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Preliminary map of upper Eocene to Holocene volcanic and related rocks of the Cascade Range, Oregon

by

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This map is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.

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

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INTRODUCTION

Since 1979 the Geothermal Research Program of the U.S. Geological Survey has 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This map is one of three in a series that shows Cascade Range geology by fitting published and unpublished mapping into a province-wide scheme of rock units differentiated by composition and age; map sheets of the Cascade Range in Washington and California complete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 less than 1 Ma. Lower grade (= lower temperature) geothermal resources may be associated with somewhat older rocks; however, volcanic rocks older than about 2 Ma 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 are analogues of today's snow-covered shield volcanoes and stratovolcanoes. The fossil hydrothermal systems of the Eocene to Pliocene vents now exposed provide clues to processes active today beneath the Pleistocene and Holocene volcanic peaks along the present 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 200 cm of annual precipitation west of the range crest. In addition, age control was scant and limited chiefly to fossil flora. Access has greatly improved via well-developed networks of logging roads. And radiometric geochronology—mostly potassium-argon (K-Ar) data—has 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, parts of the Columbia River gorge, and the Cascade Range within the Warm Springs Indian Reservation from Mount Jefferson to the Mutton Mountains (fig. 1).

This 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 radiometric 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 radiometric ages.

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, 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

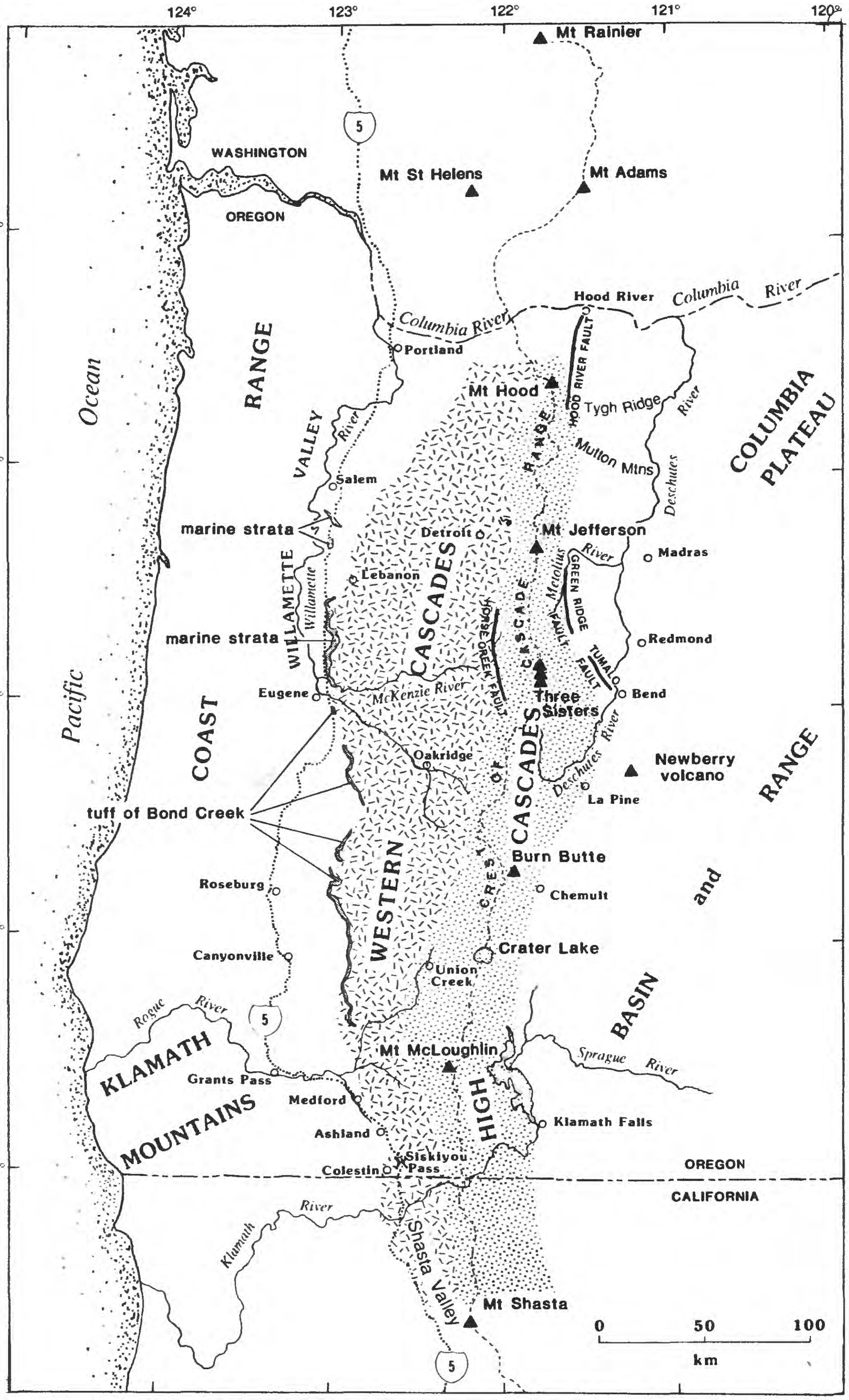

Figure 1. Index map showing geographic locations, physiographic provinces, and some faults and lithologic units mentioned in text. Approximate extent of Western and High Cascades are shown for Oregon and northern California. These two subprovince names are not used in Washington or in California south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

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 fig. 1 for index map) includes locally vented materials (N.S. MacLeod, oral commun., 1985). Lithologically, the Fisher Formation is similar to conformably overlying Oligocene volcanic rocks. However, the Fisher Formation is virtually unstudied, and the only radiometric ages are from samples near the top of the formation; these ages range from 36 to 40 Ma (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 fill in the Willamette Valley; the contact passes into the subsurface about 50 km northeast of Eugene. Distal volcaniclastic deposits of the late Eocene(?) 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, there are few published radiometric or paleontologic ages from the drill core or cuttings, so age control is poor. For rocks exposed on the surface, radiometric ages are mostly younger than about 35 Ma. Lux (1982) reported an age of 41.5±9 Ma for a sample collected near Lebanon. However, Walker and Duncan (1988) resampled this site and obtained an age of 31.7±4 Ma, which corresponds more closely with ages between about 32 and 34 Ma from other nearby sample sites in the same stratigraphic sequence.

In the southwest part of the state, geologic mapping and K-Ar ages suggest that Cascade Range volcanism was widespread by about 35 Ma. This time corresponds to the age of the tuff of Bond Creek (fig. 1), a rhyolitic ash-flow tuff exposed extensively along the western edge of the Cascade Range in the south half of the state (Hausen, 1952; 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.

South of the Rogue River, Tertiary volcanic rocks that form the base of the Cascade Range are progressively younger than 35 Ma. The base of the Tertiary volcanic section is about 30 Ma 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(?) continental sediments derived from the nearby Klamath Mountains. Continental sediments and volcanogenic sediments are locally interbedded near the top of the continental sequence.

Just south of Siskiyou Pass, basalt and andesite lava flows with K-Ar ages of about 29 Ma (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 Ma.

Farther south in California (fig. 1), the Tertiary volcanic section is lithologically similar to the section north of the state line; however, it thickens to the south. For example, the Tertiary volcanic section older than about 30 Ma is as much as 200 m thicker along the Klamath River than it is in the Siskiyou Pass area. 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, 1985). 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). Radiometric ages (Vance, 1984) indicate that, despite the greater thickness of the Tertiary volcanic section south of Siskiyou Pass, its base remains about 31 to 35 Ma old. From Siskiyou Pass south for 30 km to the Shasta Valley, Tertiary volcanogenic rocks rest unconformably on late 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; the original southern extent of Tertiary volcanogenic rocks is unknown.

In the Coast Range of Oregon, onset of Cascade volcanism is recorded in the petrology 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 Ma (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 extended 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 36 Ma, 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 36 Ma.

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 radiometric 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 conceptional 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 (in press).

Lithology and model for volcanic and sedimentary facies

A hypothetical cross section (fig. 2) illustrates our model of volcanic and sedimentary processes and relations between deposits in the Cascade Range. In this model, volcaniclastic sediments derived from a major volcano lap onto an older eroded volcano and simultaneously interfinger with contemporaneous deposits that were derived from other volcanoes (fig. 2a). 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 up on their flanks. Basaltic shield volcanoes overlap and interfinger with one another and with volcaniclastic sediments.

Figure 2b shows the facies relations interpreted from the volcanic and sedimentary deposits of figure 2a, 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 2c 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 plate for full explanation of patterns). In Table 1, p. 11, 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 from about 7 to 4 Ma (assigned to time interval T_1) contains basalt and basaltic andesite lava flows (unit Tb_1); dacititic 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 (Ts_1 with continental sediment pattern).

Composition

The compositions of volcanic rocks shown on the map are 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. However, petrography and field appearance are generally not good predictors of SiO_2 content for Cascade rocks that contain less than 57 percent SiO_2. Field classification proved unreliable, and maps that have sufficient detail and supporting chemical analyses are largely lacking.

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

Figure 2a. Typical volcanic and sedimentary features.

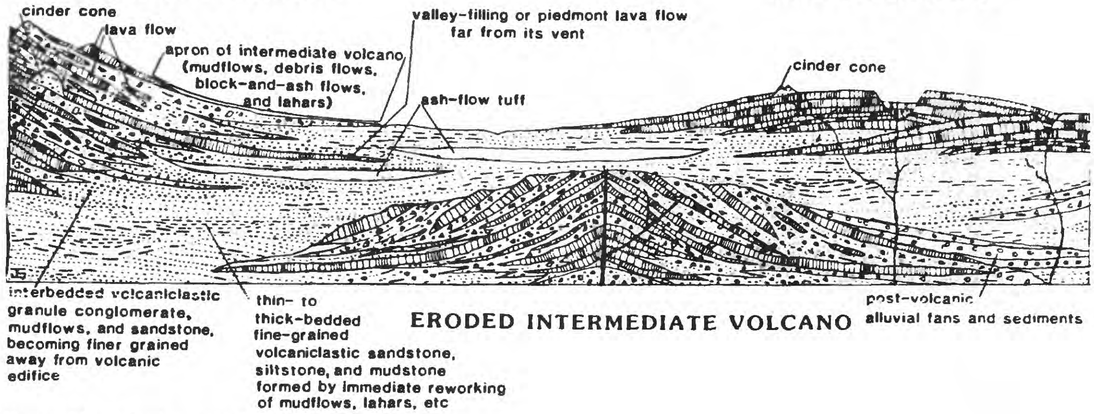

Figure 2b. Facies relations.

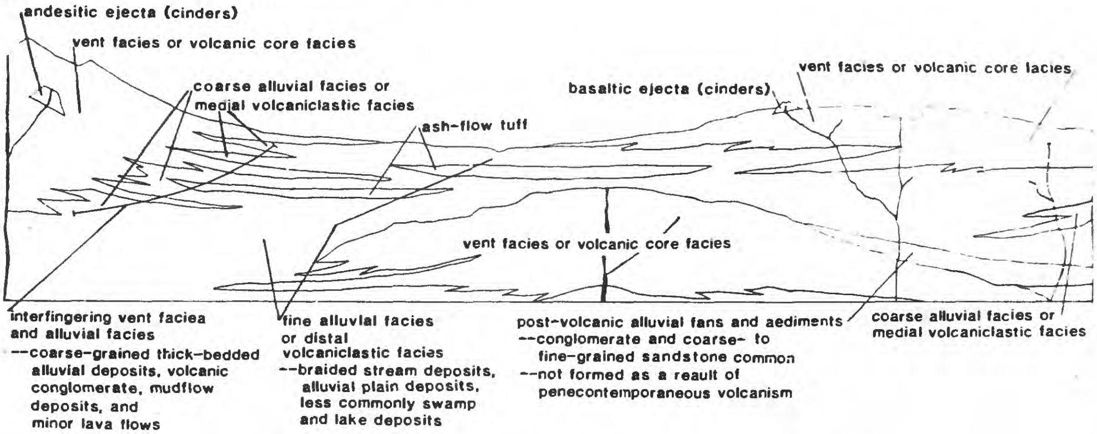

Figure 2c. Patterns used to show selected facies and rock types on geologic map.

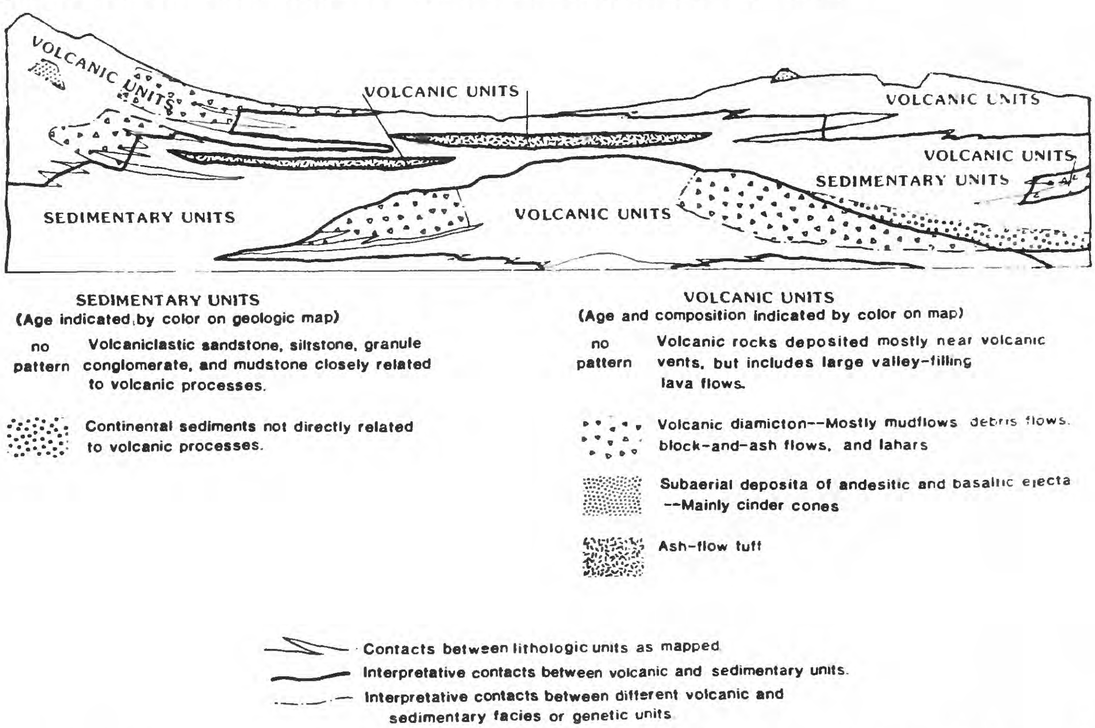

Figure 2. Hypothetical cross section showing arc-related volcanic and sedimentary rocks, facies relations, and map units as used on geologic map.

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 300 radiometric ages. We stress, however, that this map shows geology as interpreted from field studies; lithostratigraphic relations take precedent over radiometric determinations. For example, an andesitic sequence shown as 7 to 2 Ma old (unit Ta_1) might include a few andesite flows whose age is somewhat outside this interval to clearly depict lithologic relations with overlying and underlying units.

The last 2 Ma (Quaternary according to Harland and others, 1982) is subdivided into shorter intervals than the period from 45 to 2 Ma because of the important inverse relation between age and geothermal potential: geothermal potential declines rapidly as age increases (Smith and Shaw, 1975). However, many Quaternary rocks have few radiometric 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.

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

The intervals chosen and reasons for selecting them are discussed below. The subscript used for each interval correspond to the subscripts used in the *Description of Map Units*.

Q_1, 0 to 12 ka: This interval begins at the end of the last major glaciation in the Cascade Range during the latest Pleistocene and includes the entire Holocene (Waitt and Thorson, 1983; Porter and others, 1983). Most Cascade researchers relate young volcanic deposits to glacial stratigraphy; thus, the 12-ka limit for this map unit. Young volcanic deposits dated by the ^{14}C method are readily assigned to this unit.

Q_2, 12 to 25 ka: 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 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-ka 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 late Wisconsin from the middle.

Q_3, 25 to 120 ka: This interval extends 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 radiometric methods on Cascade rocks in this age range, and so some rocks may be incorrectly assigned to this unit. Imbrie and others (1984) suggested 128 ka for the boundary between the middle and late Pleistocene, whereas Richmond and Fullerton (1986) suggest 132 ka.

Q_4, 120 to 730 ka: The boundary between the Matuyama Reversed-Polarity and Brunhes Normal-Polarity Chrons marks the base of this period. Some recently published geologic maps include magnetic polarity of stratigraphic units from direct measurements. Magnetic polarity of some shield volcanoes was determined from detailed aeromagnetic maps.

Q_5, 0.73 to 2 Ma: This interval begins at the base of the Pleistocene and ends at the Matuyama-Brunhes Polarity Chron boundary (Harland and others, 1982). Although 2 Ma does not mark 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 Ma: In Washington and northern California, 7 Ma marks the approximate onset of renewed volcanism after a period of volcanic quiescence. In Oregon, most of the rocks exposed along the crest of the Cascade Range are younger than about 7 Ma. Along the subprovince boundary between the High Cascades and the Western Cascades, 7 Ma approximately corresponds to radiometric ages obtained from the base of a widespread sequence of basalt and basaltic andesite lava flows—the "ridge-capping basalt" of Sherrod (1986), "basalt of the early High Cascades eruptive episode" of Priest and others (1983), or the base of the "volcanic rocks of the High Cascade Range" of Smith and others (1982). East of the crest, volcaniclastic sediment derived from the Cascade Range began accumulating about 7 Ma ago in the upper part of the Deschutes basin, and now comprises 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 Ma: This interval marks the onset of extensive andesitic to basaltic volcanism in northern and central Oregon, but seems to be one of low 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 Ma. The Columbia River Basalt Group erupted between 17 and 6 Ma on the basis of K-Ar ages (Swanson and others, 1979; McKee and others, 1981), but more than 80 percent of the group erupted between 16.5 and 14 Ma (Hooper, 1980). 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 southern Washington were inactive. In southwestern Oregon, no rocks have been mapped with ages between 17 Ma and 7 Ma (Smith and others, 1982), suggesting that there, too, the interval from 17 Ma to 7 Ma was a time of relative volcanic quiescence. In northern California, the thickness of the stratigraphic sequence and the age data of Vance (1984) and Hammond (1983) indicate that the volume of volcanogenic rocks deposited per million years was an order of magnitude less during the period 17 Ma to 7 Ma than during previous or subsequent episodes.

T_3, 17 to 25 Ma: Several ash-flow sequences in the Western Cascade subprovince of Oregon and northern California have K-Ar ages between 25 and 23 Ma (Smith and others, 1982; Hammond, 1983; Vance, 1984; Verplanck and Duncan, 1987); thus 25 Ma is a somewhat arbitrary division but conveniently close to the Oligocene-Miocene boundary (about 24 Ma) to be useful in classifying rocks that were previously mapped simply as Oligocene or Miocene without corroborating radiometric ages.

T_4, 25 to 35 Ma: 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 Ma: The base of this interval is the approximate age of the base of several isolated, calkaline but presumably arc-related volcanic sequences in Washington and Oregon. Examples are the Tukwilla 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: 0 to 2 Ma (Q, Quaternary), 2 to 7 Ma (T_1), 7 to 17 Ma (T_2), 17 to 25 Ma (T_3), 25 to 35 Ma (T_4), and 35 to 45 Ma (T_5). Most of the geographic names mentioned are shown on figure 1.

45 to 35 Ma (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. There are almost no chemical analyses from volcanic rocks erupted 45 to 35 Ma in the Cascade Range.

Upper Eocene volcanic rocks also have been dated and mapped recently in the Portland area (M.H. Beeson, oral commun., 1988). The few outcrops are too small to show at the scale of this map.

35 to 17 Ma (T_4 and T_3)

Rocks deposited in the Cascade Range in Oregon during the broad interval of time from 35 to 17 Ma 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 Ma) than the later (25 to 17 Ma). Tholeiitic basalt also was more commonly erupted during the earlier interval than during any younger episode of Cascade Range volcanism (e.g., White and McBirney, 1978; White, 1980b; Woller and Priest, 1983). Andesite forms near-vent lavas and tuff breccia, as well as thick packets of volcaniclastic rocks. The andesitic volcaniclastic rocks are mainly beds of lapilli tuff that probably formed as debris flows.

Dacite most commonly occurs as ash-flow tuff, but domes and lava flows are locally abundant. The ash flows 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 section.

Rhyolite is relatively uncommon, occuring chiefly as a few small dome complexes. Rhyolite does form a regionally significant ash-flow tuff, the tuff of Bond Creek (Smith and others, 1980, 1982), which was erupted about 35 Ma. The tuff of Bond Creek, which is exposed from the Medford area north to Eugene, is shown on the map as unit Tr_4 and is 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.

Units deposited 35 to17 Ma show a north-south-trending grain that is well defined south of latitude 44° N. From latitudes 44-45° N., the broad areas of volcaniclastic sedimentary rocks and andesite (units Ts_4 and Ta_3) are far more complex than 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 trend approximately northeast and northwest are the main structural features in rocks 35 to 17 Ma. These faults have only small offsets, as indicated by their minor effect on map units. Their conjugate pattern, emphasized by differential erosion, created the topographic grain of 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 occur in all orientations. The timing of motion is poorly constrained, and many faults were probably active repeatedly during the Cenozoic.

Veins (Diller, 1900) and dikes (Sherrod, 1986) have trends mostly northwest or west-northwest. By inference, the least compressive stress (S_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 between 35 and 17 Ma (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, their fig. 12).

Eastward tilting of 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 plate). Local minor warping affected the rocks as well. The age of the tilting and warping is not well known, but it may have developed after 17 Ma because overlying units deposited between 17 and 11(?) Ma are tilted to the same degree (Sherrod, 1986). Near Detroit, rocks deposited 25 to 17 Ma (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 18 Ma (Sherrod and Conrey, 1988).

17 to 7 Ma (T_2)

Distribution, composition, and lithology

Basalt, basaltic andesite, and andesite are the predominant compositions erupted during the time from 17 to 7 Ma. 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 (fig. 1). Andesite (unit Ta_2) forms lava flows and less abundant volcaniclastic strata in the south-central part of the range between Oakridge and Detroit (fig. 1). 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 are absent 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 plate). However, some basalt assigned to unit Tb_1 that crops out west of the Rogue River near Union Creek could be 17 to 7 Ma. These undated outcrops, which were interpreted as being younger than 8 Ma by Smith and others (1982), are similar in their strati-

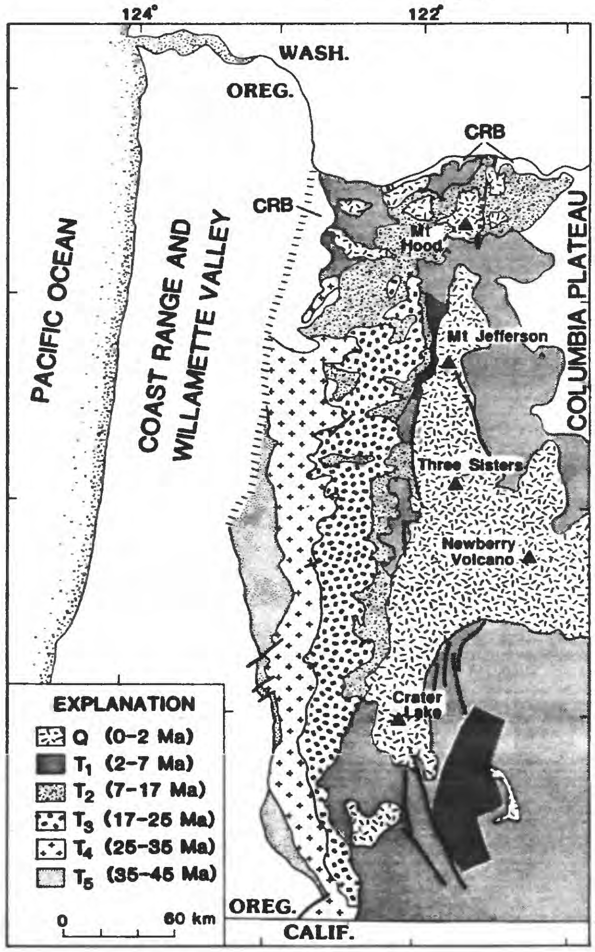

Figure 3. Generalized distribution by age of rocks in Cascade Range of Oregon.

Yonna Formation					Ts_1
Troutdale Formation					Ts_1
Deschutes Formation	Tb_1		Td_1		Ts_1
Sandy River Mudstone					Ts_1
Dalles Formation		Ta_2			Ts_2
Rhododendron Formation		Ta_2			
Sardine Formation (of Peck and others, 1964)	Tb_2	Ta_2			
Columbia River Basalt Group	Tcu Tcl				
Breitenbush Tuff	Tb_3	Ta_3			
Colestin Formation	Tb_4		Td_4		Ts_4
Little Butte Formation (of Peck and others, 1964)	Tb_3 Tb_4	Ta_3 Ta_4	Td_3 Td_4	Tr_3 Tr_4	Ts_3 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			

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 plate) for explanation of unit symbols and patterns.

graphic and topographic setting to 16-Ma rocks located only 20 km north (Verplanck and Duncan, 1987). Nevertheless, the undated rocks are very limited in extent, so by any interpretation volcanism was uncommon in the Cascade Range of southern Oregon between 17 and 7 Ma.

There is a limited record of epiclastic sedimentary rocks deposited from 17 to 7 Ma. In the Deschutes basin, strata of this age are preserved beneath plains-forming lava flows (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 Ma (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 between 17 and 12 Ma. The lower part of this sequence of tholeiitic flood basalt (unit Tcl) was emplaced between 17 and 13.5 Ma and includes the Grande Ronde and Wanapum Basalts; the upper part (unit Tcu) is limited in the Cascade Range to the 12-Ma 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 from Wanapum Basalt. From this stratigraphic relation, we conclude that the Cascade Range in northern Oregon was relatively quiescent between 17 and 13.5 Ma. Near Mount Hood, production of voluminous volcaniclastic debris began near the end of Wanapum time (after the emplacement of the Frenchman Springs member), 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

Regional folding and local thrusting along overturned anticlines in northern Oregon from 17 to 12 Ma created as much as 1 kilometer of structural relief. The continuity of folding and its maximum age are inferred from the increasing restriction of successively younger flows of 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 funnelled the younger flows along structural lows. When folding ceased is poorly known. The 12-Ma 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 Ma (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 Ma.

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

The folds in the Columbia River Basalt 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 Ma. Since 13 Ma, the rate of folding in central Washington has fallen dramatically but folding probably continues into the Quaternary epoch (Reidel, 1984). This timing fits well with the main growth for folds 17 to 11? Ma in the Cascade Range of northern Oregon. There is no published evidence that Cascade Range folding has continued since 11 Ma in Oregon.

In contrast to the regional folding that affected the northern part of the Cascade Range in Oregon, the central and southern parts were only broadly warped between 17 and 7 Ma. 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 that later work has shown to be erroneous; 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 (see fig. 1 for location map). Subsequent K-Ar dating and more detailed 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 from latitude 43°-44°, strata 17 to 12 Ma (units Ta_2 and Tb_2) dip gently (5°) east and concordantly overlie older volcanic and volcaniclastic rocks (Sherrod, 1986). This relationship indicates that gentle warping occurred there after about 12 Ma.

7 to 2 Ma (T_1)

Distribution, composition, and lithology

Basalt and basaltic andesite lava flows form over 50 percent of rocks erupted 7 to 2 Ma, but andesite and dacite are locally abundant. Basalt and basaltic andesite crop out along the western edge of the High Cascades, on the Columbia Plateau, and in the Deschutes basin and the Basin and Range. Andesite and minor dacite predominate in the Badger Butte area 15 km southeast of Mount Hood; andesite and rhyolite are common in the Burn Butte area 15 km northwest of Chemult; and 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. The most extensive of these east-side deposits occur 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 (see fig. 1 for location map). Some volcanic centers of this age probably lie buried beneath younger rocks in the Casade Range (Taylor, 1981; Smith and Taylor, 1983).

Volcanic-related and non-volcanic 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 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 Ma 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 sometime between 3.5 and 5 Ma (Sherrod, 1986). Also, there was a major reorientation of the regional stress regime, for basalt and basaltic andesite dikes older than about 4 Ma trend mostly northwest; whereas, since that time, dikes are mostly north-trending (Avramenko, 1981; Sherrod, 1986).

A north-south-trending graben 30 km wide and 50 km long engulfed the High Cascades in the central part of the Cascade Range about 4 to 5 Ma (Smith and Taylor, 1983). The central block sank at least 600 m at the Horse Creek fault on its west side (Brown and others, 1980) and as much as 1200 m at the Green Ridge fault on its east (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 through-going, 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-trending, narrow fault zone 1 to 3 km wide formed by an *en echelon* succession of normal faults. According to Timm (1979), the lower Hood River valley is not a graben. Instead, it is bounded on the west by gently east-dipping strata in the lower part of the Columbia River Basalt Group (unit Tcl) 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 Hood River valley. Inasmuch as these units are incompletely dated and correlated, offset could be in excess of 600 m. The escarpment produced by the Hood River fault existed by about 2.7 Ma, when andesite (dated by Keith and others, 1985) flowed west down the escarpment and north along the ancestral Hood River drainage (D.R. Sherrod, unpub. mapping, 1985). We presume that the Hood River fault formed between 3 and 5 Ma. The only constraint on earliest offset requires the fault to be younger than about 12 Ma because the Columbia River Basalt Group does not thicken 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 Ma. At least one of these faults cuts Quaternary rocks, however, as described next.

2 to 0 Ma

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 platform that extends from near Crater Lake north to near Mount Hood (Hughes and Taylor, 1986); see figure 4 and geologic map. A few basalt and basaltic andesite vents erupted in the Western Cascades subprovince as well, but these eruptions are volumetrically minor when compared to the volume of rock erupted in the High Cascades. Basalt and basaltic andesite that erupted in

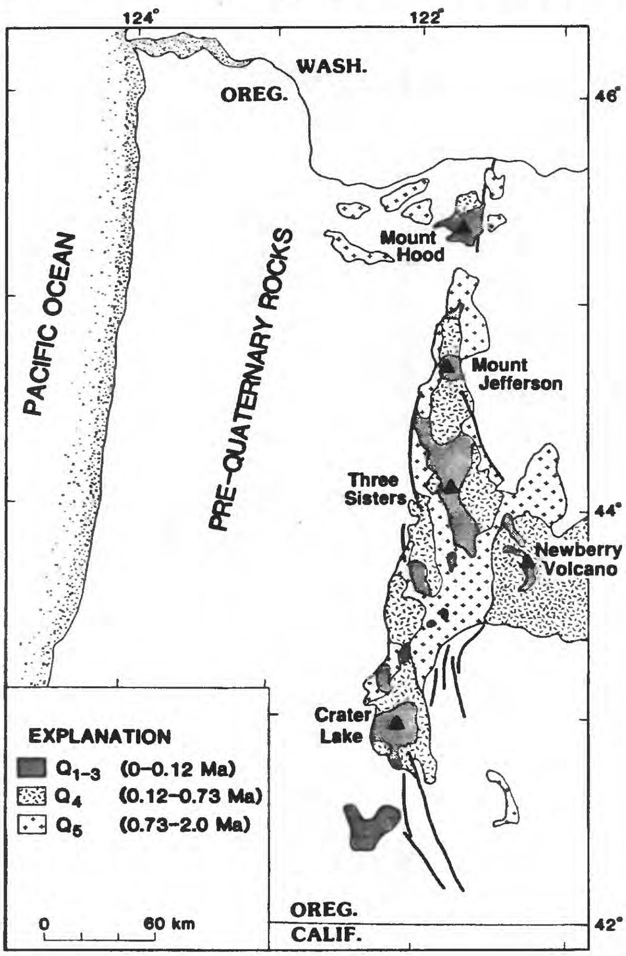

Figure 4. Generalized distribution by age of Quaternary rocks in Cascade Range of Oregon.

the Portland area between about 1 and 2 Ma (in unit Qb_5) are the most extensive of these outpourings in the Western Cascades.

Four major stratovolcanoes have been the sites for most of the andesite, dacite, and rhyolite erupted in the Oregon Cascade Range in the Quaternary. 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 andesite, dacite, and rhyolite eruptions.

Other Quaternary andesite, dacite, and rhyolite volcanoes are less conspicous 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 the Quaternary. A cluster of rhyolite domes 15 km east of the Three Sisters is sporadically exposed beneath basaltic andesite (in unit Qb_4) that forms Tam McArthur Rim. Vents associated with some of these domes erupted air-fall and ash-flow deposits that are exposed in the vicinity of 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 chiefly as lava ranging in age from 730 to 125 ka because of 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. There is some argument as to whether Newberry is 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 significant joint trends. Consequently, lineaments form the main data for structural interpretation. Lineaments in the Quaternary rocks are defined mainly by aligned cinder cones. These cone alignments mostly strike north-south, and the cones probably developed along north-trending fissures.

The few faults generally trend north-south and have dip separation of less than 150 m. North-trending normal faults are consistent with the contemporary stress regime for the map area—that is, north-south-oriented s_1 and east-west-oriented s_3 (Couch and Lowell, 1971; Zoback and Zoback, 1980). These faults are dispersed among rocks as young as about 300 ka; 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 ka, on the basis of weathering rinds developed on clasts in the gravel beds (W.E. Scott, oral commun., 1983). A north-south-trending normal fault displaces 1-Ma 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 trend northwest. The Tumalo fault (fig. 1), which extends for 30 km northwest of Bend (Taylor, 1981), displaces late Pleistocene pumice and ash deposits by a few meters (G.L. Peterson and K.L. Lite, *in* L.R. Squier Associates, Inc., 1984). Northwest-trending faults deformed the northwest flank of Newberry volcano between 730 and 6.6 ka (MacLeod and others, 1982).

Age

Cascade Range basalt and basaltic andesite erupted between 730 and 25 ka are difficult to date by conventional K-Ar methods because they contain low 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, 730-125 ka) probably include some lava of unit Qb_3 (basalt and basaltic andesite, 125-25 ka). This is surely the case at Newberry volcano east of the Cascade Range, along the Cascade Range crest from Mount Jefferson to Santiam Pass, and along the crest for 40 km south of the Three Sisters. This limited knowledge about the true age of lava in the High Cascades may hinder an accurate assessment of igneous-related geothermal resource potential.

The age of silicic rocks west of Bend was once controversial. As mentioned earlier, these rocks include rhyolite domes that are partly buried by normally polarized basalt and basaltic andesite at Tam McArthur Rim, and ash-flow and air-fall deposits (the Bend Pumice and overlying Tumalo Tuff of Taylor, 1981). Previously determined K-Ar ages ranged from about 4 to 1.8 Ma (E.H. McKee, *in* Fiebelkorn and others, 1983). Subsequently, the Bend Pumice has been geochemically correlated with the Loleta Ash (Sarna-Wojcicki and others, 1987), which is probably about 0.4 to 0.3 Ma. A.M. Sarna-Wojcicki (U.S. Geological Survey, oral commun., 1988) has also obtained serveral K-Ar determinations on plagioclase separated from pumice in the Tumalo Tuff and from whole-rock obsidian from epiclastic strata that immediately underlie the Tumalo Tuff that are between 0.4 and 0.3 Ma. Most workers now consider the Bend Pumice and Tumalo Tuff to be about 0.4 to 0.3 Ma. 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 (in Qb_5, older than 0.73 Ma). But there are at least eight reversed-polarity subchronozones reported from the Brunhes (Champion and others, 1988). Nevertheless, because long-term eruption rates are low in the Cascade Range of Oregon, 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 the Three Sisters has been about 3 to 6 km^3km^{-1} $m.y.^{-1}$ (cubic km per km of arc length per million years), and the rate is probably the same for the segment from the Three Sisters to Mount Jefferson (Sherrod, 1986). The rate at Newberry volcano has been about 10 $km^3km^{-1}m.y.^{-1}$, 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 0.73 Ma (unit Qb_5 on map). There has been very little Quaternary volcanism in Oregon south of Mount McLoughlin or north of Mount Hood (fig. 3).

For comparison with other volcanic arcs, the rate from the Lesser Antilles is about 3 to 5 $km^3km^{-1}m.y.^{-1}$; for Central America, about 30 $km^3km^{-1}m.y.^{-1}$ (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 Cascade (Silver, 1971), 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 higher 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 last 25,000 years in the Three Sisters area also are somewhat higher than the characteristic rate of 3-6 km^3km^{-1} $m.y.^{-1}$ because of the latest Pleistocene volcanism at Mt. Bachelor (unit Qb_2) (Scott and Gardner, in press) and the Holocene volcanism at McKenzie and Santiam Passes (unit Qb_1) (for example, Taylor, 1965).

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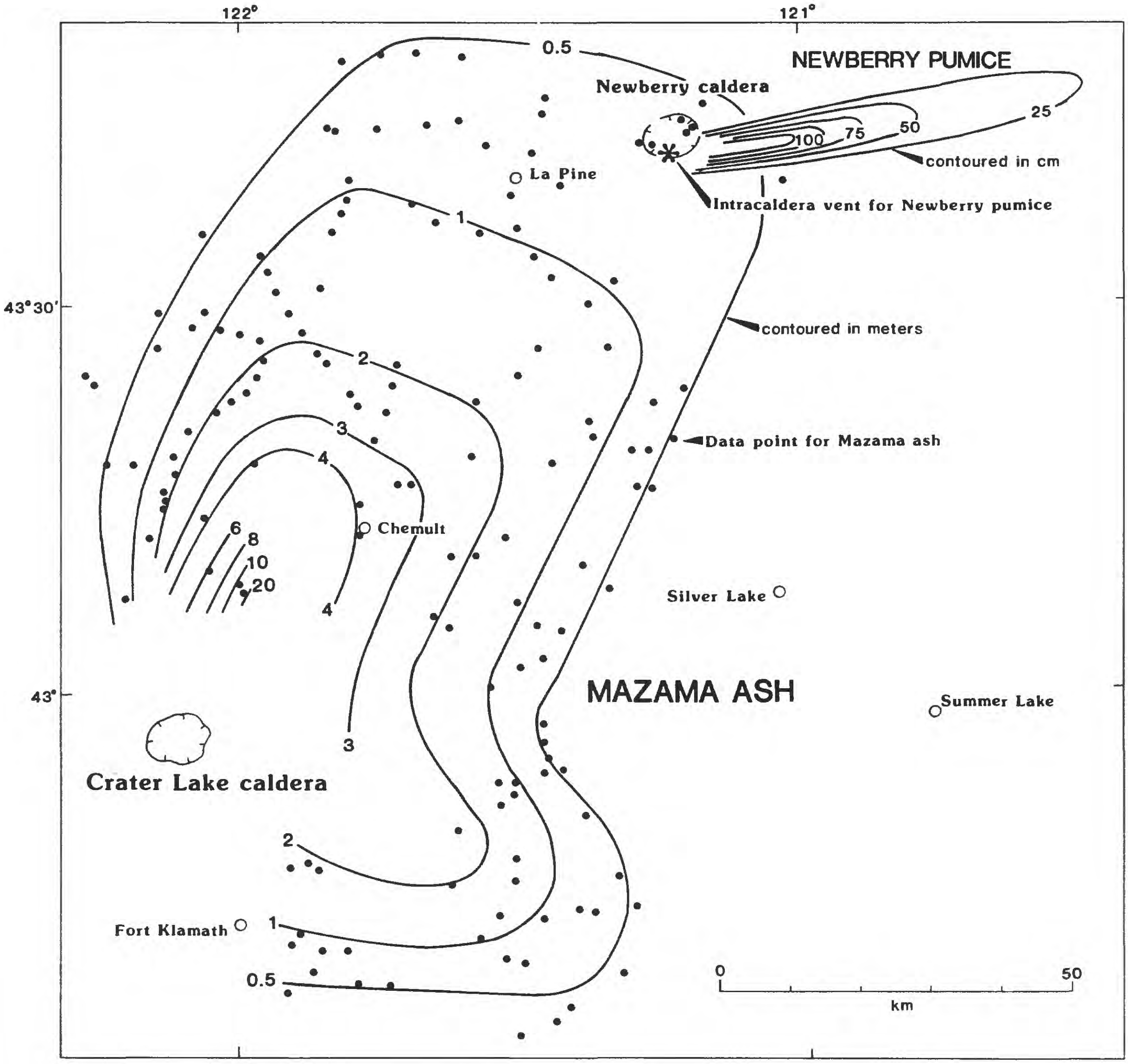

Map-figure 1. Isopach map of Mazama ash and Newberry pumice deposits.