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**GEOLOGIC MAP OF UPPER EOCENE TO HOLOCENE VOLCANIC AND
RELATED ROCKS IN THE CASCADE RANGE, WASHINGTON**

By James G. Smith

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INTRODUCTION

Since 1979 the Geothermal Research Program of the U.S. Geological Survey has carried out a multidisciplinary research effort 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This map is one of a series presently being compiled that shows Cascade Range geology by fitting published and unpublished mapping into a province-wide scheme of lithostratigraphic units; map sheets of the Cascade Range in California and in Oregon complete the series.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 volcanic 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 volcanism 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 map 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-day crest of the Cascade Range. Study of these older rocks can aid in developing models of geothermal systems. These rocks also give insight into the origins of volcanic-hosted mineral deposits and even to future volcanic hazards.

Historically, the regional geology of the Cascade Range 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; Hammond, 1980). 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's crest. In addition, age control was scant and limited chiefly to fossil flora. In the last 20 years, 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 range in Washington lacks adequate data to be shown reliably at the larger 1:500,000 scale of this map. Areas that remain poorly understood in Washington include the stratovolcanoes, Mount Baker and Mount Rainier, and Eocene to Miocene rocks of the western part of the Cascade Range between lats 122°30' and 123°.

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 my own, done since 1980. To assign all map units their correct composition and age, I also reevaluated older published maps and incorporated recently determined chemical analyses and radiometric ages.

DISCUSSION INTRODUCTION

The Tertiary and Quaternary volcanogenic Cascade Range in Washington is divided into two segments by a northeast-trending line (fig. 1; hereafter referred to as the northern Washington and southern Washington segments). Weaver and Michaelson (1985) originally drew this line parallel to the present-day direction of plate convergence between the Juan de Fuca and North American plates, basing its location on the pattern of present-day seismicity in Washington and northern Oregon. However, the two segments differ in several important geologic aspects, such as rate of volcanic production, abundance of Tertiary plutonic rocks, and style of deformation, suggesting that the line has a significance beyond the location of earthquake hypocenters.

Differences in geologic characteristics of the segments that typify the present-day Cascade Range have existed at least since Eocene time. For example, during the last million years, the southern Washington segment produced nearly 7 times more intermediate-composition and silicic magma per kilometer of arc length than the northern Washington segment. From late

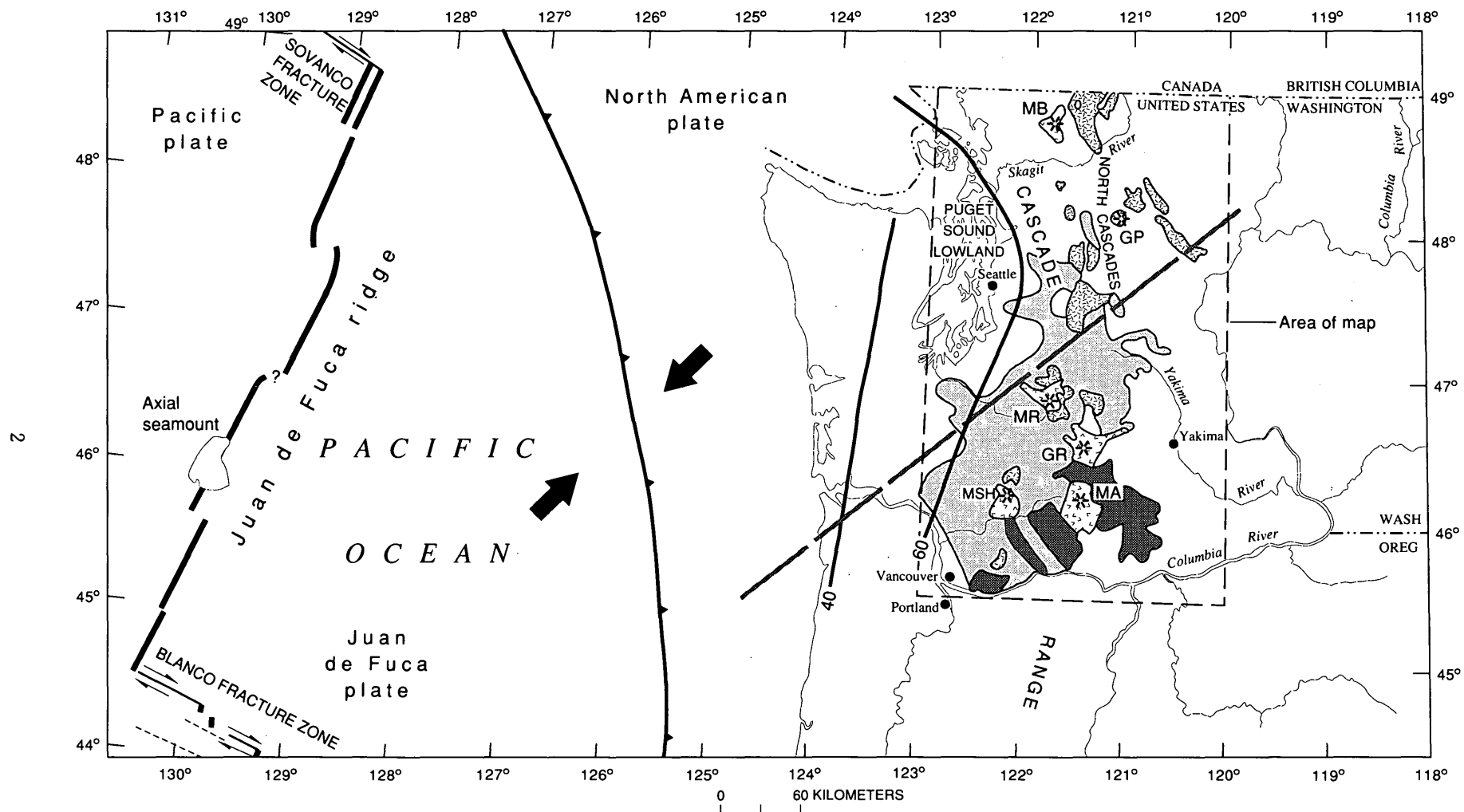













Figure 1. General setting of late Eocene to present-day Cascade Range in Washington showing selected geologic features.

EXPLANATION

-  Holocene to Pliocene stratovolcano—Star indicates peak. MB, Mount Baker; GP, Glacier Peak; MR, Mount Rainier; GR, Goat Rocks volcano; MA, Mount Adams; MSH, Mount St. Helens
-  Major Holocene to Pliocene basalt field
-  Pliocene to late Eocene volcanogenic rocks of the Cascade arc
-  Middle Miocene to late Eocene granitic epizonal intrusive rocks
-  Line dividing northern Washington segment of the Cascade Range from southern Washington segment—Based on earthquake hypocenters; from Weaver and Baker (1988)
-  40—Depth contour of Juan de Fuca plate underneath continent—In kilometers; from Weaver and Baker (1988)
-  Deformational front at base of continental slope—Sawteeth on upper plate. Interpreted as surface expression of subduction zone marking boundary between Juan de Fuca and North American plates; from Snively (1987) and Drummond (1981)
-  Location of active spreading-ridge segments—Queried where uncertain; from Morton and others (1987) along Juan de Fuca ridge and Embley and others (1987) along Blanco fracture zone
-  Active transform faults along plate boundaries—Arrows indicate direction of relative movement; from Embley and others (1987)
-  Extensions of transform faults beyond spreading ridges—From Embley and others (1987)
-  Relative plate motion—Indicates direction of present-day convergence between Juan de Fuca and North American plates; from Drummond (1981)

Miocene to early Pleistocene time, the southern Washington segment produced about 5.3 times as much intermediate-composition and silicic magma per kilometer of arc length as the northern Washington segment. Volcanic production was also greater in the southern Washington segment earlier in the Tertiary as well. Lower Oligocene to middle Miocene volcanogenic strata are not common in the northern Washington segment, but more than 4 km of strata of comparable age are present throughout much of the southern Washington segment. Late Eocene and younger epizonal granitic plutons crop out over more than 2,700 km² in the northern Washington segment, which is more than 7 times the area over which they crop out in the southern Washington segment. The Eocene to late Miocene tectonics of the northern Washington segment are characterized by north-northeast- to north-northwest-trending, steeply dipping faults, whereas the tectonics of the southern Washington segment are characterized by north- to northwest-trending, gently plunging folds. However, timing of deformation is not

well known in either segment. These persistent differences must be taken into account in any reconstructions of the Pacific Northwest. In the following section the characteristics of each segment are discussed in greater detail.

NORTHERN WASHINGTON SEGMENT

Volcanism

Quaternary volcanogenic rocks are not abundant in this segment of the Cascade Range, and volcanic production is low compared to other parts of the Cascade Range (Sherrod, 1986; Sherrod and Smith, 1989b). Volcanic activity in this segment is found at the active stratovolcanoes Mount Baker and Glacier Peak and at minor basalt flows and cinder cones 10 to 20 km south of Glacier Peak. The Mount Garibaldi volcanic field, 150 km northwest of Mount Baker in British Columbia, is also included in this segment because it is similar to Mount Baker and Glacier Peak. Each of these areas has active stratovolcanoes at its center that have erupted mainly intermediate-composition and silicic lava.

As with other estimates that follow, only an approximation of the volume of volcanic products per unit time is possible for this segment. Glaciers and streams have removed much of the evidence; older valley-filling pyroclastic and debris-flow deposits are especially likely to have been eroded. Nonetheless, an estimate of volcanic production expressed in units of cubic kilometers per kilometer of arc length per million years [km³ (km of arc length)⁻¹ m.y.⁻¹] enables comparison between segments, as long as its approximate nature is kept in mind. Estimates of the volume of magma produced at different volcanic centers are shown in table 1.

Mount Baker consists predominantly of andesite flows and subordinate dacite and basalt. The present-day volcano of late Pleistocene and Holocene(?) age sits on the eroded remnants of one or more middle Pleistocene to possibly late Pleistocene volcanoes, but details of their history are not well known. Rocks of the present cone as well as older eroded cones are all normally polarized (Swan, 1980). Potassium-argon (K-Ar) dating on the oldest sequence of flows at Mount Baker gives an age of about 400 ka, but individual determinations have large analytical errors (Easterbrook, 1975). The normal polarization and K-Ar data indicate that both the older and younger volcanoes at Mount Baker formed in the last 730,000 yr. Mount Baker forms an impressive snow-covered peak whose summit is over 3,200 m in elevation, but the volcano is perched on a high bedrock ridge and is not as voluminous as it appears. The present main cone and associated middle to late(?) Pleistocene vents have produced approximately 70 km³ of rock in the last 730,000 yr (R.L. Christiansen, written commun., 1987; fig. 2). A few flank flows, volcanic debris flows, and tephra layers contribute less than an additional 2 km³ to the total volume (Hyde and Crandell, 1978).

Products of Glacier Peak volcano comprise the main cone as well as downstream and downwind deposits of explosive volcanism. A few nearby mafic vents may also be related to volcanic activity at Glacier Peak. The main summit area of Glacier Peak is composed primarily of dacite domes and short flows (Crowder and others, 1966; Tabor and Crowder, 1969). Few radiometric ages exist for the main cone, and therefore its detailed history is poorly known. Explosive activity was particularly common at Glacier Peak; numerous pyroclastic and debris

Table 1. Estimates of magma produced at different volcanic centers in northern Washington segment of Cascade arc

Volcanic center	Volume of magma (km ³)			
	1 to 0 Ma		7 to 1 Ma	
	Intermediate composition and silicic	Mafic	Intermediate composition and silicic	Mafic
Mount Garibaldi ¹	23.7	0	0	0
Mount Baker ¹	71.6	0	0	0
Pliocene volcanic rocks under Mount Baker	0	0	7.2	0
Hannegan Volcanics	0	0	40.7	0
Glacier Peak	29.4	0	0	0
Volcanic rocks of Gamma Ridge	0	0	4.15	0
Mafic flows between Glacier Peak and Mount Rainier	0	1.3	0	0
Total volume	124.7	1.3	52.05	0

¹Minor amounts of basalt included as part of main cone.

flows, which are dominantly dacitic, came off the mountain during the last 14,000 yr and traveled westward as far as 100 km downstream. Eruptions of ash created extensive tephra deposits, mainly east and south of the peak (Porter, 1978; Beget, 1982b). Glacier Peak rocks are all normally polarized (Tabor and Crowder, 1969; Beget, 1982a). The normal polarization, the large volume of explosive products less than 14,000 yr old, and the youthful appearance of the main cone indicate that Glacier Peak formed within the last 730,000 yr and that, quite likely, the bulk of the mountain is much younger. Glacier Peak, like Mount Baker, forms an impressive snow-covered cone whose summit is over 3,200 m in elevation. Glacier Peak also sits on a high bedrock ridge and, like Mount Baker, appears more voluminous than it really is. The volume of material produced by Glacier Peak since the middle Pleistocene includes only 6 km³ of lava and pyroclastic deposits at the main cone (R.L. Christiansen, written commun., 1987) but some 20 km³ of near-vent tephra and downstream debris and pyroclastic flows (Beget, 1982b)¹. Tephra, equal to an additional 3.4 km³ of magma, was deposited away from the main cone of the volcano (Porter, 1978)². The total volume of magma produced by Glacier Peak is 29.4 km³ (fig. 2).

Other volcanic rocks in this segment include the Mount Garibaldi volcanic field (British Columbia) and small basalt flows south of Glacier Peak. The volume of the Mount Garibaldi volcanic field is equal to approximately 23.7 km³ of magma (Mathews, 1958, p. 194; fig. 2), and the volume of the basalt flows is at most 1.3 km³.

Adding the volumes produced in the last 1,000,000 yr and using 310 km for the arc length from Mount Garibaldi to the segment-dividing line (fig. 2), I calculate a volcanic production of 125 km³/310 km of arc length, which is equal to a rate of volcanic production of 0.40 km³ (km of arc length)⁻¹ m.y.⁻¹ for

the last 1 Ma (fig. 2) for intermediate-composition and silicic rocks. This is a minimum estimate; doubling it to account for ash blown far from the volcanoes and for eroded deposits still indicates a rate of volcanic production of only 0.80 km³ (km of arc length)⁻¹ m.y.⁻¹. Even this generous estimate is less by a factor of 3.5 than the rate for intermediate-composition and silicic rocks in the southern Washington segment during the same timespan.

Volcanic rocks ranging in age between 2 and 1 Ma are unknown in the northern Washington segment.

All upper Miocene and Pliocene (7 to 2 Ma) volcanogenic rocks in this segment within the United States are located within 35 km of either Mount Baker or Glacier Peak, suggesting that volcanic activity in the northern Washington segment has remained focused over approximately the same locations for the last 7 m.y. Principal stratigraphic units are the Hannegan Volcanics northwest of Mount Baker (Staatz and others, 1972), unnamed volcanic rocks under present-day Mount Baker (Brown and others, 1987), and the volcanic rocks of Gamma Ridge on the northeast flank of Glacier Peak (Crowder and others, 1966). Original areal extent and thickness of the 7- to 2-Ma volcanic rocks is unknown because of erosion. Areas of existing outcrops are not large, and only a few rocks have age determinations (Engels and others, 1976). For these reasons, only a minimum rate of volcanic production can be estimated. The approximate volume of these units, using present-day areas and thicknesses, is about 52 km³. This gives a rate of volcanic production of 52 km³/310 km of arc length from 7 to 2 Ma, equal to about 0.034 km³ (km of arc length)⁻¹ m.y.⁻¹. For the interval 7 to 1 Ma the rate equals 0.028 km³ (km of arc length)⁻¹ m.y.⁻¹. These are certainly minimum estimates, given the extensive erosion of these volcanic rocks.

Rates of volcanic production recorded by volcanogenic rocks older than a few million years cannot be directly compared with those for Pleistocene to Holocene stratovolcanoes. In young stratovolcanoes, enough of the constructional volcanic edifices remains to make estimates of original volumes possible. For volcanic rocks older than a few million years, proximal deposits of large volcanoes are largely eroded

¹It is not clear whether the volumes given by Beget (1982b) are those of the deposits or of an equivalent volume of magma. I have assumed that the volumes given are magma volumes. If the volumes are for tephra and volcanoclastic deposits, then they should be reduced by 40 to 60 percent to get the equivalent volume of dacite magma.

²The volume of dacite magma erupted was calculated from Porter's (1978) thickness and distribution data, in part using the method explained in the section on Mount St. Helens.

VOLCANIC PRODUCTION

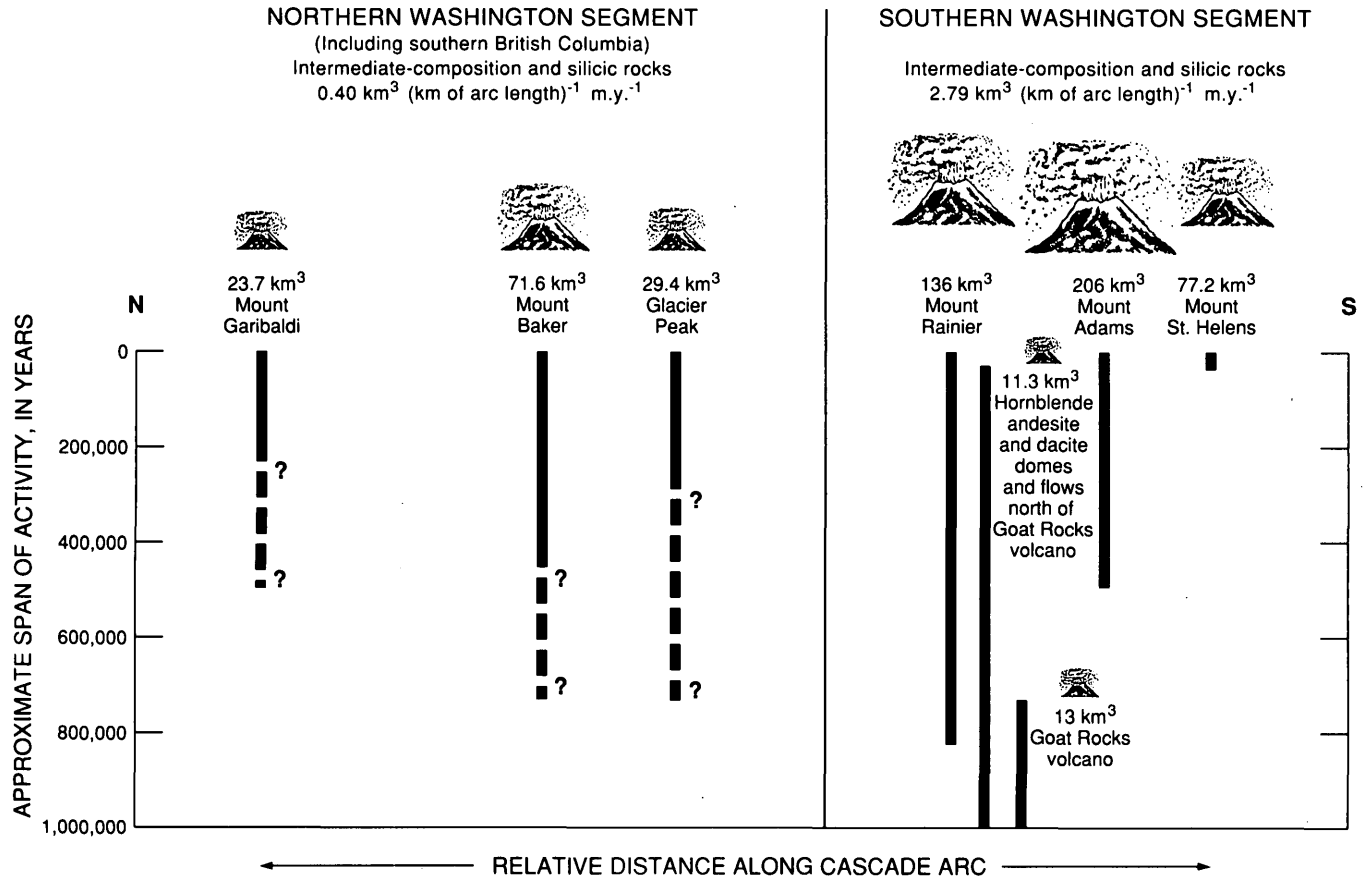


Figure 2. Volcanic production of stratovolcanoes during the last million years. Area of each volcano symbol is proportional to volume of magma produced during last million years. Vertical bar represents time interval during which stratovolcano was active; dashed line and query indicate uncertainty. Spacing between vertical bars is proportional to relative spacing of stratovolcanoes along Cascade arc. Total volume of magma produced during last million years is approximately 568 km^3 .

away, while distal alluvial facies volcanoclastic deposits are preferentially preserved (see fig. 3 on sheet 1 for an explanation of facies terms). Comparative rates of volcanic production are more accurately estimated in these older bedded rocks by using stratigraphic thickness to calculate meters of volcanogenic rock deposited per million years, rather than by trying to estimate magmatic volume. This method avoids the problem of converting less dense volcanoclastic rocks back to an equivalent volume of magma and the problem of estimating original areal extent and volume for bedded units that are now partly covered by younger rocks or partly eroded.

In the northern Washington segment, upper Eocene to lower Oligocene volcanogenic rocks are not widespread, and middle Oligocene to upper Miocene volcanogenic rocks are present only in local areas and have imprecise thicknesses and age ranges. So little is known about middle Oligocene to upper Miocene volcanogenic rocks that deposition rates were not calculated. Volcanogenic rocks (fig. 1; geologic map) belong mostly to the upper Eocene to lower Oligocene volcanic rocks of Mount Persis (Tabor and others, 1982a) and the coeval

Barlow Pass Volcanics (Vance, 1957). These sequences are poorly exposed, strongly folded, faulted, intruded by younger plutons, and locally metamorphosed. Therefore, the numbers below are useful only in comparing rates of deposition of volcanogenic rocks between the northern Washington and the southern Washington segments.

The volcanic rocks of Mount Persis crop out in the foothills of the Cascade Range east of Seattle. They are dominantly pyroxene andesite, andesite breccia, and tuff that includes minor interbedded volcanic sandstone and siltstone. They are late middle Eocene to early Oligocene (approximately 45 to 35 Ma in age) (Tabor and others, 1982a). The top of the formation is eroded but 1,500 m of section is preserved (R.W. Tabor, oral commun., 1987). The age and thickness indicate an approximate deposition rate of 150 m/m.y. The Barlow Pass Volcanics crops out in the headwaters of the Sauk and Stillaguamish Rivers. The formation is slightly metamorphosed, folded, and locally faulted; it consists of basalt, rhyolite, and andesite flows, interbedded tuffaceous sandstones, argillite, and micaceous arkosic rocks. The formation is late middle Eocene to early Oligocene

(approximately 45 to 35 Ma) in age, although the age is not well constrained. The section is approximately 1,220 m thick (Vance, 1957; Tabor and others, 1982a). The resulting deposition rate is 122 m/m.y. Because this rate is for all rocks, not just the volcanogenic ones, it is somewhat high.

Granitic rocks

Granitic plutons of batholithic dimensions are another characteristic of the northern Washington segment. Even though the Cascade volcanic chain is more than 1,100 km long, large granitic plutons are mostly restricted to this segment. Prominent plutons in this segment include the Chilliwack composite batholith (Staatz and others, 1972), the Cloudy Pass batholith (Tabor and Crowder, 1969), the Railroad Creek and Duncan Hill plutons (Cater, 1982; Church and others, 1984), the Squire Creek pluton and Index and Grotto batholiths (Yeats, 1964; Frizzell and others, 1984), and the Snoqualmie batholith (Erickson, 1969; Frizzell and others, 1984). Post-middle Eocene granitic plutons crop out over more than 2,700 km² in this segment; this is 7 times the area that they cover in the southern Washington segment. Many plutons are described as having been emplaced at shallow levels; some may have vented to the surface (Tabor and Crowder, 1969; Erickson, 1969).

Tectonics

Present-day seismicity in the northern Washington segment is characterized by two spatially distinct groups of earthquake hypocenters (Taber and Smith, 1985; Weaver and Michaelson, 1985). A zone of shallow crustal seismicity extends under the Puget Sound lowland into the foothills of the Cascade Range. Earthquake hypocenters are diffuse throughout this area and less than 25 km deep; they have little obvious relation to mapped geology (Taber and Smith, 1985). West of Puget Sound, an elongate cluster of subcrustal hypocenters that are deeper than 30 km defines a distinct Benioff zone dipping east at approximately 11° (Taber and Smith, 1985). East of Puget Sound, a few deeper hypocenters suggest that the Benioff zone dips more steeply as it plunges eastward toward the Cascade Range. The subcrustal earthquakes are believed to originate within the subducting Juan de Fuca plate, not at the plate boundary (Taber, 1983; Taber and Smith, 1985; Weaver and Baker, 1988). Subcrustal earthquakes have been recorded only in the northern Washington segment. Weaver and Baker (1988) used these deep hypocenters to construct 40- and 60-km contours in the upper part of the Juan de Fuca plate (fig. 1). No subcrustal earthquakes have been recorded at depths greater than 80 km, nor have any been recorded directly under the present-day Cascade volcanic chain. Therefore, the configuration of the Juan de Fuca plate under the present-day strato-volcanoes is unknown.

North-northeast- to north-northwest-trending, steeply dipping fault systems are the most prominent structural features of this segment. Many faults extend for more than 50 km and are regionally significant. Examples of prominent faults include the Straight Creek fault zone, which extends as a Tertiary fault for 110 km from east of the Grotto batholith southward at least to Manastash Ridge, where it is covered by the Columbia River Basalt Group; the Entiat fault, which extends southeastward for 60 km from the Cloudy Pass batholith to east of the map area; and the prominent set of northwest-trending faults just

west of Darrington. Many Tertiary faults are parallel to underlying Paleozoic and Mesozoic structures; others are pre-Tertiary faults reactivated in the Tertiary (Misch, 1977; Tabor and others, 1984). For example, the Straight Creek fault was a major Late Cretaceous to early Tertiary strike-slip fault that has as much as 160 km of right-lateral offset (Frizzell, 1979). Between the late Eocene and middle Miocene, the fault reactivated but movement was dominated by normal displacement (Tabor and others, 1984).

Details of timing and offset along these faults are not well known, and only those segments of faults that show probable post-45-Ma movement are shown on the geologic map. For example, the Straight Creek fault zone extends well north of its termination shown on the map. However, because the fault cuts only Mesozoic rocks in its northern part, possible post-late Eocene movement cannot be evaluated, and that part of the fault is not shown on the map.

The geologic map shows that, in general, major faults displace Eocene volcanic and sedimentary rocks and are cut by middle Miocene plutons. These relations suggest a period of normal faulting in the northern Washington segment between 40 and 22 Ma. Other shorter faults offset Miocene plutons and Miocene and Pliocene volcanic rocks east of Mount Baker and in the headwaters of the Skykomish River. These faults do not show a consistent trend and may be related to local features. For example, in the headwaters of the Skykomish River, faults largely bound the Eagle Tuff (Yeats, 1977). Yeats suggested that the tuff may be the down-dropped fill inside a 22- to 24-Ma caldera. The Eagle Tuff and the adjacent Grotto batholith have radiometric ages within 2 m.y. of each other, and Yeats (1977) also suggested that they may be genetically related.

Few descriptions mention folding in rocks younger than the middle Eocene. Vance (1957) described the Barlow Pass Volcanics as strongly folded, generally dipping less than 35°; his map suggests a gently south-plunging, open syncline. Farther west, in the foothills of the Cascade Range, Frizzell and others (1984) contrasted the pronounced deformation of the lower to upper Eocene Puget Group with the more mildly deformed upper Eocene volcanic rocks of Mount Persis, but few fold axes are shown on their map.

The paucity of upper Eocene to upper Miocene sedimentary and volcanic rocks and the large areas underlain by granitic plutons and pre-Eocene basement rocks are conventionally used as evidence for major post-middle Miocene regional uplift of the northern Washington segment. However, details of timing of the uplift and the amount are rarely stated. Isostatic rebound following late Pleistocene glacial unloading of the Puget Sound lobe of the Cordilleran ice sheet at approximately 12 ka can account for as much as 0.14 km of uplift in the northern Washington segment (Thorson, 1981). Beyond that amount, stratigraphic evidence suggests little if any differential uplift of the northern Washington segment.

Upper Eocene rocks crop out at approximately the same elevation along the west side of the range in both segments for 250 km from Seattle southward to the Columbia River—an unlikely coincidence if extensive post-middle Miocene differential regional uplift had taken place. Areas underlain by upper Eocene rocks and their present-day elevations are as follows. (1) The volcanic rocks of Mount Persis are exposed in the Cascade foothills approximately 40 km east of Puget Sound at

elevations between 50 and 1,600 m. (2) The contact between the volcanic rocks of Mount Persis and the unconformably underlying pre-Tertiary bedrock is visible between elevations of 500 to 750 m (Tabor and others, 1982a), although to the west the contact projects below sea level under the Puget Sound lowland. (3) In the southern Washington segment, upper Eocene volcanic rocks of the Northcraft Formation crop out along the southern edge of the Puget Sound lowland and extend southward into the Centralia-Chehalis area at elevations between 100 and 1,000 m. (4) The contact between the upper Eocene Northcraft and the underlying middle Eocene McIntosh Formation ranges in elevation from 100 to 250 m (Snively and others, 1958). (5) Upper Eocene basaltic and volcanoclastic rocks assigned to the Goble Volcanics by Phillips (1987a, b) crop out approximately 50 km south of the Centralia-Chehalis area along the Cowlitz River at elevations between 50 and 750 m.

Miocene plutons in the northern Washington segment and coeval volcanic rocks in the southern Washington segment can also be used to estimate differential uplift. The presumed elevation of the Earth's surface in Miocene time for the North Cascades is estimated from the present-day elevation of a pluton's roof and the depth at which it was intruded. The elevation of the restored Miocene Earth's surface is then compared to the elevation of Miocene volcanic rocks in the southern Washington segment; any difference should be the approximate amount of differential uplift between the two segments. This method suggests that post-middle Miocene differential uplift is no more than 1.5 km. However, assumptions are required that may not be correct. The first assumption is that depths of intrusion of the plutons are well known. The second assumption is that the elevation of the Earth's surface above the Miocene plutons in the northern Washington segment was approximately equal to the elevation at which coeval volcanic rocks were deposited in the southern Washington segment. Unfortunately, there is no way of evaluating this assumption.

Details of the calculations are as follows. The roof of the 25- to 17-Ma Snoqualmie batholith is presently about 1,500 m above sea level. Erickson (1969) estimated that the Earth's surface lay 1,220 to 1,440 m above the roof of the pluton. Therefore, the Earth's surface in Miocene time would have been at an elevation of 2,720 to 2,940 m above present-day sea level. The roof of the 22-Ma Cloudy Pass batholith is presently about 1,500 to 2,200 m above sea level. Tabor and Crowder (1969) state, "Intrusive breccias and hypabyssal phases suggest that the magma came close to the surface and probably vented." These observations suggest that the Cloudy Pass batholith was probably intruded at slightly shallower depths than the Snoqualmie batholith. I will use a figure of 800 to 1,200 m as the distance from the presently exposed roof of the Cloudy Pass batholith to the Earth's surface at the time of intrusion. These figures indicate elevations of 2,300 to 3,400 m for the elevation of a restored middle Miocene Earth's surface. In the southern Washington segment, volcanic rocks that are 25 to 17 Ma are presently exposed between 750 and 2,200 m above sea level. If the assumptions for this method are correct, then no more than 1,500 m of differential uplift is indicated between the middle Miocene Earth's surface in the northern Washington segment and the elevation of coeval volcanic rocks in the southern Washington segment.

SOUTHERN WASHINGTON SEGMENT

Volcanism

Quaternary volcanogenic rocks are much more voluminous in this segment than in the northern Washington segment, and both intermediate-composition and basaltic rocks are common (table 2). Andesitic and dacitic activity is concentrated around four major stratovolcanoes—Mount Adams, Mount Rainier, Mount St. Helens, and Goat Rocks volcano. Additional intermediate-composition and silicic volcanism occurs in a field of small widely dispersed volcanoes north of Goat Rocks volcano. Major Quaternary basaltic fields include the Tumac Mountain area, located 20 km southeast of Mount Rainier; the Indian Heaven volcanic field located 40 km southeast of Mount St. Helens; basaltic fields peripheral to Mount Adams that are located both north and south of the present main cone; and a field of numerous, mostly isolated, small volcanoes south of Mount St. Helens between Vancouver and the Wind River. Perhaps part of the extensive Simcoe volcanic field, 10 to 70 km southeast of Mount Adams, should be included here, but its age and relation to development of the Cascade arc is poorly known. The few published K-Ar ages (Shannon and Wilson, 1973; Phillips and others, 1986) indicate that much of the field is Pliocene in age. However, the youthful appearance of some cinder cones and volcanoes suggests that a significant part of the field is Quaternary in age.

Mounts Adams and Rainier should be considered dormant. Mount St. Helens is presently active, following renewed eruptions in 1980. The Goat Rocks volcano is extinct and deeply eroded. Goat Rocks volcano and Mount Adams, along with Mount Baker and Glacier Peak, lie between 70 and 110 km east of the 60-km contour drawn by Weaver and Baker (1988) in the upper part of the Juan de Fuca plate. Mounts Rainier and St. Helens are between 50 and 60 km east of the 60-km contour (fig. 1).

Mount Adams is a late Pleistocene and Holocene strato-volcano built on the eroded remains of middle and late Pleistocene volcanic centers. Almost no details of the volcano's history were known until quite recently, but summaries of work in progress by Hildreth and others (1983) and Hildreth and Fierstein (1985) have outlined its history. Two samples of the oldest volcanic rocks peripheral to the present volcano have K-Ar ages of 400 and 470 ka (Hopkins, 1976; Hildreth and others, 1983). A younger, but still deeply eroded volcanic center has a K-Ar age of about 200 ka. The present main cone is built on top of the eroded remnants of this 200-ka volcano, indicating the youth of the main cone. However, nearly all the main cone above 2,300 m was constructed in latest Pleistocene time, probably between 20 and 10 ka (Hildreth and others, 1983; Hildreth and Fierstein, 1985). Lava flows that erupted from the present main cone contain from 54 to 62 percent SiO_2 ; flows erupted from flank vents penecontemporaneous with the main cone are, on the average, more silicic, although their SiO_2 content ranges from 49 to 61 percent. The eruptive style of Mount Adams is characterized by numerous thin flows that came from the summit area or flank vents. Fragmental deposits are uncommon except near the main vent. Historic activity at Mount Adams is unknown, but the volcano has erupted from flank vents at least 7 times during the Holocene (Hildreth and Fierstein, 1985). The peripheral, flank, and main cone vents

Table 2. Estimates of magma produced at different volcanic centers in southern Washington segment of Cascade arc

Volcanic center	Volume of magma (km ³)			
	1 to 0 Ma		7 to 1 Ma	
	Intermediate composition and silicic	Mafic	Intermediate composition and silicic	Mafic
Mount Rainier	136	0	0	0
Mount Adams ¹	206	0	0	0
Basalt fields peripheral to Mount Adams	0	10.3	0	4.9
Mount St. Helens ¹	77.2	0	0	0
Tumac Mountain area	0	9.8	0	9.8
Hornblende andesite and dacite dome and flows north of Goat Rocks volcano	11.3	0	3.8	0
Goat Rocks volcano	13	0	38.8	0
Twin Lakes to Bumping Lake dacite porphyry	0	0	25.7	0
Devils Horns rhyolites	0	0	46.6	0
Devils Washbasin basalt	0	0	0	0.37
Simcoe volcanic field ²	0	0	1	45.5
Indian Heaven volcanic field	1.1	21.3	10.1	37.9
Small volcanoes south of Mount St. Helens between Vancouver and the Wind River	1.5	5.4	0.64	3.2
Total volume	446.1	46.8	125.6 ²	56.2 ²

¹Minor amounts of basalt included as part of main cone.²Simcoe volcanic field not included in totals.

define a recently active north-south locus of volcanism 40 km long but only 5 km wide (Hildreth and others, 1983), implying underlying structural control.

Surprisingly little is known about Mount Rainier considering it is such a large volcano and is so close to major population centers. It has never been mapped in detail, and only scant chemical and radiometric data are available. The most complete description is in Fiske and others (1963), although they included all of the volcano's eruptive products in a single map unit. Products of the earliest known eruptions include thick intracanyon andesite flows on the north and west sides of the mountain and an extensive volcanoclastic alluvial apron, the Lily Creek Formation, on the northwest flank. Eruptions at Mount Rainier probably began more than 840 ka in the early Pleistocene on the basis of a few radiometric determinations, magnetic polarity measurements, and stratigraphic relations of the Lily Creek Formation with glacial deposits (Fiske and others, 1963; Crandell, 1963; Easterbrook and others, 1981). The present main cone of Mount Rainier is built of alternating thin andesite flows and breccia layers. From what is known, all Mount Rainier rocks are chemically similar—nearly all rocks contain from 58 to 64 weight percent SiO₂ (Fiske and others, 1963; McBirney, 1968; Condie and Swenson, 1973). Five explosive eruptions large enough to deposit tephra layers thicker than 1.5 cm a few kilometers from the vent have occurred within the last 10,000 yr, and more than 55 volcanic debris flows have been shed off the mountain into the surrounding lowlands during the same time period (Crandell, 1969; Crandell, 1971; Mullineaux, 1984).

Mount St. Helens is the youngest and most active strato-volcano in the Cascades; it began erupting only about 40 ka

(Crandell and Mullineaux, 1978). This short history has been divided by Crandell and Mullineaux (1978) into nine eruptive periods with dormant intervals between them. Each eruptive period consists of many closely spaced, commonly explosive volcanic events. Individual eruptive periods lasted from hundreds to thousands of years. Intervening dormant intervals were somewhat longer, ranging from a few hundred to 15,000 yr (Crandell and others, 1981; Mullineaux and Crandell, 1981).

There are two main parts to the volcano—an old Mount St. Helens and the present main cone (Hopson, 1971). From 40 to 2.5 ka, old Mount St. Helens erupted only dacite. Domes and short, thick lava flows constructed a dome field while pyroclastic flows, volcanic debris flows, and ash built an extensive fragmental apron around the domes, filled valleys that drained the mountain with volcanic diamicton, and blanketed downwind areas with thick tephra layers (Mullineaux and Crandell, 1981; Crandell, 1988). About 2.5 ka the composition of eruptive products broadened and the present main cone started forming. Dacite continued to erupt, but andesite and basalt also appeared for the first time. The composite, symmetrical, young main cone was built entirely during the last 2,500 yr on top of the thick fragmental apron and domes of old Mount St. Helens. This cone was partially destroyed by the May 1980 eruption.

Because so many eruptions of Mount St. Helens were violently explosive, pyroclastic flows, volcanic debris flows, and tephra form important components of the volcano's products. An extensive apron of fragmental deposits nearly encircles the mountain, and major streams that drain it have thick fills of volcanic diamicton. More than 35 volcanically induced floods have inundated streams as far as 50 km from the volcano, and six of the largest volcanic debris flows probably reached the

Columbia River more than 100 km away. Remnants of these flood deposits can still be mapped as far as 75 km downstream (Scott, 1988). Widespread tephra deposits are volumetrically important, and individual tephra layers form distinctive time-stratigraphic markers throughout the Pacific Northwest. More than 100 individual tephra layers, each representing one or more explosive events, can be traced back to Mount St. Helens. Sequences of tephra layers of about the same age that can be distinguished by differences in composition are grouped together into sets for stratigraphic purposes. Presently, 10 distinctive sets of Mount St. Helens tephra are recognized (Mullineaux, 1986).

The extinct Goat Rocks volcano was active from late Pliocene to early Pleistocene time (Ellingson, 1969; Clayton, 1983; Swanson and Clayton, 1983); it is the oldest recognized stratovolcano in the Cascade Range of Washington that is younger than the Columbia River Basalt Group. Its volume is less than that of Mount Baker and about equal to that of Mount St. Helens. Deeply eroded remains of flank and intracanyon flows, now topographically inverted, cap ridges in the headwaters of the Tieton, Klickitat, and Cispus Rivers. Radially distributed flows whose initial dips increase upflow are the principal evidence of the former volcano's size and location. About half of a radial dike swarm whose focus is consistent with that of the flows (D.A. Swanson, oral commun., 1987) is also preserved. Likely vent areas are indicated by small intrusions and altered areas near the projected confluence of the flows and dike swarm. Pyroxene andesite flows predominate, but breccia interbeds become more common near vent areas. On the north flank of the main volcano, andesite flows are intercalated with basalt flows from a large basaltic shield, indicating contemporaneous andesitic and basaltic volcanism (Swanson and Clayton, 1983; Clayton, 1983).

Small-volume hornblende andesite and dacite domes and short flows located mostly north of Goat Rocks form a north-trending, diffuse, elongate volcanic field approximately 30 km long and 15 km wide (Clayton, 1983).

Mafic volcanic activity in the Tumac Mountain area formed two major shield volcanoes, Hogback and Tumac Mountains, as well as numerous small shields, cinder cones, and valley-filling flows. Thin olivine basalt and basaltic andesite are the most common rock types. The Hogback Mountain volcano was active during the late Pliocene and early Pleistocene and is deeply eroded. The Tumac Mountain volcano formed within the last 730 ka and has a constructional shape (Clayton, 1983).

The Indian Heaven volcanic field consists chiefly of a series of north-south-trending, coalescing, polygenetic shield volcanoes. Cinder cones and subglacial palagonitized hyaloclastic pillow lava complexes are also present. The dominant composition is basalt and basaltic andesite. Low-potassium, high-aluminum tholeiite is common. Strong alignment of vents suggests that volcanism was structurally controlled (Church and others, 1983; Hammond, 1985, 1987).

Small, dominantly basaltic monogenetic volcanoes are present in two other areas in southern Washington—south of Mount St. Helens between Vancouver and the Wind River and on the north and south flanks of Mount Adams. Vent alignments in both areas suggest underlying structural control, although none is apparent at the surface.

I have calculated the volcanic production rate [km^3 (km of

arc length) $^{-1}$ m.y. $^{-1}$] for three separate time periods—0–1 Ma; 1–7 Ma; and about 17–36 Ma (middle Miocene to early Oligocene)—in the southern Washington segment. The youngest span (0–1 Ma) is the same in both the southern and northern Washington segment. The spans of the two older time periods are slightly different but still comparable.

Mount Adams is the most voluminous present-day stratovolcano in Washington. Widespread tephra layers and mass-flowage deposits are not common (Hildreth and others, 1983; Vallance, 1986). The largest recognized mass-flowage deposits are found in the valley of the White Salmon River (Hopkins, 1976; Vallance, 1986). Their combined volume is less than 0.05 km^3 . Andesitic lava flows are mostly confined to the main cone, which has an estimated volume of 206 km^3 (fig. 2).

Mount Rainier is the second most voluminous present-day stratovolcano in Washington. Important components of its total volume include (1) the main cone, (2) volcanic debris flows away from the main cone, (3) large intracanyon lava flows, and (4) the Lily Creek Formation. Tephra units are volumetrically unimportant. Mullineaux (1984) recognized 10 separate tephra units, which range in thickness from less than 1 to 150 cm. However, most tephra units are not widespread. Mullineaux (1984) calculated a total probable minimum volume of 0.51 km^3 , which equals about 0.3 km^3 of dense-rock-equivalent andesite. The volume of the main cone is approximately 87 km^3 . The volume of mudflows and volcanoclastic fluvial deposits away from the main cone is about 10 percent of the volume of the main cone. The combined volume of the four largest Holocene mudflows and debris flows amounts to only 2.2 km^3 : "Osceola," 2.03 km^3 (Crandell, 1971, p. 26); "Electron," 0.153 km^3 (Crandell, 1971, p. 57); "Paradise," 0.102 km^3 (Crandell, 1971, p. 36); and "Round Pass," 0.153 km^3 (Crandell, 1971, p. 55). These deposits are less dense than the lava flows from which they originated, and volume estimates need to be corrected for the difference between the bulk densities. Unfortunately, there are no published bulk densities for consolidated Cascade mudflows or volcanoclastic fluvial deposits. The most applicable bulk densities are those measured for the debris-avalanche and debris-flow deposits of May 18, 1980, at Mount St. Helens, which range from 1.53 to 2.01 g/cm^3 (Voight and others, 1981, p. 373; Major and Voight, 1986; Glicken, in press). Using 1.77 g/cm^3 (midpoint between the maximum and minimum values of the debris-avalanche deposit) as the average bulk density of Mount Rainier volcanic debris flows and 2.7 g/cm^3 for the density of andesite, the andesitic rock equivalent for the four largest Mount Rainier mudflows and debris flows is 1.44 km^3 . Total volume of large intracanyon flows is estimated to be about 40 km^3 on the basis of their area and thickness as mapped by Fiske and others (1963) and Buckovic (1974). The volume of the Lily Creek Formation can be estimated from its original extent and thickness (Crandell, 1963, p. A18, A20) as 11 km^3 , which must also be corrected to give an equivalent volume of magma. The Lily Creek Formation consists predominantly of mudflows, volcanic debris flows, and volcanic alluvial deposits, so 1.77 g/cm^3 is also an appropriate value for its bulk density. The andesitic rock equivalent of the Lily Creek Formation is estimated as 7.4 km^3 . Adding all the individual components, the approximate total volume of magma produced by Mount Rainier is 136 km^3 (fig. 2).

As at Mount Rainier and Glacier Peak, an important fraction

of Mount St. Helens deposits now lies beyond its main cone. The total volume of Mount St. Helens consists of (1) the main cone and minor flank flows; (2) valley-filling mudflows, volcanic debris flows, and pyroclastic deposits; and (3) tephra. Using planimetric methods, the volume of the main cone before May 1980 was calculated as 24.4 km³ (Sherrod and Smith, 1989b). Crandell and Mullineaux (1973, p. A20) estimated its volume as 27 km³. The volume of the minor flank flows is estimated as less than 0.6 km³. They also estimated the volume of valley fill that formed between about 13 and 2 ka as 3 to 4 km³. The volume of valley fill younger than 2 ka is probably small. Estimating the volume of valley fill that formed between 40 and about 13 ka is difficult because the deposits are deeply eroded. On the basis of what remains, mostly on the south side of the volcano, I estimate the volume of this older valley fill to be about the same as that of valley fill formed between 13 and 2 ka. Correcting the 6 to 8 km³ of valley fill for the difference between the bulk density of the deposits (again using an approximate value of 1.77 g/cm³) and the density of dacite (approximately 2.4 g/cm³) gives approximately 4.4 to 5.9 km³ of dacitic rock equivalent.

No published measurements exist for tephra volume erupted from Mount St. Helens before May 1980. Estimates are hard to make because no detailed isopach maps or thickness data for tephra layers deposited before 1980 have been published. To estimate volume of tephra produced by Mount St. Helens, I used a ratio method based on relating thickness of tephra layers to their volume. Sarna-Wojcicki and others (1981) compared volume and thickness at arbitrarily chosen distances from the source for modern ash-fall deposits and constructed an empirical curve for estimating volume where thickness is known. Using this curve, they calculated that the volume of Mount St. Helens tephra layer Yn is 4.5 to 5 km³. The thickness of tephra layer Yn is 45 percent of the thickness of the complete tephra set Y (all thickness measurements made 8 to 10 km downwind and given in Mullineaux, 1986). If thickness is proportional to volume for the complete tephra set, then 4.5 to 5 km³ for layer Yn extrapolates to 10.0 to 11.1 km³ for all of tephra set Y. This estimate compares well with an estimate of 10 km³ for the volume of tephra set Y made by Crandell and Mullineaux (1973, p. A20). Assuming that volume is proportional to thickness for all Mount St. Helens tephra and that the volume of tephra set Y is approximately 10 km³, then the total volume of tephra is 73 km³ on the basis of a total thickness of 1,460 cm (Mullineaux, 1986, table 1). To convert this volume to an equivalent volume of dacite magma, the average bulk density of the tephra must be estimated. Bulk densities of uncompacted tephra from May 18, 1980, are mostly between 0.5 and 1.0 g/cm³. Compaction by rain alone commonly increased bulk density by a factor of 2 (Sarna-Wojcicki and others, 1981). On the basis of these data, an average bulk density of 1.55 g/cm³ seems reasonable for pre-1980 tephra. Therefore, the dacitic magma equivalent of Mount St. Helens tephra is about 47 km³. For comparison, Sarna-Wojcicki and others (1981) calculated that the tephra of May 18, 1980, was equal to about 0.20 to 0.25 km³ of solid rock. Adding all the individual components, the total volume of magma produced by Mount St. Helens is about 77.2 km³ (fig. 2).

Clayton (1983, table 2) gives the volume of the Goat Rocks volcano as 60 km³ and its age as 3 to 0.7 Ma. He also estimates that 40 percent of the volume is breccia and tuff, which equals 24 km³. Correcting this volume for the difference between the

bulk density of volcanoclastic deposits (1.77 g/cm³) and the density of andesite (2.7 g/cm³) gives approximately 16 km³ of andesitic rock equivalent. The total dense-rock-equivalent volume of the Goat Rocks volcano is then 52 km³. Details of age versus volume are not known, so I arbitrarily assigned 13 km³ or one-third of the total volume as the volume of volcanic products younger than 1 Ma (fig. 2). Although there are many possible sources of error in this calculation, the volume of the Goat Rocks volcano is small compared with the total volume of the other stratovolcanoes, and errors in its volume will not change the total calculated volume by much.

The volume of the remaining intermediate-composition and silicic volcanic areas in southern Washington, the hornblende andesite and dacite domes and flows north of Goat Rocks, is given as 15 km³ by Clayton (1983). I estimate that one-fourth, or approximately 11.3 km³, was erupted in the last million years.

Adding the volumes of intermediate-composition and silicic magma produced in the last million years and using 160 km for the arc length (the distance from the segment-dividing line to the Columbia River; fig. 2), I calculate a volcanic production of 446 km³/160 km of arc length, which is equal to a rate of volcanic production of 2.79 km³ (km of arc length)⁻¹ m.y.⁻¹ (fig. 2). If mafic as well as intermediate-composition and silicic volcanism is included (table 2), the volcanic production rate is 3.08 km³ (km of arc length)⁻¹ m.y.⁻¹. For comparison, Sherrod (1986, table 1) calculated rates of 3 to 6 km³ (km of arc length)⁻¹ m.y.⁻¹ for the Cascade Range in central Oregon over the last 3.5 Ma. The central Oregon rates include mafic as well as intermediate-composition lavas.

About 90 percent of all upper Miocene to lower Pleistocene (7 to 1 Ma) volcanogenic rocks in the southern Washington segment lie within 45 km of the Goat Rocks volcano. The rest are in the Indian Heaven area volcanic field, 35 km southwest of Mount Adams. Extensive erosion and partial cover by younger rocks obscure the original areal extent and thickness of these rocks. Therefore, only a minimum rate of volcanic production can be calculated.

Clayton (1983) described principal units and calculated volumes in the Goat Rocks area. The oldest unit is a sequence of Pliocene rhyolite flows, breccia, and vitric tuff beds probably erupted from a caldera (Clayton's, 1983, Devils Horns rhyolite). Clayton (1983, table 1) estimated the volume of this silicic unit as 60 km³ and breccia and tuff content as 85 percent. I have reduced its volume to 44.5 km³ of magma equivalent, using Clayton's ratio of fragmental rocks to flows and 1.6 g/cm³ as the average bulk density of the fragmental rocks and 2.3 g/cm³ as the density of rhyolite.

The late Pliocene to early Pleistocene Goat Rocks volcano grew mainly on top of the Pliocene rhyolitic center. As described above, approximately 52 km³ has erupted from this volcano; about 39 km³, or two-thirds erupted before 1 Ma.

A sequence of Pliocene dacite domes and short flows coeval with the rhyolite unit and the early part of the Goat Rocks volcano crops out on ridges between the Tieton River and Rattlesnake Creek (Clayton's, 1983, dacite porphyry). Nearly all the dacite domes and flows are composed of dense lava. Clayton (1983, table 2) estimated that the volume of the domes and flows was between 15 and 30 km³ and breccia and tuff content as 10 percent. I have reduced this volume to 25.7 km³ of dacitic rock equivalent using appropriate values for density of

fragmental rocks and dacite (table 2).

The Pliocene to Holocene Indian Heaven volcanic field is predominately basalt. The field consists of a chain of coalesced shield volcanoes, associated cinder cones, and thin tephra deposits (Church and others, 1983; Hammond, 1985). A few small Pliocene and early Pleistocene andesite volcanoes are located along the east and west margins of the field. Hammond (1985) estimated the volume of the andesite volcanoes older than 1 Ma as about 10 km³ and the volume of basalt older than 1 Ma as about 38 km³. Other areas in this segment produced about 4.5 km³ of intermediate-composition and silicic magma between 7 and 1 Ma (table 2).

Volcanic production of intermediate-composition and silicic magma for the southern Washington segment between 7 and 1 Ma equals about 126 km³. This is equal to a rate of volcanic production of 126 km³/[(160 km of arc length)(6 m.y.)] or 0.131 km³ (km of arc length)⁻¹ m.y.⁻¹. Including mafic magma erupted exclusive of the Simcoe volcanic field increases the rate to 0.189 km³ (km of arc length)⁻¹ m.y.⁻¹. These low rates agree with the relative paucity of volcanic rocks ranging in age between 7 and 1 Ma shown on the map. These rates are, however, approximately 4.5 to 7 times greater than the rate for coeval rocks in the northern Washington segment.

Middle Eocene to middle Miocene volcanogenic rocks are widespread throughout the southern Washington segment; even so, estimating rates of volcanic production is not possible because of uncertainties in volume. However, rates of deposition can be calculated in a few places on the basis of stratigraphic thickness between dated rocks. Analytical uncertainty of radiometric ages for this time period precludes calculation of meaningful rates for intervals of less than several million years, and radiometric ages are not always well tied to measured stratigraphic sections. Eocene volcanogenic rocks lack sufficient precise age determinations to calculate meaningful rates. Lower Oligocene to middle Miocene rocks have sufficient data on thickness and age to calculate plausible rates of deposition in only four areas (see discussion below). To minimize uncertainty, rates were calculated over the entire time of volcanogenic deposition for each area. Despite these uncertainties, the estimates agree surprisingly well. As more radiometric age determinations and careful stratigraphic measurements are made, the calculation of volcanic production rates for shorter time intervals will become more meaningful.

Mount Rainier is the first area where a middle Tertiary rate of deposition is calculated. Fiske and others (1963) mapped the area around Mount Rainier and defined three formations of pre-upper Miocene volcanogenic rocks. On the basis of generalized lithologic and temporal correlation, the names of these sequences have been extended by many authors throughout southern Washington. The oldest unit is the Ohanapecosh Formation, which is made up of the following components: (1) lava flow-mudflow complexes that are the vent facies of large volcanoes; (2) adjacent coarse alluvial facies volcanoclastic rocks that form the depositional aprons around the large volcanoes; and (3) minor ash-flow tuff and rhyolite. The unconformably overlying Stevens Ridge Formation consists of quartz-bearing ash-flow tuff and alluvial facies volcanoclastic beds that were probably deposited on a volcanoclastic alluvial plain. The Fifes Peak Formation conformably overlies the Stevens Ridge Formation in the Mount Rainier area and is

composed predominantly of basalt and pyroxene andesite flows, which are the vent facies of many coalesced volcanic centers. For each formation, Fiske and others (1963) listed their preferred thickness as well as maximum and minimum probable thicknesses. The preferred thicknesses total approximately 4,700 m. The formations contain only scattered, poorly preserved fossils unsuitable for reliable age determination. Recently, V.A. Frizzell, Jr., R.W. Tabor, and J.A. Vance dated the three formations using K-Ar and fission-track methods on samples collected as near to the type localities as possible. Their data indicate that the base of the Ohanapecosh Formation is about 36 Ma and that the youngest ages on the Fifes Peak Formation are about 17 Ma (V.A. Frizzell, Jr., oral commun., 1987). On the basis of the thickness and age data, the rate of deposition for lower Oligocene to middle Miocene volcanogenic rocks in the Mount Rainier area is approximately 247 m/m.y.

Frizzell and others (1984) mapped the Ohanapecosh, Stevens Ridge, and Fifes Peak Formations in the Snoqualmie 30' by 1° quadrangle. The total thickness of these three formations, as measured from cross sections on their map, is 4,500 m. Using the limiting ages of 36 and 17 Ma for these formations, the rate of deposition for these units is approximately 237 m/m.y.

Northwest of Mount St. Helens, between the North Fork Toutle and Cowlitz Rivers, Evarts and Ashley (1984) mapped an east-dipping section of upper Oligocene to lower Miocene volcanogenic strata. The section lies between two broad gently south-plunging folds—an anticline to the west and a syncline to the east. Strata within the section are approximately 3,600 m thick (R.C. Evarts, oral commun., 1987) and were deposited between 33 and 23 Ma (limiting ages are best estimates based on data in Evarts and others, 1987, and unpublished ⁴⁰Ar/³⁹Ar data supplied by L.B.G. Pickthorn, written commun., 1988). On the basis of the thickness and age data, the rate of deposition for these strata is approximately 360 m/m.y.

South of Mount St. Helens, along the Lewis River near Swift Reservoir, Oligocene to middle Miocene volcanogenic rocks dip gently east. For this section, Phillips and others (1986) give K-Ar age determinations of 28.5 and 19.9 Ma for two samples that are separated by approximately 2,700 m of volcanogenic strata. Reconnaissance mapping showed that the section is structurally uncomplicated. The rate of deposition calculated from the age and thickness is approximately 314 m/m.y.

Rates of deposition calculated for the four areas in the southern Washington segment range from 237 to 360 m/m.y. The range is small considering the lack of precision in thickness and age data. The rates of deposition for this segment are also similar to rates calculated by Verplank and Duncan (1987) in the Western Cascade Range of central Oregon for a similar timespan.

Granitic rocks

In contrast to the northern Washington segment, granitic plutons do not crop out over large areas in the southern Washington segment. Post-middle Eocene granitic plutons underlie only 730 km² in the southern Washington segment compared to 2,700 km² in the northern Washington segment. Prominent granitic plutons in the southern Washington segment include the subvolcanic Tatoosh pluton (Fiske and others, 1963) and its satellite, the Carbon River stock (Fischer, 1970; Frizzell and others, 1984); unnamed plutons in the headwaters of the Bumping River (Simmons and others, 1983); the epizonal

Spirit Lake pluton (Evarts and Ashley, 1984; Evarts and others, 1987); and the Silver Star stock and related small plutons (Schriener, 1978; Schriener and Shepard, 1981). Radiometric ages indicate that granitic plutons were intruded between 24 and 14 Ma; most ages are between 22 and 17 Ma (Mattinson, 1977; Power and others, 1981; Frizzell and others, 1984; Evarts and others, 1987).

Tectonics

Present-day seismicity in the southern Washington segment is characterized by the near absence of subcrustal earthquakes. Consequently, the geometry of the Juan de Fuca plate is poorly known underneath southern Washington. The frequency of crustal earthquakes is also lower in southern Washington than it is farther north (Weaver and Michaelson, 1985), except for the concentration of earthquakes that are less than 25 km deep along the St. Helens seismic zone (Weaver and Smith, 1983). This zone passes under Mount St. Helens and extends from 30 km southeast of the volcano to 60 km northwest. Focal mechanisms of shallow earthquakes that are concentrated in the zone indicate mostly right-lateral strike-slip faulting along nearly vertical fault planes (Weaver and Smith, 1983). The zone does not correspond with any mapped geologic feature (Evarts and Ashley, 1984; Phillips, 1987a).

Weaver and Michaelson (1985) used seismicity in Washington and northern Oregon, combined with the distribution of active stratovolcanoes and other vents, to develop a segmentation model for the Cascade Range that is analogous to the segmented Nazca subduction zone where it extends beneath the Pacific side of the South American plate. According to this model, the young shallow-dipping Juan de Fuca plate in the northern Washington segment is strongly coupled to the overriding North American plate, resulting in moderate crustal seismicity in the North American plate. A postulated moderate dip on the subduction zone under the Cascade Range results in limited volcanic production. Farther south, in northern Oregon, the subduction zone associated with the arc is postulated to dip more steeply, as much as 30°, resulting in extensive volcanism but almost no seismicity. The southern Washington segment forms a transition zone between the seismically active northern Washington segment and the nearly aseismic Oregon segment. This model, combined with the distribution of volcanogenic rocks and the rate of volcanic production in the two Washington segments, implies a stable plate-tectonic regime in the Cascade Range in Washington for at least the last 45 to 40 m.y., although it does not rule out short-term fluctuations in rate and direction of plate motion.

In contrast to the northern Washington segment, folds rather than long through-going faults are the prominent structures in the southern Washington segment. Most faults are less than 15 km long and strike nearly northwest, parallel or slightly oblique to nearby fold axes.

Faults are abundant, however, in the drainages of the Yakima and Naches Rivers where the Straight Creek fault zone intersects the Olympic-Wallowa lineament. Raisz (1945) originally defined this lineament on the basis of its physiographic expression but was undecided whether the lineament "represents a transcurrent fault-zone, or an accidental alignment of different features." On the present geologic map, the lineament is made of different structural elements, and just west of the Cascade crest it is not clearly defined. The Olympic-Wallowa

lineament and the Straight Creek fault zone meet in an area of complex geology on Manastash Ridge just before the lineament disappears under the Columbia River Basalt Group. Arcuate faults and tight folds in the Straight Creek fault zone swing southeast and merge obliquely with the Olympic-Wallowa lineament. Details cannot be shown on a map of this scale. The reader should consult Frizzell and others (1984) and Tabor and others (1984) for detailed maps and descriptions of a complex geologic history involving vertical and transverse faulting, folding, and sedimentation that lasted from early Tertiary time until at least the intrusion of the 25-Ma Snoqualmie batholith.

The White River fault (Frizzell and others, 1984) is another unusually long fault for this segment of the Cascades. The fault forms a 60-km-long, west-northwest-trending splay off the Olympic-Wallowa lineament. The fault starts at the headwaters of the Naches River, extends across the Cascade Range, and disappears under glacial deposits in the Puget Sound lowland. Correlation of stratigraphic units across the fault (Frizzell and others, 1984) suggests more than 1.5 km of normal north-side-up separation since middle Miocene time. How the fault fits into the regional geologic history is not completely understood. Wells (1989) suggests that the Olympic-Wallowa lineament marks the boundary between a compressional volcanic arc segment to the north and an extensional arc segment to the south.

North- to northwest-trending, gently plunging folds characterize the southern Washington segment. Many individual fold axes have been traced as far as 50 km, and folds 10 to 20 km long are common. In general, folds in the northeast part of the segment have higher amplitudes and shorter wavelengths than those in the southwest. Near Mount Rainier, major fold axes in Oligocene and Miocene rocks are spaced 5 to 10 km apart; limbs typically dip 20° to 50° (Fiske and others, 1963; Schasse, 1987). Between Mount St. Helens and the Columbia River, major fold axes in upper Eocene to Miocene rocks are 8 to 15 km apart, and limbs typically dip 5° to 30° (Roberts, 1958; Phillips, 1987a). Still farther south in the Western Cascade Range of Oregon, folds die out completely, and the volcanic rocks of the Western Cascade Range form a gently east-dipping section that strikes north to northwest (Sherrod and Smith, 1989a).

Many areas are not mapped in detail, and fold axes in these areas are only approximately located. Volcaniclastic and ash-flow-tuff sequences (rocks shown as alluvial and distal facies on fig. 3B, sheet 1) were deposited nearly horizontal, and their present attitudes accurately reflect regional structures. Flows and coarse-grained volcaniclastic sequences (rocks shown as vent facies on fig. 3B, sheet 1), however, may have been deposited with significant initial dip on the upper flanks of volcanoes, and their attitudes cannot be used to map regional structures. Thus, fold axes are particularly difficult to trace through volcanic centers. In some areas on the map, fold axes trend nearly at right angles to the regional fold trend; most of these areas are either poorly mapped or are probably near vents. More detailed mapping is needed to define fold axes more precisely.

The similar north to northwest trend of most fold axes in Eocene through middle Miocene rocks in the southern Washington segment suggests a uniform stress field. However, the age of folding and its relation to proposed changes in the

plate-tectonic regime are unclear. In some areas, Eocene rocks are more tightly folded than the overlying Oligocene and Miocene rocks, and unconformities separate formations, suggesting episodic deformation. Elsewhere, older formations are no more tightly folded than younger ones, contacts are conformable, and formations interfinger, suggesting that deformation postdates deposition of the youngest beds.

One area where the rocks were folded in multiple episodes is between the Naches and Yakima Rivers on the east side of the range (Tabor and others, 1984). There, a sequence of Eocene fluvial, feldspathic sedimentary rocks and less abundant intercalated volcanic beds are overlain by Oligocene volcanogenic rocks of the Cascade arc. Successively younger formations are less tightly folded than older ones, and unconformities between formations are common. Tabor and others (1984) attributed the deformation to "dominantly vertical movement along the Straight Creek fault and its southeasterly splays" Movement took place over an interval of at least 20 Ma ". . . and vertical movements, significant since early Eocene Swauk deposition, followed late Eocene Naches deposition but tapered off by late Oligocene and ceased by Miocene time. . . ." Because the Straight Creek fault zone and Olympic-Wallowa lineament merge in this area, it is not clear whether deformation took place in response to regional stresses or was localized along the preexisting Straight Creek fault zone and Olympic-Wallowa lineament.

West of the Cascade Range along the continental margins of Washington and Oregon, Snively and others (1980) and Snively (1987) described in detail a close interplay between changes in the plate-tectonic regime and the sedimentary record. In their models, periods of more rapid underthrusting by the Juan de Fuca plate resulted in folding episodes in the overlying North American plate that were recorded as regional unconformities. In southwest Washington, only a few kilometers west of the Cascade Range, extensive regional unconformities occur as follows: in the middle Eocene at the base of the McIntosh Formation, in the late Eocene between the McIntosh and Cowlitz Formations and also between the Cowlitz and Lincoln Creek Formations, in the early Miocene between the Lincoln Creek and Astoria(?) Formation, and near the boundary between the early and middle Miocene at the top of the Astoria(?) Formation. Successively younger formations in any particular area are less folded than older ones, although differences may be subtle and apparent only on a regional scale.

Many of these formations, or their landward equivalents, have been mapped eastward to the margins of the Cascade Range where they interfinger with and are overlain by volcanogenic rocks (Fisher, 1957; Snively and others, 1958; Roberts, 1958; Gard, 1968; Vine, 1969; Buckovic, 1979; Wells and others, 1983; Phillips, 1987a, b; Schasse, 1987). During the Eocene, a broad coastal plain, which was part of an extensive deltaic system, existed along the west margin of the modern Cascade Range. West of the deltaic coastal plain was shallow marine water.

Between the Carbon River and Mount Rainier, Gard (1968) and Buckovic (1979) mapped part of the extensive Eocene delta system of southern Washington and the Cascade volcanogenic strata that overlie it. More than 2,000 m of arkosic sediment was deposited in this delta. Sediment was transported by large rivers from crystalline sources to the east across the area of the

modern Cascade Range.

Within the delta, thick piles of volcanogenic rocks formed around a few volcanic centers. For example, near Morton the volcanogenic Northcraft Formation is as much as 750 m thick. Away from the main volcanic accumulation, volcanogenic strata thin and interfinger with enclosing arkosic deltaic sedimentary rocks (Snively and others, 1958; Gard, 1968; Buckovic, 1974). Near Issaquah, the thickest section of the volcanogenic Northcraft Formation is about 2,100 m. There, too, volcanogenic strata thin rapidly away from the main volcanogenic accumulation and interfinger with the enclosing arkosic sedimentary rocks of the Puget Group (Warren and others, 1945; Buckovic, 1979).

Starting in the latest Eocene or earliest Oligocene, volcanic activity along the axis of the Cascade arc greatly increased. As a result, continental volcanogenic strata derived from the growing Cascade arc to the east built slowly westward out over the delta, burying much of it. Volcanogenic deposits continued to accumulate along the axis of the range until middle Miocene time when volcanic activity waned or possibly stopped altogether in the Washington Cascades (Swanson, 1978; Hammond, 1980; Frizzell and others, 1984; Korosec, 1987a; Evarts and others, 1987).

West of the growing continental volcanogenic apron, the shallow-water Lincoln Creek Formation of late Eocene to early Miocene age became the oldest marine formation in southern Washington to record the overwhelming influx of fine-grained volcanoclastic sediment derived from the growing Cascade volcanoes (Beikman and others, 1967; Armentrout, 1973; Prothero and Armentrout, 1985).

No close correlation has been recognized between changes in plate motion, regional unconformities, and folding episodes along the western flank of the Cascade Range similar to correlations recorded in the Cenozoic rocks along the continental margin of southern Washington. Folds are attributed to a poorly constrained period of deformation that took place between early Oligocene and late Miocene time. For example, in the coal fields of the Cascade foothills east of the Seattle-Tacoma area, Vine (1969) described conformable and interfingering contacts between formations within the upper lower to upper part of the Eocene Puget Group as well as in the overlying unnamed lower Oligocene volcanic rocks. Farther west, unnamed volcanic rocks were described as interfingering with volcanic sandstone and tuff assigned to the Lincoln(?) Formation of Weaver (1912, p. 10-22; equivalent to the Lincoln Creek Formation of present-day terminology).

Truly regional unconformities are difficult to document within the volcanogenic core of the Cascade arc in southern Washington. The range's stratigraphy is complex—hundreds of vents produced many hundreds of complexly interbedded lithologic units. As depicted in the facies models (fig. 3, sheet 1), local unconformities abound and spatially and temporally separate volcanic centers repeatedly erupted similar lithologies.

In spite of the stratigraphic complexity, regional unconformities have been proposed on the basis of lithologic similarities between widely separated stratigraphic sections and relative proportions of distinctive rock units such as ash-flow tuff (Hammond, 1979, 1980). The regional importance of these unconformities is difficult to demonstrate because intervening areas are not yet mapped in detail. On large-scale detailed

maps, proposed regional unconformities extrapolated from local unconformities may prove hard to extend when adjacent areas are mapped in detail. For example, on the basis of detailed mapping in the Mount Rainier area, Fiske and others (1963) proposed that the "Ohanapecosh Formation was folded regionally, altered . . . uplifted and deeply eroded before the overlying Stevens Ridge Formation was deposited on it." Detailed mapping just north and east of the Mount Rainier area (Tabor and others, 1982b; Frizzell and others, 1984) failed to find such a period of folding, alteration, uplift, and erosion. Only 80 km south of Mount Rainier near Mount St. Helens, Evarts and others (1987) documented active volcanism and deposition of hundreds of meters of volcanogenic strata during this same 4-m.y. period of supposed regional deformation.

Many unconformities, periods of deformation, changes in volcanic production rate, or shifts in chemical composition have been proposed as regionally significant in the Washington Cascades. Theoretically, regionally significant events should be linked to changes in the plate-tectonic regime. However, events proposed as regionally significant in the Cascade Range remain largely uncorrelated with changes in relative plate motion. Some late Eocene to middle Miocene Cascade events proposed as regionally significant by different authors include (1) 50 Ma, start of Cascade volcanism, composition is dominantly andesitic (Hammond, 1979); (2) 30 Ma, change from dominantly andesitic to mixed andesitic and silicic volcanism, regional unconformity (Hammond, 1979, 1980); 28 to 24 Ma, Ohanapecosh Formation folded on a regional scale and uplifted, followed by deposition of the Stevens Ridge Formation (Fiske and others, 1963; ages from V.A. Frizzell, Jr., oral commun., 1987); (4) pre-17 Ma, extensive erosion surface developed on rocks underlying the Columbia River Basalt Group (Tabor and others, 1982b); (5) approximately 17 Ma, cessation of Cascade volcanism in Tieton River area (Swanson, 1978); (6) 17 Ma, cessation of volcanism in southern Washington (Evarts and others, 1987); (7) post-17 Ma, folding of the Stevens Ridge and Fife Peak Formations along older axes (Fiske and others, 1963); and (8) 15 Ma, change from mixed andesitic and silicic to slightly more silicic than andesitic volcanism, regional unconformity (Hammond, 1979, 1980). Of all these events, only those which took place about 50 Ma and about 17 Ma correlate with major unconformities along the continental margin that are linked by Snively (1987) to changes in relative plate motion.

The event along the continental margin that caused the middle Miocene unconformity at the top of the Astoria(?) Formation discussed earlier is also recorded throughout the southern Washington segment by a sharp decrease in volcanic production. Very few volcanic rocks that originated in the Cascades of southern Washington have radiometric ages between 17 and 10 Ma (Laursen and Hammond, 1974, 1979; Engels and others, 1976; Phillips and others, 1986), suggesting that volcanism certainly waned and perhaps stopped altogether in southern Washington during this time interval. Indirect evidence also exists for a middle Miocene lull in Cascade volcanism. Sedimentary rocks deposited in the southern Washington segment from 17 to 10 Ma, although not widespread, are continental epiclastic sandstone and conglomerate sequences that formed by erosion of older volcanic edifices and not in direct response to volcanic activity. Finally, volcanogenic beds of Cascade origin are rarely interbedded with flows of the

Grande Ronde, Wanapum, and Saddle Mountains Basalts (16.6 to 6 Ma) of the Columbia River Basalt Group, as would be expected if Cascade and Columbia River Basalt Group had been simultaneously active.

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