 17 and 14.5 m.y. ago and includes the Grande Ronde and Wanapum Basalts (ages from Tolan and others, 1989); the upper part (unit Tcu) is limited in the Cascade Range to the 12-m.y.-old Pomona Member of the Saddle Mountains Basalt. In Oregon, Cascade Range-derived volcaniclastic interbeds are few and thin in the lower part of the Columbia River Basalt Group, with the exception of the Vantage Member of the Ellensburg Formation that locally separates Grande Ronde Basalt from Wanapum Basalt. From this stratigraphic relation, we conclude that the Cascade Range in northern Oregon was relatively quiescent between 17 and 14.5 m.y. ago. Near Mount Hood, voluminous volcaniclastic debris began being deposited near the end of Wanapum time (after the emplacement of the Frenchman Springs Member of the Wanapum Basalt), according to drill core from Old Maid Flat holes OMF-1 and OMF-7a (G.R. Priest and M.W. Gannett, Appendix A in Priest and Vogt, 1982).

## Structure

Folding and local thrusting along anticlines in northern Oregon from 17 to 12 m.y. ago created as much as 1 km of structural relief. The protracted evolution of the folds and their maximum age are inferred from the increasing restriction of successively younger flows of the Grande Ronde and Wanapum Basalts to the axial regions of synclines (Vogt, 1981; Beeson and others, 1985). Presumably the early-erupted lava was folded into synclines and anticlines that funneled the younger flows along structural lows. Cessation of folding is poorly dated. The 12-m.y.-old Pomona Member of the Saddle Mountains Basalt is thrust over volcaniclastic rocks of unit $Ta_2$ in the south wall of the Columbia River Gorge (Anderson, 1980). Elsewhere in the area, the Last Chance Andesite of Priest and others (1982), which is about 11 to 9 m.y. old (Priest and others, 1982; Keith and others, 1985), is only slightly faulted and probably not folded. Therefore, much of the regional folding that affected the Columbia River Basalt Group and younger rocks in the Cascade Range of northern Oregon had probably culminated by about 11 m.y. ago.

The Breitenbush anticline (Thayer, 1936; White, 1980a) in the area from Detroit 17 km northeast to Breitenbush Hot Springs formed after 17 m.y. ago, because strata in unit $Ta_3$ (known locally as the Breitenbush Tuff of Thayer, 1939, or the Breitenbush Formation of White, 1980b) are internally concordant. The folded strata were beveled by erosion prior to emplacement of unconformably overlying 12-m.y.-old andesite (unit $Ta_2$) (Sherrod and Conrey, 1988).

The folds in the Columbia River Basalt Group of the Cascade Range in Oregon are similar in form and age to folds in the Yakima fold belt of central Washington. Reidel (1984), in calculating fold rates on the Saddle Mountains uplift of the Yakima fold belt, showed that 65 to 70 percent of the 1.4 km of structural relief was developed between about 17 and 13 m.y. ago. Since 13 m.y. ago, the rate of folding in central Washington has lessened dramatically, but folding probably has continued into the Quaternary (Reidel, 1984). This timing fits well with the main growth for folds 17 to 11(?) m.y. ago in the Cascade Range of northern Oregon. There is no published evidence that Cascade Range folding has continued since 11 m.y. ago in Oregon.

In contrast to well-defined folds that deformed the northern part of the Cascade Range in Oregon, the central and southern parts were only broadly warped between 17 and 7 m.y. ago. Many anticlines and synclines mapped by Peck and others (1964) in their rapid reconnaissance of the central Oregon Cascade Range were based on stratigraphic assignments subsequently found to be incorrect; only the Breitenbush anticline has been substantiated. For example, Peck and others (1964) showed the Sardine syncline extending from Detroit 70 km southwest to the McKenzie River (fig. 1). Subsequent K-Ar dating and additional mapping (Walker and Duncan, 1988) has shown that the supposed "Sardine syncline" is a broadly homoclinal sequence of gently east-dipping strata.

In the south-central part of the Cascade Range (latitude 43°–44°), strata emplaced from 17 to 12 m.y. ago (units $Ta_2$ and $Tb_2$) dip gently (5°) east and concordantly overlie older volcanic and volcaniclastic rocks (Sherrod, 1991). This relation indicates that gentle warping occurred there after about 12 m.y. ago.

## 7 TO 2 M.Y. AGO ($T_1$)

### Distribution, composition, and lithology

Basalt and basaltic andesite lava flows form more than 50 percent of the rocks erupted from 7 to 2 m.y. ago, but andesite and dacite are locally abundant. Basalt and basaltic andesite crop out along the west edge of the High Cascades, on the Columbia Plain, and in the Deschutes basin and the Basin and Range province. Andesite and dacite predominate in the Badger Butte area 15 km southeast of Mount Hood, whereas andesite predominates in the Mountain Lakes area 30 km northwest of Klamath Falls. Andesite, dacite, and rhyolite of this age with Cascade chemical affinities form lava flows, domes, and pyroclastic rocks along the east side of the Cascade Range and in adjacent parts of the Basin and Range province. The most extensive of these east-side deposits occur at four localities: near Tygh Ridge, in the Metolius River area of the Deschutes Basin, at Yamsay Mountain, and in the Sprague River valley east of Crater Lake (fig. 1). Some volcanic centers of this age probably lie buried beneath younger rocks in the Cascade Range (Taylor, 1981; Smith and Taylor, 1983).

Volcanic-related and nonvolcanic sediment (unit $Ts_1$) accumulated as alluvial fans and lacustrine deposits in three major depocenters: a kilometer-deep basin in the Portland area; the Deschutes basin, which extends from Redmond to Madras (Deschutes Formation, table 1); and several interconnected shallow basins northeast of Klamath Falls. Other rocks assigned to unit $Ts_1$ are mostly thin volcaniclastic alluvial fan deposits adjacent to the Cascade Range and in the Basin and Range province.

### Structure

The interval from 7 to 2 m.y. ago was a critical period in the structural evolution of the Cascade Range in Oregon. In the central region, uplift in the Western Cascades subprovince occurred between 5 and 3.5 m.y. ago. Also, there was a major reorientation of the regional stress regime—basalt and basaltic andesite dikes older than about 4 m.y. strike mostly northwest; dikes younger than 4 m.y. strike mostly north (Avramenko, 1981; Sherrod and Pickthorn, 1989).

A north-trending graben 30 km wide and 50 km long developed in the High Cascades in the central part of the Cascade Range between about 5 and 4 m.y. ago (Smith and Taylor, 1983). The west side of the central block sank at least 600 m along the Horse Creek fault (Brown and others, 1980), and the east side sank as much as 1,200 m along the Green Ridge fault (Hales, 1974; Conrey, 1985). Elsewhere in the High Cascades, however, a graben failed to develop. Major faults alternately bound the west and east sides of the High Cascades, but a throughgoing subsided central block is lacking.

The Hood River fault is an example of a major fault that probably formed during this time. The Hood River fault is a north-northwest-striking, narrow fault zone 1 to 3 km wide formed by an *en echelon* succession of normal faults. According to Timm (1979), the Hood River Valley is not a graben. Instead, it is bounded on the west by gently east-dipping strata in the lower part (unit Tcl) of the Columbia River Basalt Group and on the east by the Hood River fault. We apply this interpretation to the Upper Hood River Valley as well.

Offset on the Hood River fault near Mount Hood is 300 to 600 m on the basis of map units that Wise (1969) correlated across the Upper Hood River Valley. Inasmuch as these units are incompletely dated and correlated, offset could be more or less than 600 m. Faulting may have occurred in late Pliocene or early Quaternary time, but the only constraint on earliest offset requires the fault to be younger than about 12 m.y. because the Columbia River Basalt Group does not change thickness across the fault.

Some faulting in the southern part of the Cascade Range and adjoining Basin and Range province may have occurred during the time from 7 to 2 m.y. ago. At least one of these faults cuts Quaternary rocks, however, as described in the next section.

## 2 TO 0 M.Y. AGO ($Q_5$ TO $Q_1$)

### Distribution, composition, and lithology

Volcanism in the Cascade Range during the past 2 million years has been mostly limited to the High Cascades subprovince. Accumulations of basalt and basaltic andesite lava, which erupted from numerous cinder cones, lava cones, and shields with volumes as large as 15 $km^3$, built a broad ridge that extends from near Crater Lake north to near Mount Hood (see figure 4 and map sheet 1). A few basalt and basaltic andesite vents erupted in the Western Cascades subprovince as well, but these eruptions are volumetrically minor compared to those in the High Cascades. Basalt and basaltic andesite that erupted in the Portland area between about 2 and 1 m.y. ago (in unit $Qb_5$) are the most extensive of these outpourings in the Western Cascades.

Four major composite volcanoes or volcanic complexes have been the sites for most of the andesite, dacite, and rhyolite erupted in the Oregon Cascade Range during Quaternary time. From north to south they are Mount Hood, Mount Jefferson, Three Sisters-Broken Top, and Crater Lake (fig. 1). Mount McLoughlin, a scenic, steep-sided cone 55 km south of Crater Lake, appears on many location maps as an andesitic composite volcano, but it is composed entirely of basaltic andesite (unit $Qb_3$ on map; Maynard, 1974). East of the Cascade Range proper, the caldera of Newberry volcano has been a site of several andesitic, dacitic, and rhyolitic eruptions.

Other Quaternary andesite, dacite, and rhyolite volcanoes are less conspicuous because they are deeply eroded or largely buried by basalt and basaltic andesite lava flows. The Mount Jefferson area is underlain by numerous andesitic and dacitic vents that erupted throughout Quaternary time (Conrey, 1991). A cluster of rhyolite domes 15 km east of the Three Sisters

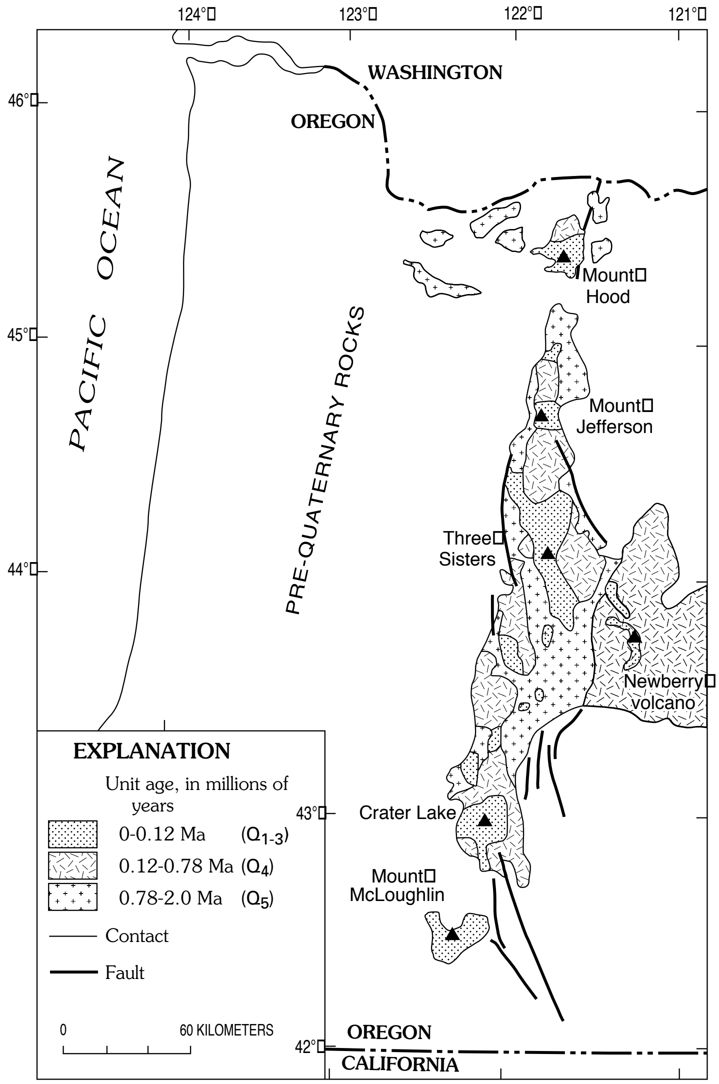


**Figure 4.** Generalized distribution by age of Quaternary rocks in Cascade Range of Oregon.

is sporadically exposed beneath basaltic andesite (in unit $Qb_4$). Vents associated with some of these domes erupted pumice-fall and ash-flow deposits exposed near Bend, 35 km east of the Three Sisters. A deeply eroded middle Pleistocene composite volcanic center ranging from andesite to rhyolite is exposed in the Burn Butte area, 40 km north of Crater Lake.

Newberry volcano, located about 60 km east of the Cascade Range crest, has been a major locus of volcanism throughout the Quaternary (MacLeod and Sherrod, 1988; see also K-Ar ages from drill-core samples reported in Swanberg and others, 1988). The volcano is shown on this map chiefly as lava ranging from 780,000 to 125,000 years in age owing to the difficulty in separating younger from older flows on the ash-covered flanks of the volcano. Newberry's volume, more than 400 $km^3$, is much greater than that produced by volcanoes along an equivalent length of the High Cascades to the west. Arguably, Newberry may be classified as a volcano of the Basin and Range province instead of the Cascade Range. Newberry is shown on this map because of its proximity to the Cascade Range, its calc-alkaline geochemistry typical of the Cascade arc, and its potential as a geothermal resource.

### Structure

Quaternary rocks in the High Cascades are essentially undeformed. Folds are lacking, faults are limited in extent and magnitude, and most rocks lack regionally coherent joint trends. Consequently, lineaments form the main data for structural interpretation. Lineaments in the Quaternary rocks are defined mainly by aligned cinder cones. Most cone alignments trend northerly, and the cones probably developed along north-striking fissures.

The few faults generally have northerly strikes, with dip separation of less than 150 m. These faults are dispersed among rocks as young as about 300,000 years; younger rocks are generally unfaulted. However, some faults near the Little Deschutes River north of Chemult (fig. 1) are inferred to cut poorly indurated sedimentary rocks (unit Qs), some of which are perhaps as young as 150,000 years, on the basis of weathering rinds developed on clasts in the gravel beds (W.E. Scott and D.R. Sherrod, unpub. data, 1983). A north-south-striking normal fault displaces 1-m.y.-old lava along 40 km of its length in the southern part of the High Cascades (Smith and others, 1982).

Faults on the east flank of the Cascade Range near Bend commonly strike northwest. The Tumalo fault (fig. 1), which extends for 30 km northwest of Bend (Taylor, 1981), displaces upper Pleistocene pumice and ash deposits a few meters (G.L. Peterson and K.L. Lite, in L.R. Squier Associates, Inc., 1984). Northwest-striking faults deformed the northwest flank of Newberry volcano in middle or late Pleistocene time (MacLeod and others, 1995).

The contemporary stress regime for the map area is dominated by north-south-oriented $\sigma_1$ and east-west-oriented $\sigma_3$ (Couch and Lowell, 1971; Zoback and Zoback, 1980). The axis of the volcanically active High Cascades may be locally dominated by a vertically oriented $\sigma_1$ (Priest, 1990), perhaps owing to forces associated with rising magma. Also, as indicated by the Klamath Falls earthquakes (for example, Wiley and others, 1993), the central and southern High Cascades are partly influenced by basin-range extension with its vertically oriented $\sigma_1$ and broadly east-west-oriented $\sigma_3$ (Zoback and Zoback, 1991).

## AGE

Cascade Range basalt and basaltic andesite erupted between 780,000 and 25,000 years ago are difficult to date by conventional K-Ar methods because they contain small potassium concentrations and are too young to have generated sufficient radiogenic argon for an accurate age determination. Thus, in many cases rocks may be assigned incorrectly to units $Qb_4$, $Qb_3$, or $Qb_2$. For example, large areas assigned to unit $Qb_4$ (basalt and basaltic andesite, 780,000-125,000 years old) probably include some lava of unit $Qb_3$ (basalt and basaltic andesite, 125,000-25,000 years old). This is surely the case at Newberry volcano east of the Cascade Range, along the Cascade Range crest from Mount Jefferson south 30 km to Santiam Pass, and along the crest for 40 km south of the Three Sisters.

The age of silicic rocks west of Bend was once controversial. These rocks include rhyolite domes that are partly buried by normally magnetized basalt and basaltic andesite east of the Three Sisters and ash-flow and pumice-fall deposits (the Bend Pumice and overlying Tumalo Tuff of Taylor, 1981). Previously determined K-Ar ages ranged from about 4 to 1.8 m.y. (Fiebelkorn and others, 1983). Subsequently, however, 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 m.y. Also, several K-Ar age determinations ranging from 0.4 to 0.3 m.y. have been obtained from plagioclase contained in pumice of the Tumalo Tuff and from whole-rock obsidian within epiclastic strata that immediately underlie the Tumalo Tuff (Sarna-Wojcicki and others, 1989). Most workers now consider the Bend Pumice and Tumalo Tuff to be about 0.4 to 0.3 m.y. old. The substantially younger age assignment (middle Pleistocene instead of Pliocene) is critical for assessing geothermal resource potential. On the map, the Bend Pumice and overlying Tumalo Tuff are combined in unit $Qr_4$ and patterned to indicate an origin as chiefly ash flow.

All Quaternary rocks with reversed-polarity magnetization were assigned to pre-Brunhes chronozones (for example, in unit $Qb_5$, older than 0.78 m.y.). At least eight reversed-polarity subchronozones have been reported from the Brunhes (Champion and others, 1988), so a finding of reversely polarized rock is not a certain indicator of its relative antiquity. Nevertheless, long-term eruption rates have been low in the Cascade Range of Oregon during Quaternary time (Sherrod and Smith, 1990), and it is unlikely that large areas or thick stratigraphic sections of reversely polarized rocks could have formed during the short intervals of time represented by the reversely polarized subchronozones in the Brunhes. Some small volcanoes with reversely polarized lava may be younger than shown, however.

## VOLCANIC PRODUCTION RATES

The volcanic production rate for Quaternary magma along the crest of the Cascade Range from Crater Lake to Mount Jefferson has been about 3 to 6 $km^3 km^{-1} m.y.^{-1}$ (cubic kilometers per kilometer of arc length per million years) (Sherrod and Smith, 1990). Locally greater rates characterize a broad graben east and north of the Three Sisters (Priest, 1990; Hill and Priest, 1992). The rate at Newberry volcano has been about 10 $km^3 km^{-1} m.y.^{-1}$, or about 2 to 3 times that along the main axis of the Cascade Range (MacLeod and Sherrod, 1988). The rate along the arc must decrease south of Crater Lake and north of Mount Jefferson, for rocks in those areas are predominantly older than 0.78 m.y. (unit $Qb_5$ on map). There has been little Quaternary volcanism in Oregon south of Mount McLoughlin or north of Mount Hood (fig. 4).

For comparison with other volcanic arcs, the rate from the Lesser Antilles is about 3 to 5 $km^3 km^{-1} m.y.^{-1}$; for Central America, about 30 $km^3 km^{-1} m.y.^{-1}$ (Wadge, 1984). These data strengthen Wadge's suggestion that extrusion rate correlates with convergence rate of a volcanic arc: 2 to 3 $cm\text{-}yr^{-1}$ for offshore Cascades (Silver, 1971; Riddihough, 1984), 2 to 3.7 $cm\text{-}yr^{-1}$ for Lesser Antilles, and 8.1 $cm\text{-}yr^{-1}$ for Central America (see Wadge, 1984, for references).

The short-term volcanic production rate in the Crater Lake area is substantially greater than the characteristic rate for the range crest because of the large volume (more than 60 $km^3$) of pumice and ash blown out of that area during the Holocene climactic eruptions of Mount Mazama (Bacon, 1983). Short-term rates for volcanism during the past 25,000 years in the Three Sisters area also are somewhat higher than the characteristic rate of 3-6 $km^3 km^{-1} m.y.^{-1}$ because of the latest Pleistocene volcanism (unit $Qb_2$) at Mount Bachelor (Scott and Gardner, 1992) and Holocene volcanism (unit $Qb_1$) at McKenzie and Santiam Passes (for example, Taylor, 1965).

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