A TECTONIC MODEL FOR EVOLUTION OF THE CASCADE RANGE

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ABSTRACT

Four volcanic and plutonic episodes in the evolution of the Cascade Range are recognized: (1) dominantly andesitic volcanism of the lower Western Cascade Group (WCG) with comagmatic plutonism in the North Cascades, 50-30 Ma; (2) mixed andesitic and silicic volcanism with continuing plutonism of middle WCG, 30-15 Ma; (3) slightly greater silicic than andesitic volcanism and plutonism culminating WCG, 15-5 Ma; and (4) dominantly basaltic volcanism of High Cascade Group (HCG), 5-0 Ma. Epizonal plutons form two north-trending belts underlying the northern part of the range. Folding in northern part of the range was along northwest to north trends while broad subsidence prevailed in the southern part 50-12 Ma. East-trending Yakima folds were superimposed on the northern part of the range while the southern part continued subsiding 12-5 Ma. Uplift began in the North Cascades possibly as early as 50 Ma, in southern Washington 20 Ma, attaining as much as 1½ km elevation. In the south uplift has been negligible and the HCG accumulation accounts for the topography. With a change in the subduction regime, the style of WCG volcanism shifted to HCG basaltic outpourings along north-south structures and extension pervaded the range, diverging plutonic belts and bowing the range westward in southern Oregon.

This evolution can be traced in a tectonic model which starts with the growth of the Cascade volcanic arc on the back side of the Coast Range-Klamath Mountains block. They rifted from the continent along the Olympic-Wallowa lineament (OWL) and together rotated about a pivot in the Olympic Mountains, with OWL becoming a transition zone between the southern Cascade arc and the stationary North Cascades. Active subduction pressed the northern pivotal end of the block against the continent. Rotation occurred during episodes 1 and 2, with the ranges reaching north-south positions before outpourings of Columbia River Basalt. During rotation the Blue and Ochoco Mountains were dragged northward by the Cascade arc along probable northwest- to west-trending faults and uplifted during Yakima folding. Thinned Mesozoic rocks underlie the central Columbia Plateau; rifted and rafted pre-middle Miocene volcanic rocks underlie southeastern Oregon. Active subduction culminated in episode 3, with wanning subduction and extension characterizing episode 4.

INTRODUCTION

The sprawling tectonic pattern of the Pacific Northwest has puzzled geologists for years. How was a narrow belt of the Cordillera deformed to a Z-shaped orogenic belt (Fig. 1)? When was the belt formed? And what is the tectonic relationship of the oblique Coast and Cascade Ranges to the belt? According to King (1959, 1977), the belt is composed of a series of smaller metamorphic belts and batholiths but is largely covered by broad expanses of volcanic rocks. The belt was formed in the late Mesozoic as part of the Nevadan orogeny. Its northern, or Columbia, embayment was filled with volcanic rocks and accreted to the continent during the Cenozoic. Wise (1963), following the global tectonics of Carey (1958), interpreted the spreading pattern of the belt to have continuously formed since the Paleozoic in response to a regional right-lateral distortion, or megashear, which is causing east-west extension in the Basin and Ranges and north-south compression in the Columbia embayment. Hamilton (1966, 1969) pictured the belt as an orocline that was caused principally by westward extension during the Cenozoic when the Klamath Mountains and Sierra Nevada moved northwestward and the Basin and Ranges spread apart behind them. Hamilton further believed that during the Cenozoic the Mesozoic terrain of northeastern Oregon pivoted away from the Idaho batholith, and that the Cenozoic volcanic rocks of southwestern Washington and northwestern Oregon covered former oceanic crust of the Columbia embayment.

Geophysical studies sustain Hamilton's picture. According to Warren and Healy (1973), the crust thickens from about 15 km beneath the western margin of the Coast Range to more than 30 km along the eastern margin of the Cascade Range (Fig. 1). The Willamette Valley is not a major structure and the ranges lack roots (Thiruvathukal and others, 1970). The crustal thickness beneath the Klamath Mountains ranges from 20 in the west to about 35 km in the east, continuing at that thickness beneath southeastern Oregon. Below the central Columbia Plateau the crust thins to 23 km (Hill, 1972). Deep resistivity studies across the Olympic-Wallowa lineament (OWL in Fig. 1) indicate low resistivity value in north-cental Oregon and high resistivity values in southern Oregon and easternmost Washington (Cantwell and Orange, 1965). In addition, seismic-refraction studies of the upper mantle beneath the central Columbia Plateau (Hill, 1972) and west of the Cascade Range in Washington and northern Oregon (Berg and others, 1966) reveal Vp velocities of more than 7 km/sec. These determinations suggest that granitic crust underlies the Blue Mountains (Thiruvathukal and others, 1970). Basaltic oceanic crust, although thicker than average, is interpreted to underlie the Coast and Cascade Ranges and possibly the southwestern Columbia Plateau and Klamath Mountains.

Refinements of Hamilton's concept were forthcoming. Dickinson (1976) postulated that basaltic seamounts collided with the North American continent during middle Eocene to form the Coast Range and a magmatic arc (the Challis-Absaroka arc of Snyder and others, 1976) stepped rapidly westward from northeastern Washington and central Idaho to form the Cascade Range during middle and late Eocene.

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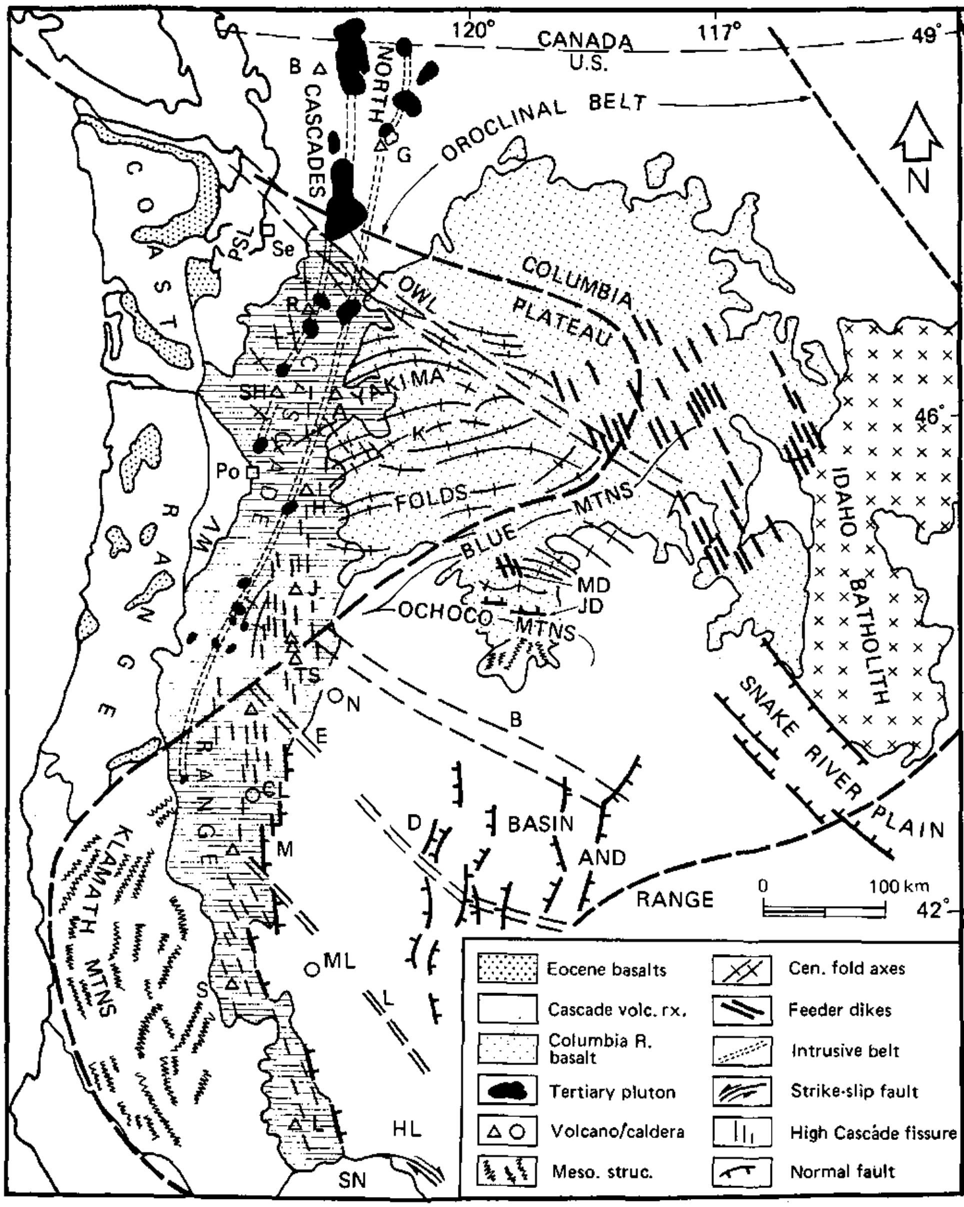


Figure 1. Generalized geologic map of the Pacific Northwest, showing the major Cenozoic tectonic elements, based on King and Beikman (1974), with additions from King (1959), Lawrence (1976), Wright (1976), Walker (1977), Swanson and Wright (1978), and Hammond (1976, 1979a, b), with modifications. Cities: Po=Portland, Se=Seattle. Fault zones: B=Brothers, D=Denio, E=Eugene, HL=Honey Lake, JD=John Day, K=Klickitat, L=Likely. Landmarks: MD=Monument dike swarm, PSL=Puget Sound Lowland, SN=northern end of the Sierra Nevada, WV=Willamette Valley. Volcanoes: A=Mount Adams, B=Mt. Baker, CL=Crater Lake, G=Glacier Peak, H=Mt. Hood, J=Mt. Jefferson, L=Lassen Peak, ML=Medicine Lake caldera, N=Newberry caldera, R=Mt. Rainier, S=Mt. Shasta, SH=Mt. St. Helens, TS=Three Sisters.

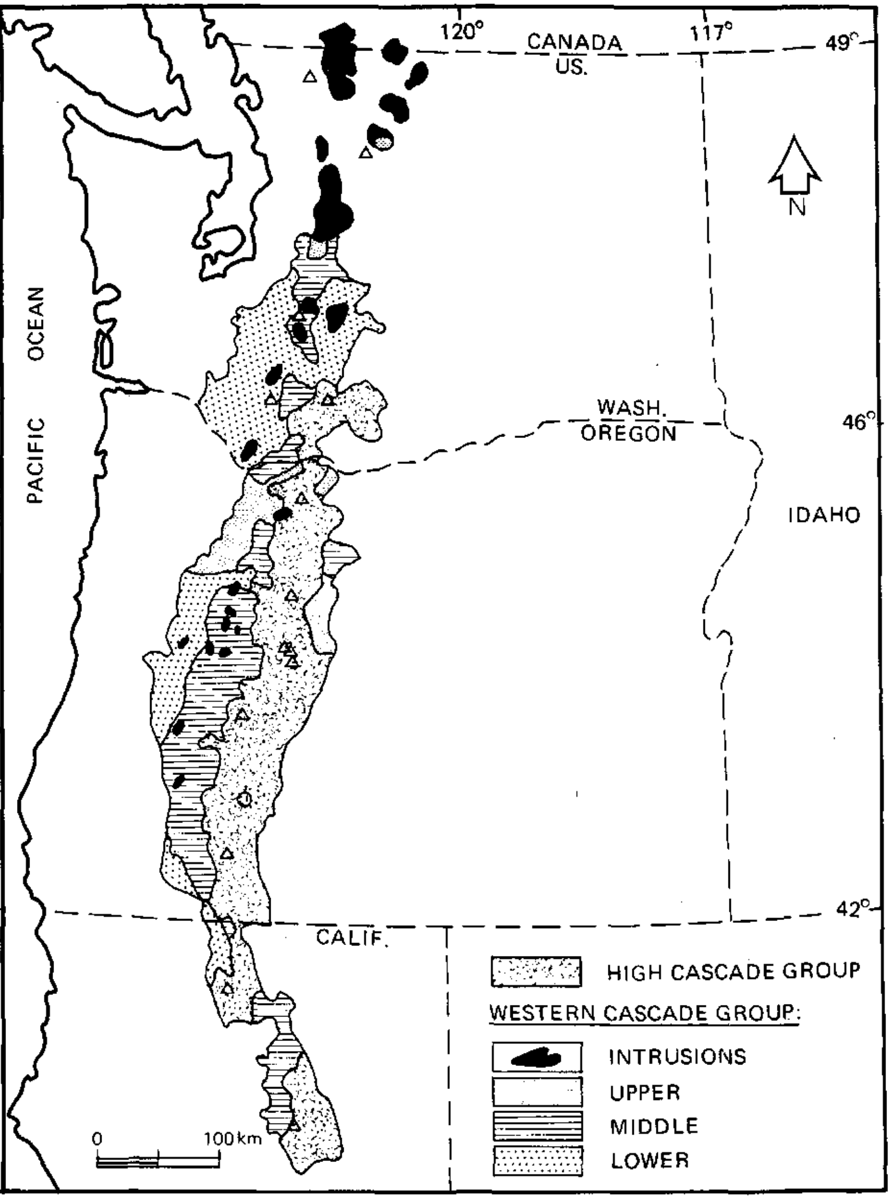


Figure 2. Generalized geologic map of the volcanic Cascade Range, showing distribution of the parts of the Western Cascade Group, High Cascade Group, and Tertiary granitic intrusions; taken from Figure 1 with modifications. Patterns as in Figure 1.

From paleomagnetic directions, Simpson and Cox (1977) determined that part of the Oregon Coast Range rotated about 70° clockwise into position during middle Eocene to middle Miocene. They proposed two paleogeographic models to explain the position of the Coast Range. In model 1, the Coast Range block, as a slab of oceanic plate undergoing subduction, rotated during early Eocene from a southern point near the Klamath Mountains. The block rafted against the continent by middle Eocene but continued to rotate until middle Miocene. In model 2, after being rafted against the continent in middle Eocene as an oceanic aseismic ridge, the Coast Range, together with the Klamath Mountains, thereafter rotated from a point at its northern end. During this time the Blue Mountains rafted away from the Idaho batholith, creating gaps which were filled with old crust or volcanic rocks, most of which were eventually covered by younger volcanic rocks. Model 2 follows Hamilton's concept. Although both models have major unresolved problems (Simpson and Cox, 1977), evidence that the Coast Range has rotated is convincing. Choiniere and others (1976), Cox and Magill (1977), and Plumley and Beck (1977) show that a large segment of the Coast Range has rotated as a unit, as suspected by Simpson and Cox. If the Coast Range has rotated, how has the Cascade Range formed? Possibly as a separate tectonic element, as Dickinson (1976) proposed, during the same time interval in which the Coast Range rotated? Model 2 of Simpson and Cox seems to best answer these questions, for at least three reasons. (1)Early to middle Eocene marine basalts of the Olympic Mountains contain interstratified subaerial flows and are overlain and interbedded with sediments containing dioritic boulders and plant debris (Cady, 1975). Similar interbedded sedimentary rocks containing fossil tree leaves also occur in middle to late Eocene Tillamook basalts of the northern Oregon Coast Range (Nelson and Shearer, 1969). These stratigraphic associations require that deposition of the basalts, along a large segment of the range, was near the continental margin, a condition satisfied in model 2. Furthermore, thick sections of similarly derived sediments from granitic and metamorphic terrains are interbedded with the lower part of the volcanic strata composing the Cascade Range in central Washington and southernmost Oregon. These sedimentary rocks indicate that the Cascade Range developed initially on or near the continent, a condition also satisfied by model 2. (2)Although the Coast Range and Cascade Range overlie different crustal thicknesses, suggesting different tectonic settings (M. E. Beck, Jr., 1978, personal communication), late Eocene to middle Oligocene strata extend from the Cascade Range and overlap the Coast Range in Oregon (Hoover, 1963; Wells and Peck, 1961) and in southwestern Washington (Snavely and others, 1958; Roberts, 1958), indicating that the ranges lay adjacent during part of the Coast Range rotation. This relationship requires that the Cascade Range also rotated. (3)Lastly the evolution of the Cascade Range in the light of its stratigraphic development and structural framework is accommodated in model 2. A speculative elaboration of model 2 is briefly as follows:

A volcanic arc, consisting of a linear volcanic field of largely andesitic stratovolcanoes, extending across continental and possible oceanic crust, and generated by the subduction of Pacific oceanic lithosphere, formed initially on the eastern, back side of a coastal block, recognized as the Coast Range-Klamath Mountains. The arc assemblage composes the Western Cascade Group, the lower stratigraphic unit underlying the Cascade Range. With rotation during middle to late Eocene, the coastal block and volcanic arc split, or rifted, from the North American continent along a zone now part of the Olympic-Wallowa lineament. Together coastal block and Cascade arc rotated westward against an active subduction zone, arriving at approximate north-south positions in middle Miocene. The volcanic arc was partly uplifted and capped by volcanic rocks of the High Cascade Group to form the Cascade Range, under conditions of wanning offshore subduction during Plio-Pleistocene.

FRAMEWORK OF THE CASCADE RANGE

The Cascade Range extends about 1100 km from Mount Garibaldi in British Columbia southward to Lassen Peak in northern California (Fig. 1). The 250-km long North Cascades, bounded on the south by the Olympic-Wallowa lineament (OWL) at Snoqualmie Pass, is composed predominantly of pre-Cenozoic sedimentary, metamorphic, and plutonic rocks. Remnants of Tertiary volcanic rocks occur locally; granitic plutons are abundant. The North Cascades, like the entire range, are crowned by snow-clad stratovolcanoes, Glacier Peak, Mount Baker, and Mount Garibaldi. In contrast, the southern 850-km extent is underlain almost exclusively by Cenozoic volcanic and intrusive rocks, forming the volcanic Cascade Range. The volcanic rocks are separated stratigraphically into a Western Cascade Group (WCG) and a High Cascade Group (HCG; Callaghan, 1933; Williams, 1942, 1957; and Peck and others, 1964). The WCG, of Eocene to early Pliocene, and from about 5 to 8½ km thick, consists chiefly of calc-alkaline andesite, rhyodacite, and lesser basalt, in the form of lava flows, pyroclastic flows, mudflows, and volcaniclastic deposits. Pyroclastic flows have wide geographic distribution, form marker beds, and thus serve to subdivide the group into lower, middle, and upper parts. The strata are gently to moderately warped, dip commonly ranging from 5 to 45°, forming broad to narrow, open upright, parallel folds. Locally the strata are faulted and intensely fractured. They are altered hydrothermally (Grant, 1969; Peck and others, 1964), and converted locally to clays and zeolites, especially in deeper stratigraphic levels (Wise, 1961; Fiske and others, 1963; Hartman, 1973), making K-Ar dating uncertain and questionable. In addition, these strata are intruded by hundreds of dike complexes, many of which probably form the roots of former volcanoes, and a number of epizonal (high-level) granitic plutons, of mostly quartz diorite, some as large as batholiths, forming two north-south belts (Fig. 1). The WCG forms the bulk of the range, covering the entire width of the range in southern Washington and more than half the western width of the range in Oregon and northern California (Figs. 2, 3). Perhaps the group is misnamed, because, in addition to its extension across the range in southern Washington, the strata are traceable into the base of Mount Jefferson (Hammond, 1976) and reappear eastward in the Mutton Mountains in northern Oregon (Wells and Peck, 1961). Similar strata which may be correlative crop out as Pliocene volcanic rocks east of Klamath Falls in southern Oregon (Peterson and McIntyre, 1970).

In contrast to the WCG, the HCG is composed predominantly of high-alumina olivine basalt and basaltic andesite which have erupted from many shield volcanoes and cinder cones. Also present are small amounts of hornblende and/or pyroxene andesite, forming scattered generally older eroded volcanoes and linearly disposed youthful pyroxene andesite and dacite stratovolcanoes. This group is of Plio-Quaternary age and has an accumulated thickness averaging ½ km. Rocks are fresh, undeformed and retain positions of original dip, except where locally flexed and faulted chiefly along north-trending zones. Dikes and plugs are

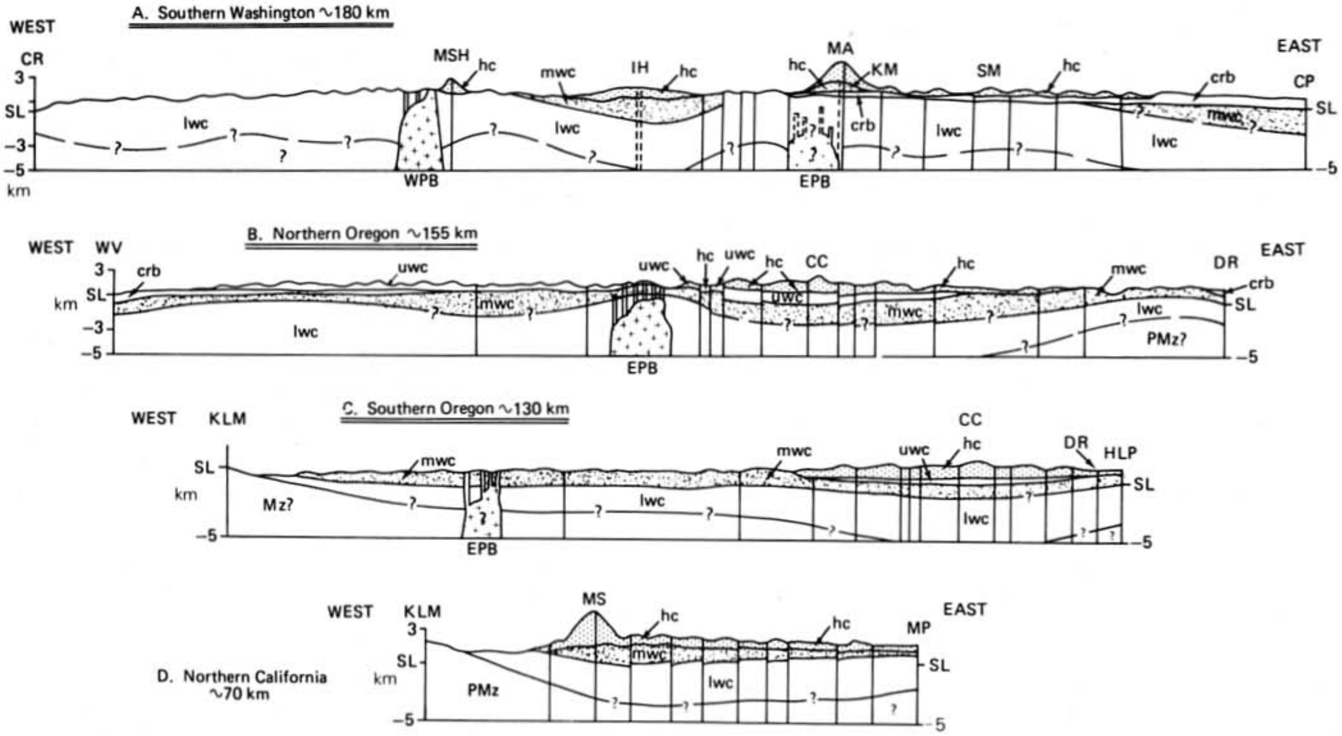


Figure 3. Schematic cross-sections of volcanic Cascade Range, showing main stratigraphic units and structures. Each section is drawn through the approximate middle of designated part of Cascade Range. Major nearby landmarks are projected into section. Vertical exaggeration about 1.6x. Landmarks: CC=Cascade crest, CP=Columbia Plateau, CR=Columbia River, DR=Deschutes River, HLP=High Lava Plain, IH=Indian Heaven fissure zone, KLM=Klamath Mountains, KM=King Mountain fissure zone, MA=Mount Adams, MP=Modoc Plateau, MS=Mount Shasta, MSH=Mount St. Helens, SM=Simcoe Mountains, WV=Willamette Valley. Rock units: crb=Columbia River Basalt, EPB=eastern plutonic belt, hc=High Cascade Group, lwc=lower Western Cascade Group, mwc=middle Western Cascade Group, Mz=Mesozoic rocks, PMz=Paleozoic-Mesozoic rocks, uwc=upper Western Cascade Group, WPB=western plutonic belt.

sparse except where defining eroded volcanic centers. The HCG generally underlies the crest of the range, forming a narrow belt in Oregon and northern California and extending discontinuously northward in Washington.

Stratigraphy of the Cascade Range

Western Cascade Group

The WCG is subdivided stratigraphically into a lower, middle, and upper part (Figs. 2-4). The middle part is distinctive, consisting predominantly of interstratified pyroclastic and lava flows, whereas the lower and upper parts contain mixed lithologies. Where units underlie or overlie sequences of pyroclastic flows, they are assigned to the lower or upper part respectively. An additional subdivision of the group is the large volume of intrusions, which intrude all stratigraphic parts, were emplaced during the same time, and because they are also petrographically and chemically similar, are considered to be comagmatic.

Lower Part

The lower part of the WCG is 1½ to 5 km thick and consists of, in order of abundance, andesitic, basaltic, and silicic volcanic rocks. This part is exposed chiefly along the western margin of the range except in Washington (Fig. 2). Thick sequences of basalt lava flows compose broad shield volcanoes, such as the Goble volcanic rocks (Wilkinson and others, 1946), whereas andesitic lava flows form the broad base of stratovolcanoes recognized in the Mount Wow and Sarvent complexes of Mount Rainier National Park (Fiske and others, 1963). The lava sequences give way eastward to thick accumulations of volcaniclastic rocks, including lithic-rich mudflow deposits, well-bedded lacustrine, fluvial, and minor air-fall tuff beds. The volcanic centers from which the rocks originated thus appear to lie along the western margin of the range. Although mapping is chiefly reconnaissance the number of lenticular lava complexes of andesite greatly exceed those of basalt, indicating that the stratovolcanoes predominate over shield volcanoes.

Northeast of Mount Rainier correlative strata of the Ohanapecosh Formation (Vance and Naeser, 1977; Fig. 4) contain sedimentary rocks derived from a granitic-metamorphic terrain bordering the north end of the volcanic belt. A small amount of similar nonvolcanic sedimentary rocks are also interstratified in the base of the Colestin Formation, along the California-Oregon border, indicating the presence here of nearby granitic terrain, probably the Klamath Mountains.

Few epizonal granitic plutons are exposed among the lower WCG in Oregon. However, many are present in the North Cascades and the remnant silicic pyroclastic rocks here indicate that probably some plutons broke through to the surface. The maximum age obtained from these strata is 45 Ma; the minimum age is 30 Ma (Fig. 4). Therefore, the age range of the lower part of the WCG is placed at about 50 to 30 Ma.

Middle Part

The middle part of the WCG, ranging from ½ to 3 km thick, consists of interstratified light-colored pyroclastic flows, beds of volcaniclastic rocks including mudflow deposits, and dark-colored pyroxene andesite and a few basalt lava flows. Pyroclastic rocks and lava flows form about equal volumes. The middle part is separated from the underlying part by a regional unconformity marked generally by a basal pyroclastic flow. Pyroclastic flow sequences range up to as much as 3000 m thick locally. Separate pyroclastic flows extend discontinuously for distances up to 40 km.

The pyroxene andesite lava flows, in lenticular sequences 200 to 800 m thick, commonly form the base and apron of broad stratovolcanoes, such as Tieton volcano (Swanson, 1966, 1978) in the Washington Cascades. In areas where the lavas are thin or lacking, the stratigraphic interval is occupied by a distal volcaniclastic facies consisting chiefly of andesitic mudflow and conglomerate deposits, which are assigned to the Eagle Creek Formation (Wise, 1970). Interbeds of Eagle Creek lithology occur with the Grande Ronde lava flows of the Columbia River Basalt in the north-Oregon Cascades (J. L. Anderson, 1978, personal communication), indicating that outpouring of the basalt to the east began before cessation of middle Western Cascade deposition.

The interstratified sequences of pyroclastic and andesitic lava flows, characteristic of the middle part of the WCG, indicates that volcanism consisted chiefly of eruptions from stratovolcanoes and probably calderas. These deposits extend across the range, particularly in Oregon (Fig. 2), and suggest that volcanoes were widely distributed. The greater abundance of pyroclastic flows in the middle part in comparison with the lower part of the WCG indicates increasing emplacement of silicic magma. Sequences of the pyroclastic flows have been assigned to the Stevens Ridge Formation in Washington (Fiske and others, 1963; Hammond, 1979a) and to the Breitenbush Formation in the northern Oregon Cascades (Thayer, 1936, 1939; Hammond, 1976). Sequences of the lava flows have been assigned to the Fifes Peak Formation (Fiske and others, 1963; Swanson, 1966, 1978). In the southern Oregon Cascades the units are intimately interstratified and mapped together, for example, as the Little Butte and Heppsie formations (Wells, 1956). Oldest and youngest dates obtained from the strata are 28 and 16 Ma respectively (Fig. 4). The age range of the middle part of the WCG is, therefore, placed at about 30 to 15 Ma.

Upper Part

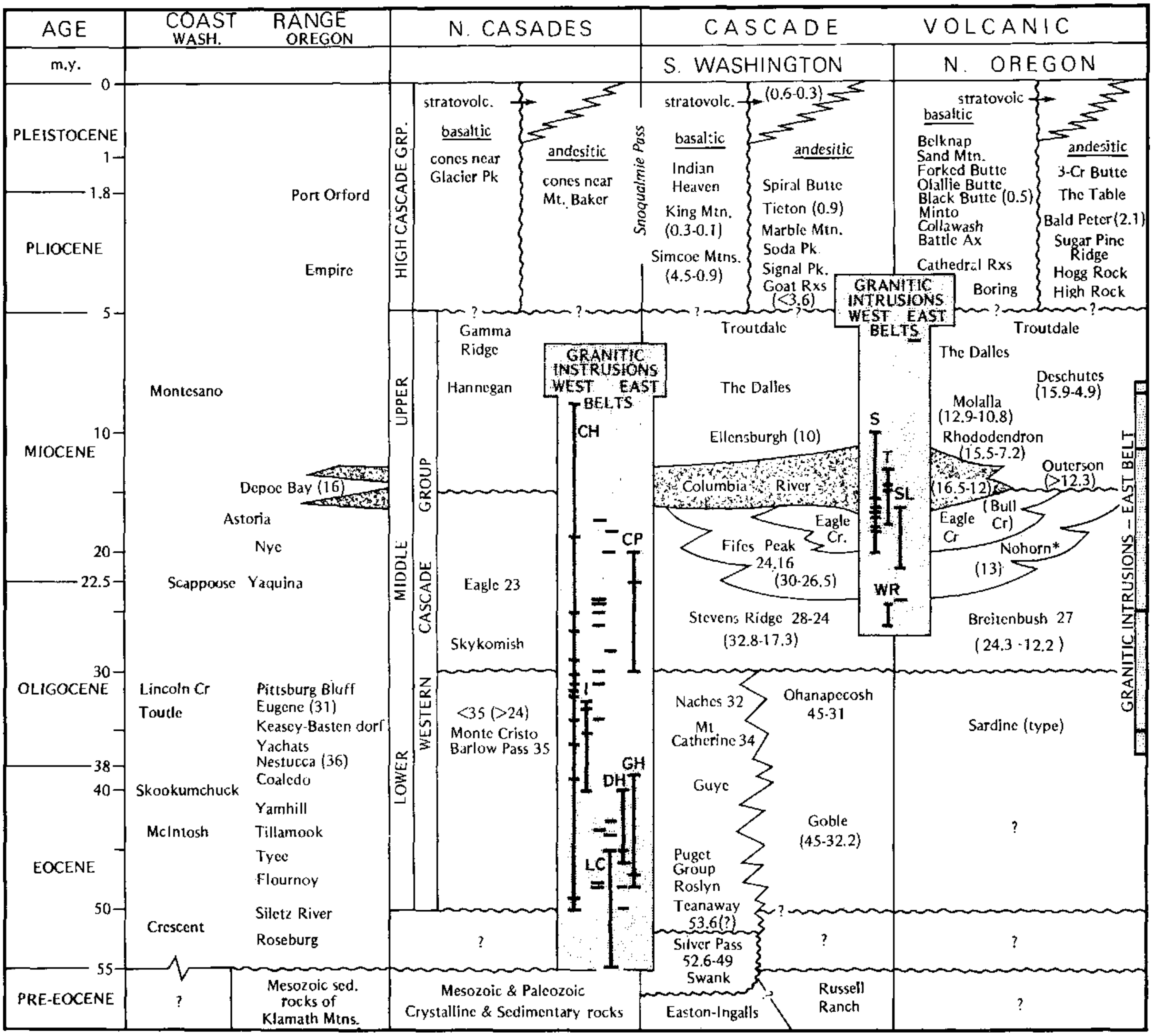
The upper part of the WCG consists predominantly of interstratified varicolored hornblende dacite and andesite pyroclastic flows, mudflows, and fluvial volcaniclastic deposits, and brown to gray pyroxene andesite porphyry lava flows. Distribution of the upper part is sporadic and is probably more extensive beneath the HCG. The basal strata, although not distinctive lithologically, generally rest unconformably upon beds of the middle WCG. Thickness of the upper part ranges from 1/4 to 3/4 km. Lava flows of Columbia River Basalt are interstratified with the upper part in southern Washington and northern Oregon. Excluding Columbia River Basalt, the rocks of the upper part may be the most silicic of the WCG, although locally derived basalt lava flows occur increasingly upsection along the eastern margin of the northern Oregon Cascade Range (Hales, 1974). Most rocks of the upper WCG appear to have erupted from stratovolcanoes and probable calderas. The silicic volcanic rocks represent a continuation of the high-level magmatism of the middle part of the WCG. Dates from the rocks range from 15.9 to 4.9 Ma; accordingly the age limits of the upper part of the WCG are about 15 to 5 Ma (Fig. 4).

Granitic Intrusions

The granitic intrusions were emplaced during formation of the WCG, between about 50 and 10 Ma (Fig. 4), and consequently are considered to be comagmatic. The main intrusions consist chiefly of biotite-hornblende quartz diorite and granodiorite, pyroxene diorite, and lesser quartz monzonite and granite, and are surrounded by a plethora of hornblende and/or pyroxene andesite porphyry and dacite dikes (Buddington and Callaghan, 1936; Fiske and others, 1963; Tabor and others, 1968, 1969; Erikson, 1969; Hammond, 1979a). The granitic plutons form two belts extending southward from the Canadian border, a western belt ending near Portland, and an eastern belt continuing along the western slope of the Oregon Cascade Range (Figs. 1-3). Their projections diverge southward. An elongated zone of hydrothermal alteration coincides with the belts, especially in Oregon (Peck and others, 1964). Of the two belts, the western belt is slightly younger; most plutons in Washington were emplaced between 35 and 15 Ma, with the overall age decreasing southward (Fig. 4). The eastern belt was emplaced generally between 50 and 25 Ma in Washington but plutons as young as 8 Ma occur in Oregon. Because of the abundant plutons exposed in the deeper stratigraphic levels of the WCG in Washington and the abundance of silicic pyroclastic flows in Oregon and northern California, more plutons probably underlie this part of the range than are exposed.

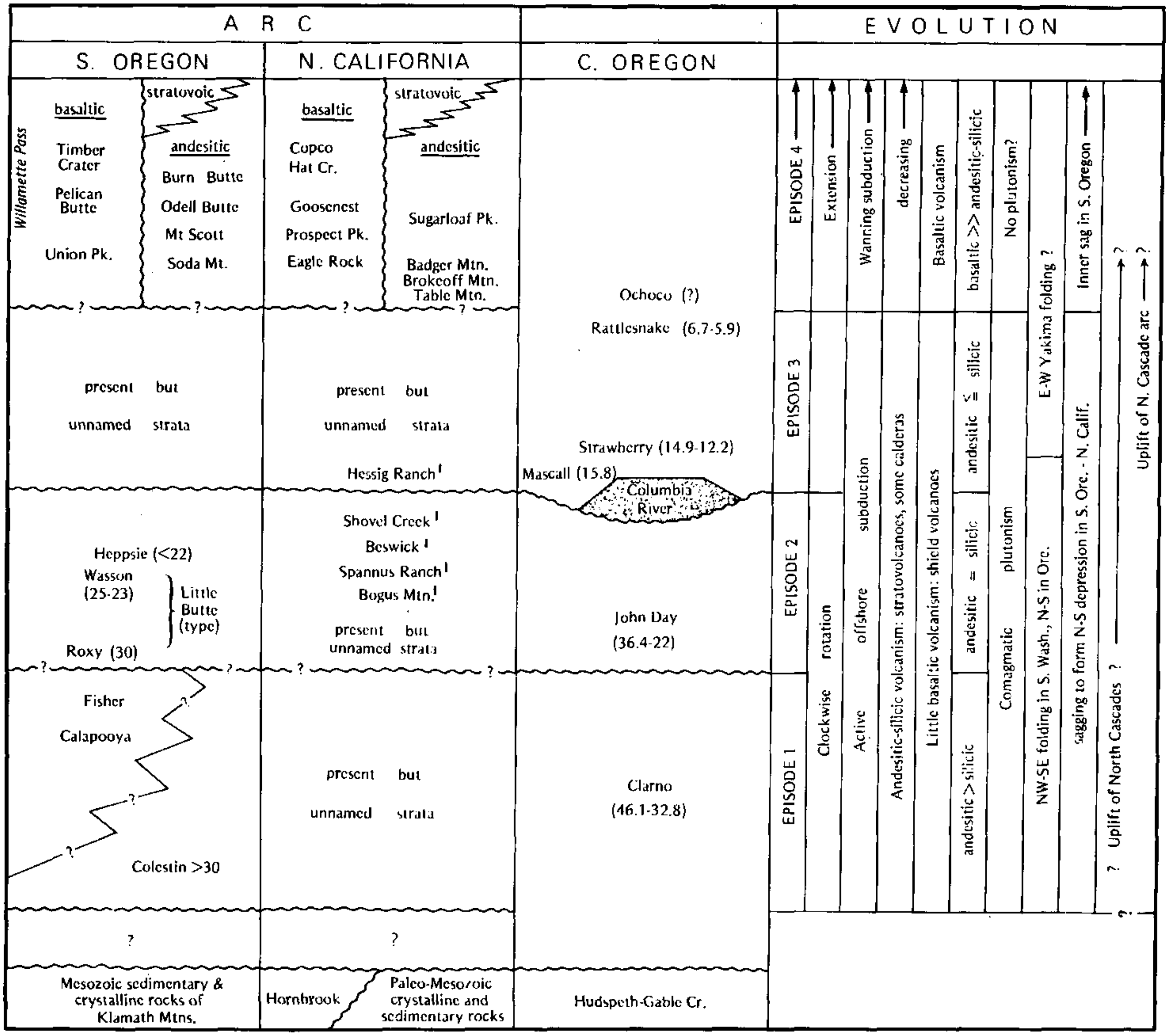
High Cascade Group

The HCG consists of about 85 percent high-alumina olivine basalt and basaltic andesite and about 15 percent hornblende and/or pyroxene andesite and lesser dacite (McBirney, 1978). Rocks of different compositions are interstratified and unconformably overlie the WCG (Figs. 2-4). The high-alumina olivine basalt and basaltic andesite (see analyses of Thayer, 1937; Sheppard, 1960; Waters, 1962; Greene, 1968; Wise, 1969, 1970; and McBirney, 1978) have erupted from many cinder cones and shield volcanoes and coalesce to form a platform, about ½ to 1 km thick, along the crest of the range from Mount Adams southward. These rocks have erupted intermittently, commonly as single eruptive episodes from each volcanic center, since about 4.5 Ma (Fig. 4). Their distribution delineates the extent of the HCG, which forms an almost contiguous belt about 45 km wide (Figs. 2, 5). Some eruptive centers lie outside the belt but are too small to show in Figure 2. Most high-alumina olivine basalt and basaltic andesite have erupted along north-south crater rows or fissure zones, e. g., the Indian Heaven and King Mountain zones in Washington (Hammond, 1979a; Fig. 3A), Sand Mountain row (Taylor, 1968), and the chain south of Bachelor Butte (Peterson and others, 1976) in northern Oregon. Elsewhere single cones and shield volcanoes are breached along north-south fissures, e. g., Forked Butte, south of Mount Jefferson (B. L. Gannon, 1978, personal communication). Regionally, the number of fissure zones and volcanic centers erupting high-alumina basalt and basaltic andesite diminish northward in Washington (Hammond, 1979a), with only three centers located north of the OWL. To the south of the OWL the number of centers increases as does the thickness and the width of the High Cascade belt, reaching a maximum in southern Oregon (Fig. 5). From



*Informal stratigraphic name (Hammond, 1976).

Figure 4. Stratigraphic Framework of the Cascade Range. Major formational units of the Western Cascade Group and location names of rock units of the High Cascade Group are arranged in columns according to regional subdivisions of the range--North Cascades of Washington; and volcanic Cascade Range: southern Washington, northern Oregon, southern Oregon, the latter two are separated at Willamette Pass, and northern California. The column on the left for the Coast Range (from Wells and Peck, 1961; Baldwin, 1976; Huntting and others, 1961) gives stratigraphic units south of the Olympic Mountains and serves as a reference to probable correlative units. The North Cascades column is from Misch (1966), Tabor and Crowder (1969), and Vance and Naeser (1977). Column for central Oregon (from Walker, 1977) shows probable correlative units with Western Cascade Group and associated units which originated in region. The units are shown according to age in approximate stratigraphic order. The vertical boxes between the columns represent the time spans of emplacement and solidification of the granitic intrusions in the western and eastern plutonic belts. The ticks indicate dates on the plutons. A vertical line connecting ticks is the time span of an individual pluton: Ch=Chilliwack, CP=Cloudy Pass, DH=Duncan Hill, GH=Golden Horn, I=Index, LC=Leroy Creek, S=Snoqualmie, SL=Spirit Lake, T=Tatoosh, and WR=White River. The High Cascade Group is separated into two types in each column: basaltic (olivine basalt and basaltic andesite) on left, and andesitic (andesite and dacite) with young stratovolcanoes at top, on right. Numbers are ages: range of fission-track (F-T) age is shown first, followed by K-Ar age in parentheses. Almost all dates on plutons are K-Ar. A F-T date on a formational unit of the Western Cascade Group older than 15 Ma is preferred to the K-Ar date on the same unit because of diagenesis and widespread hydrothermal alteration of these older rocks. The K-Ar date in most cases is younger. Radiogenic ages are from Laursen and Hammond (1974, 1978, 1979), Frizzell and Tabor (1977), Robyn and others (1977), Vance and Naeser (1977), Smith (1977), and J. S. Vance and M. E. Beck, Jr., (1978, personal communica-



¹Informal stratigraphic name (Hammond, 1979b).

tions); some were provided by the Mobil Oil Corporation, Denver. Rock units underlying the Western Cascade Group are shown across the bottom of the figure. The column on the right summarizes the episodes of volcanism, plutonism, and deformation in the evolutionary tectonic model of the Cascade Range.

Mount Jefferson southward, possibly as far as California, the age of basaltic volcanism appears to vary across the range. In general oldest rocks lie along the margins; the youngest lie in the center coinciding approximately with the line of High Cascade stratovolcanoes, but there are many exceptions.

Some hornblende and/or pyroxene andesite and minor dacite form older, deeply eroded volcanic centers that are disposed irregularly along the range; some are outside the belt of the HCG. These rocks appear to form some of the oldest strata of the HCG, although none are specifically dated. An age of 3.6 Ma for Goat Rocks, southern Washington (Fig. 4), is based on the tentative correlation of a welded tuff 12 km to the southwest with pyroclastic rocks at the base of the Goat Rocks volcanic complex (Hammond, 1979a). Some andesites were forerunners to the present High Cascade stratovolcanoes, and are either partly buried, e. g., Sandy River volcano at Mount Hood (Wise, 1969), or wholly buried with only vestiges remaining, as in the Andesite of Bee Flat at Mount Rainier (Fiske and others, 1963). At other locations these rocks form youthful volcanoes, such as Spiral Butte in Washington (Hammond, 1979a). Thus, the hornblende and/or pyroxene andesite and dacite have as long a history of eruptions as the voluminous high-alumina olivine basalt and basaltic andesite.

Pyroxene andesite, dacite, and a little basalt constitute the imposing cones of the present stratovolcanoes. No rocks of these volcanoes have been dated paleomagnetically older than 690,000 y. (McBirney, 1978). The oldest K-Ar date is 600,000+60,000 y. on andesite of Mount Rainier (Crandell and Miller, 1974). These rocks are probably the continuation of

Latitude	km
Mount Adams, Washington (not including Simcoe Basalt field)	25
Mount Hood, Oregon (not including Boring Basalt)	35
Mount Jefferson	40
North Sister	50
Diamond Peak (Willamette Pass)	55
Crater Lake	60
Average width	44.2
Mount McLoughlin	30*
Mount Shasta, California	45*
Lassen Peak	35*

Figure 5. Width of volcanic belt of the High Cascade Group measured along latitudes through High Cascade stratovolcanoes. Width increases southward except where* foreshortened by faulting along eastern margin.

the volcanic pattern established with eruption of the hornblende and/or pyroxene andesite and dacite. The low volume of these rocks in comparison with the WCG and with concomitant basaltic rocks suggests a change in the subduction regime. This change is related to a deceleration in the rate of subduction beginning about 8 Ma (Atwater, 1970) and is reflected in a shift from andesitic to basaltic volcanism (Lipman and others, 1972; Snyder and others, 1976). The stratovolcanoes are probably the products of remnant magmatism under conditions of wanning subduction.

Structures of the Cascade Range

Strata of the WCG are gently to moderately folded and faulted. In contrast strata of the HCG are generally undeformed, are flat-lying or gently inclined away from volcanic centers, except along north-south fault zones and a flexure zone between Mount Jefferson and the California border.

Folding

Within the WCG of southern Washington two fold patterns are superimposed. An older northwest trend of open, upright, irregularly spaced folds, whose limbs dip moderately 10 to 45°, is characteristic of the western slope of the range (Fig. 1). This fold pattern parallels the regional structural grain of the pre-Cenozoic terrain of the North Cascades, indicating recurrent deformation along an inherited Mesozoic trend. Narrower folds in which dips commonly exceed 45°, forming open to tight, upright folds, occur along the OWL on both slopes of the range.

A younger fold pattern, part of the Yakima fold system, characteristic of the western Columbia Plateau (Newcomb, 1970), is superimposed on the older northwest fold trend (Fig. 1). On the eastern flank of the range, between the OWL and the Columbia River. the trend splays from northwest to southwest. The southwest trend continues into the Oregon Cascades as far south as Mount Jefferson. To the east the Yakima folds extend into the Blue Mountains. Inasmuch as the Yakima folds involve lava flows of upper Columbia River Basalt, their age of deformation is considered to have commenced about 12 Ma (Kienle and others, 1978a). Deformation producing the Yakima folds appears to have ceased about 5 Ma because fold crests and transecting Klickitat faults (Fig. 1) are overlain by non-deformed Simcoe Basalt (Hammond, 1979a), dated at 4.5 Ma. However, focal mechanism solution to the 1976 Deschutes Valley earthquake indicates that a north-south compressive stress field, possibly similar to that in which the Yakima folds developed, continues to affect the region (Couch and others, 1976).

In the Oregon Cascades from Mount Jefferson southward to Willamette Pass (E, the Eugene fault zone in Fig. 1), a broad gentle fold system extends north-south involving all WCG and the lower strata of the HCG. These lower High Cascade strata dip as much as 5° eastward beneath the crest of the range. From Willamette Pass southward to Mount Shasta the WCG forms a homoclinal sequence in which the lower strata dip eastward as much as 50°, decreasing upsection to less than 20° (Figs. 1; 3C, D). Because Western Cascade strata reappear east of the range in Oregon, dipping westward for the most part, the structural relationship here indicates that a north-south depression underlies the range in southern Oregon (Wells and Peck, 1961; Fig. 3C) and probably in northern California (Fig. 3D).

Southwest of Mount Jefferson and along the contact with the WCG, lower strata of the HCG are locally flexed sharply eastward as much as 40° in a narrow zone which coincides with a pronounced Bouguer gravity anomaly gradient of -50 mgals in 30 km (Berg and Thiruvathukal, 1967). The flexure has not been traced, but the gravity gradient extends southward, flattening appreciably before the California border. The structure appears to form the western limb of a narrow trough of the HCG. This trough lies within the broad depression of Western Cascade strata underlying the southern Oregon Cascade Range.

Faulting

Two principal fault directions occur in the volcanic Cascade Range, one northwest and another north-south (Fig. 1). The northwest trend parallels the older northwest fold pattern in Washington and is believed to have developed concurrently with that fold system (Hammond, 1979a). Many northwest-trending faults occur along the OWL where it crosses the Cascade Range. No evidence of movement on the faults within the last 5 m.y. occurs here. The Klickitat faults offset Yakima fold axes dextrally yet the fault traces are overlain by non-disturbed High Cascade olivine basalt, indicating that movement was principally between 5 and 12 Ma, probably concurrent with Yakima folding (Kienle and others, 1978a). Northwest-trending faults occur on the western slope in Oregon (Wells and Peck, 1961; J. L. Anderson, 1978, personal communication) and abundantly in northern California (Hammond, 1979b). It is unknown if movements on these faults post-date the upper WCG. Where the young northwest-trending fault zones of Lawrence (1976) cross the Oregon range crest no faults can be clearly discerned. The trends are revealed in the topography and show dextral offset of the north-south alignment of structures within the HCG. The Eugene and McLoughlin faults appear to dextrally displace the north-south axis of the range (Fig. 1). The amount of displacement along these northwest zones is concealed by High Cascade volcanic rocks. Most displacement appears to be transferred to the north-south-trending faults characteristic of the range crest.

East-west extension on these north-south faults seems to be the dominant tectonic pattern affecting the HCG and locally the Western Cascade strata.

North-south faults occur in Washington between Mounts St. Helens and Rainier and Goat Rocks, but the most obvious north-south structures are the two fissure zones, Indian Heaven and King Mountain, between Mounts St. Helens and Adams (Fig. 3A; Hammond, 1979a). Additional north-south structures are indicated by the approximate alignment of Soda Peak and Marble Mountain with Mount St. Helens and the centers of the Goat Rocks volcanic complex with Spiral Butte (Hammond, 1979a), and the ellipticity of Mount Adams formed by northward migration of the main crater (Hopkins, 1976). Immediately south of the Columbia River north-south faults are well developed, forming the Mount Hood fault zone (Newcomb, 1969) and possibly outlining the Hood River graben (Allen, 1966). Farther south equally strong north-south faults occur northwest of Mount Jefferson (Fig. 3B; Hammond, 1976; J. L. Anderson, 1978, personal communication) and between Mount Jefferson and Green Ridge, on the eastern slope (Hales, 1974). North-south alignments occur, for example, at The Table, south of Mount Jefferson (B. L. Gannon, 1978, personal communication), in the dacite plugs and flows south of South Sister, and in The Sisters themselves (Williams, 1944). Locally north-south faults along both sides of the crest of the range separate inner-lying HCG from outer WCG. A sharp flexure zone extends along the western margin of the HCG from southwest of Mount Jefferson (near Santiam Junction) to about the California border. However, no evidence of a continuous north-south fault-bounded graben along the crest, as envisioned by Allen (1966), can be delineated. Many north-south structures from Mount Jefferson southward, especially well displayed on the eastern slope, are reflected in crater rows and discontinuous faults cutting cinder cones and shield volcanoes. At Mount McLoughlin the extension faulting turns to the southeast and continues to the Sierra Nevada (Fig. 1). From Willamette Pass (E, Fig. 1; Fig. 3C, D) southward into California the eastern margin of the range is chopped by closely spaced normal faults (Pease, 1969) which cut basalt lava flows of both the HCG and the High Lava Plains (western part of the Basin and Range province), and therefore prevent the tracing and distinction of lava flows which erupted in the Cascade Range. Where faulting is extensively developed, the terrain has been arbitrarily assigned (Wells and Peck, 1961; Macdonald, 1966) to the Basin and Range province, thereby reducing the width of the belt of the HCG (Fig. 5).

The east-west-trending Honey Lake shear zone (Wright, 1976) is the probable southern termination of the range (Fig. 1). It lies within a zone of marked crustal thinning north of the Sierra Nevada (Eaton, 1966), and the fault possibly offsets Mesozoic structures of the Klamath Mountain on the west and the Sierra Nevada on the southeast.

Uplift of the Cascade Range

Only the northern half of the volcanic Cascade Range (southern Washington and northern Oregon) appears to be uplifted. Most of the evidence presented here is based on the assumption that Columbia River Basalt flows were nearly flat-lying and extended into and locally across the range before its uplift in southern Washington and northern Oregon. However, D. A. Swanson (1977, personal communication) points out that part of the apparent uplift of the range may be due to differential subsidence of the lava flows in the Columbia Plateau. South of the OWL the lava flows dip 5-10^{o} eastward, and their projection to the crest of the range indicates possibly as much as 1½ km of uplift since middle Miocene. Part of this uplift may be attributed to uplift of the Russell Ranch block of pre-Tertiary rocks (Hammond, 1979a). The block may have risen differentially with respect to surrounding Western Cascade strata in late Cenozoic time. At Steamboat Mountain, located between Mount St. Helens and Mount Adams, Grande Ronde flows of the Columbia River Basalt Group crop out just below 6000 ft (1829 m) elevation (Hammond, 1979a), indicating as much as 1 km of uplift with respect to the foothills of the Cascade Range. Southward, the average elevation of the basalt lavas decreases to the Columbia River Gorge where a maximum uplift of about 600 m is indicated (compare Fig. 3B, C, D). From the Columbia River southward the eastward dip of the lava flows diminish, suggesting even less uplift than in the Gorge. Wells and Peck (1961) show negligible uplift of the range in Oregon. In their cross-sections the range is interpreted as a trough, composed almost entirely of the WCG, covered at its center by a thin capping of the HCG. A gravity low (Berg and Thiruvathukal, 1967) extends southward beneath the Oregon Cascade Range and reflects this downwarp. From Mount Jefferson southward little evidence exists indicating uplift of the range. The younger High Cascade lavas have flowed down and away from the crest, which is regarded as a topographic high formed largely if not entirely of accumulated volcanic deposits. To the south along the Klamath River, the rim of High Cascade basaltic lavas shows only a 60 m increase in elevation from just west of Copco Lake eastward to the Oregon-California line, a distance of about 25 km (Hammond, 1979b). The lavas bevel east-dipping strata of the WCG. The rim cannot be traced eastward but in another 5 km the lavas are cut by northwest-trending normal faults across which the surface is stepped down to the east. At most the relief on the Western Cascade-High Cascade contact along the Klamath River is 100 m. How much of this represents uparching of the range crest after outpouring of the basaltic lavas and/or relief upon the surface buried by the lavas is not known. Thus, the amount of uplift in the range from central Oregon to northern California appears negligible.

Dating the time of uplift of the range in southern Washington is also uncertain. Much of the strata of the upper WCG, such as The Dalles and Ellensburg (Fig. 4) dip away from volcanic centers and are, therefore, unreliable indications of age of uplift. However, these strata are bevelled by the basal contact of High Cascade lava flows where traced into the range. At best, the age of beginning uplift is estimated to be between 10 and 4.5 Ma, based on the youngest date of unwarped Ellensburg and the oldest age of Simcoe Basalt which unconformably overlies Ellensburg (Fig. 4; Sheppard, 1967; Hammond, 1979a). However, if uplift is attributed to isostasy in response to a concentration of high-level plutons in the Cascade Range, then uplift may have begun as early as 50 Ma in the North Cascades and 20 Ma in southern Washington. In any case, uplift appears to have climaxed after initiation of Yakima folding because all folds plunge away from the range in southern Washington (Hammond, 1979a) and may have continued until the outpouring of Simcoe Basalt 4.5 Ma.

EPISODES IN THE EVOLUTION OF THE CASCADE RANGE

Four episodes in the stratigraphic and tectonic evolution of the Cascade Range are recognized (Fig. 4). They are summarized as follows:

Episode 1, occurring 50 to 30 Ma, corresponds to the lower WCG. During this time andesitic and some silicic volcanism dominated activity within the 1100-km long belt. Eruptions were centered at stratovolcanoes. Basaltic volcanism at shield volcanoes was minor. Volcanic rocks were locally interstratified with terrigenous sedimentary rocks. Epizonal granitic plutonism began at the same time in the North Cascades. The strata were folded and faulted along a northwest trend in the northern part of the belt (Washington) and along a north-south trend in the central part of the belt (northern Oregon), whereas a north-south subsidence commenced, forming a broad trough, in its southern part (southern Oregon-northern California). Structures in the north developed under a compressive stress. To the south extension prevailed, and the volcanic belt gradually attenuated. Uparching in the North Cascades probably began at this time, accompanied by vigorous erosion.

Episode 2, lasting from 30 to 15 Ma, is characterized by deposition of the middle WCG. Widespread andesitic and silicic volcanism, now in about equal volumes, continued. Volcanism was centered at many randomly spaced stratovolcanoes and probable calderas. Columbia River Basalt lava began to flow into the central part of the belt (southern Washington and northern Oregon) towards the end of the episode. Emplacement of epizonal granitic plutons continued, increasing in number and extending southward along the belt. Deformation continued along the northwest trend in the northern part of the belt, in the North Cascades and southern Washington, and along the north-south trend in the middle part of the belt, while gradual subsidence continued in the southern part, under the prevailing regional stresses established in episode 1. Uparching continued in the North Cascades and spread along the belt to southern Washington about 20 Ma.

Episode 3, between 15 and 5 Ma, is represented by deposition of the upper WCG. Andesitic and slightly greater silicic volcanism continued and became concentrated probably at widely spaced large stratovolcanoes and a few calderas. Basaltic volcanism at shield volcanoes was subordinate but more abundant than during episode 2. During this episode granitic plutonism culminated. Columbia River Basalt lava flows continued to intermittently flood the central part of the belt and interstratified with Cascade rocks until about 10 Ma. Deformation continued along the established northwest and north-south structural trends. Between about 12 and 5 Ma a shift in the regional compressive stress field east of the volcanic belt formed the east-west-trending Yakima fold system, which was superimposed on the older fold pattern in southern Washington-northern Oregon. This regional stress probably continues today to affect the area east of the range. Subsidence continued in the southern part of the belt. Uparching of the northern part of the range culminated about 5 Ma.

Episode 4, covering the last 5 m.y., denotes a decrease in widely scattered andesitic-dacitic volcanism at stratovolcanoes and a few domes and calderas. Abundant basaltic shield volcanoes and cinder cones, many aligned north-south as crater rows, dominate the volcanic belt, now the Cascade Range. These rocks form the HCG. The andesitic-dacitic volcanoes are scattered the length of the range but basaltic volcanoes are more abundant south of Mount Rainier. North-south structures, generally normal faults and the crater rows, characterize the deformation during this time, indicative of prevailing east-west extension. Northwest-trending faults penetrate the eastern slope of the range in Oregon and dextrally offset the north-south structures. Extension bows the range westward in southern Oregon.

ORIGIN OF THE CASCADE VOLCANIC BELT

Recent papers (Atwater, 1970; Lipman and others, 1972; Church, 1973, 1976; Dickinson, 1976; Snyder and others, 1976; McBirney, 1978) on plate tectonics of the Pacific Northwest and the Cascade Range conclude that the range is a volcanic arc, that its volcanic rocks are products of the subduction of the Juan de Fuca plate, and that the arc formed initially between 35 and 60 Ma. The WCG has characteristics indicative of a volcanic arc origin. First, its rocks comprise a calc-alkaline suite in which andesite predominates and silicic rocks and basalt are subordinate. The bulk whole-rock chemistry of the rocks averages 60 percent SiO_2 (Peck and others, 1964; McBirney, 1978). Second, rocks of the WCG contain an average initial $^{87}Sr/^{86}Sr$ ratio of 0.7036 (Hedge and others, 1970). This ratio compares favorably with analyzes of island arc rocks, indicating little to no contamination with crustal rocks during their genesis (Church, 1976). Third, magnetic profiles of the ocean floor off the Oregon-Washington coast reveal that between 50 and 8 Ma the Juan de Fuca plate has been subducted beneath the North American plate (Atwater, 1970).

The linear array of calc-alkaline andesitic-dacitic stratovolcanoes and associated high-alumina basalt, forming the HCG, is generally considered characteristic of a volcanic arc (Miyashiro, 1974; Church, 1973, 1976; McBirney, 1978). An average initial $^{87}Sr/^{86}Sr$ ratio of 0.7035 is indicative of an uncontaminated mantle origin (Hedge and others, 1970; Peterman and others, 1970; McBirney, 1978). The bulk whole-rock chemistry of the High Cascade rocks, which averages 52.5 percent SiO_2 (McBirney, 1978), differs markedly from the WCG. This difference suggests a change in the tectonic evolution of the range, possibly a transition, from formerly a more silicic and mature to presently an immature volcanic arc (Jakeš and White, 1972), or, because of the concentration of north-south extensional faulting, to a rifting volcanic zone (Lipman and others, 1972; Snyder and others, 1976). In any case, this change in the style of Cascade volcanism accompanies a shift in the direction of movement of the Pacific plate and a decrease in the rate of subduction of the Juan de Fuca plate about 8 Ma (Atwater, 1970). Lack of a well-defined Benioff zone beneath the range, and an indication of a major regional compressive stress oriented north-south and a tensional stress east-west, based on first-motion studies of local earthquakes suggest that the rate of subduction is wanning (Crosson, 1972; Couch and others, 1976).

TECTONIC MODEL

The main features of the Cascade Range which must be integrated into a tectonic model, serving to explain its origin, are listed as follows:

1. The range evolved primarily as a volcanic arc.
2. During its early growth the north and south ends of the arc lay adjacent to granitic-metamorphic terrains.
3. Also during its early growth the range lay along the eastern side of the Coast Range and Klamath Mountains.
4. Lack of shear zones and major strike-slip faults between the Coast Range-Klamath Mountains and the Cascade Range and the mutual overlap of strata suggest that the two tectonic elements developed adjacent to one another and they rotated as a single block with minimal internal adjustments.
5. Widespread continuity, particularly middle Western Cascade strata, indicates that the volcanic arc behaved as a unit and not as separate tectonic blocks

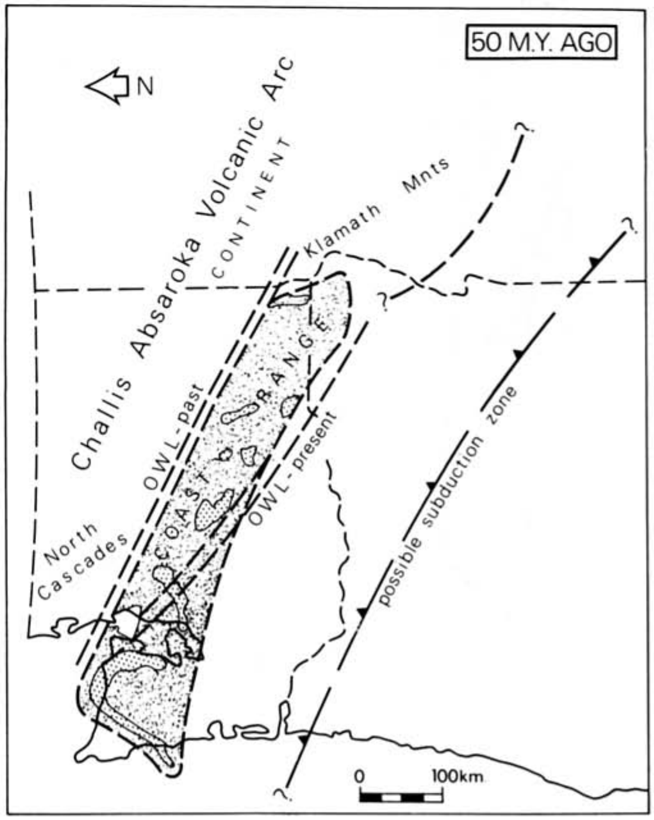


Figure 6. (left, top) Idealized paleogeologic map of Pacific Northwest about 50 Ma, showing approximate position of the Coast Range-Klamath Mountains (coastal block) against continental margin along Olympic-Wallowa lineament (OWL) and possible paleogeographic relationship to the North Cascades and the Challis-Absaroka arc of Snyder and others (1976). Past and present positions of OWL are shown. Position of Coast Range lies about 5° east of present position of OWL, showing amount of Cenozoic extension yet to occur in this region. Compare with Figure 1. Patterns as in Figure 1.

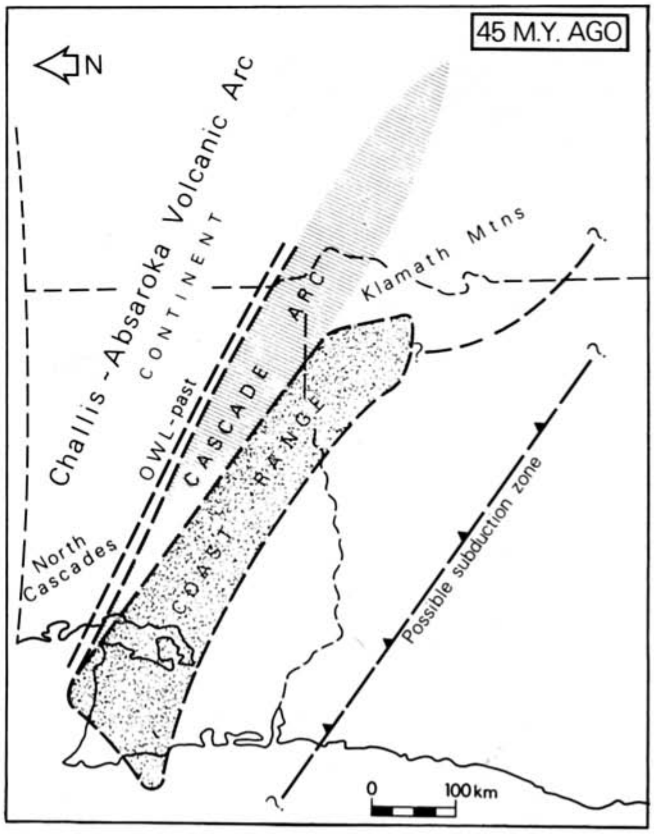


Figure 7. (left, bottom) Idealized paleogeologic map of Pacific Northwest about 45 Ma, after coastal block had rotated about 10° and when Cascade arc was in its infancy, developing within the rift zone along the OWL and on the back (eastern) side of the coastal block. Past position of the OWL is shown; the OWL has since extended westward. Compare with Figures 1 and 6. Challis-Absaroka arc was in final activity as volcanism shifted westward to Cascade arc. Patterns as in Figure 1.

or a segmented volcanic arc.

6. Limited distribution and volume of Western Cascade strata and High Cascade basaltic rocks but a concentration of Tertiary epizonal granitic plutons amid a broad expanse of Mesozoic terrain in the North Cascades indicates that:

a. Western Cascade volcanism had been extensive in the North Cascades;

b. uplift began earlier in the North Cascades, perhaps beginning 50 Ma with emplacement of the plutons; and

c. erosion has been extensive in the North Cascades during the Cenozoic.

Plutons may be equally developed in the southern Cascade Range but are not exposed due to lesser uplift and extensive covering by late Cenozoic volcanic rocks. The narrow transition between essentially Mesozoic North Cascades and the volcanic southern Cascades across the OWL suggests a break in the crustal continuity of the range.

7. Deformation of Western Cascade strata in southern Washington and northern Oregon was under a compressive stress until about 12Ma.

8. A probable tensional stress existed in the arc in southern Oregon and northern California from about 50 to 12 Ma.

9. The generally east-trending Yakima folds were superimposed on the north- to northwest-trending folds of the northern Cascade arc between 12 and 5 Ma.

10. The two belts of granitic plutons appear genetically related to Western Cascade volcanism; their final emplacement appears to match the culmination of Western Cascade deposition. The belts are parallel in the North Cascades but diverge southward, with the western belt terminating in southern Washington. More plutons probably underlie the range, especially in southern Oregon and northern California.

11. Elevation of the northern Cascade Range was due to isostatic adjustment of the eroded Mesozoic granitic crust and/or the concentration of high-level plutons during the Tertiary. Elevation of the southern Cascade Range was due to accumulated volcanic rocks of the HCG.

12. Change from chiefly andesitic volcanism of the WCG to basaltic volcanism of the HCG accompanies a deceleration in the subduction rate of the Juan de Fuca plate.

13. Development of north-south structures characteristic of the HCG is also due to deceleration of the subduction rate and may indicate prevailing regional

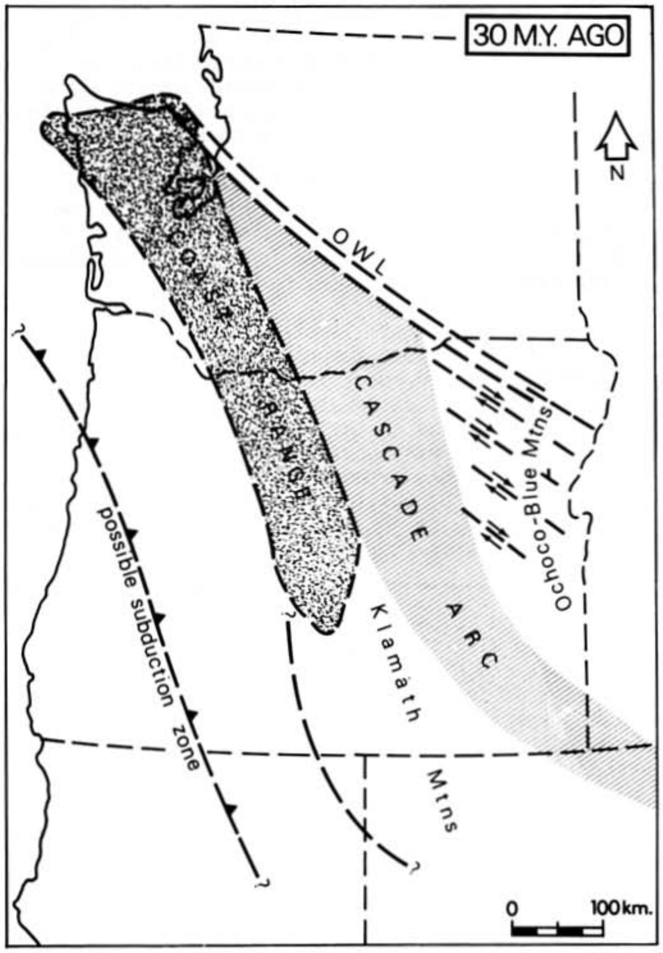


Figure 8. Idealized paleogeologic map of Pacific Northwest about 30 Ma at completion of episode 1 (deposition of lower Western Cascade Group) in evolution of the Cascade Range. Coastal block has rotated about 40°. The OWL is in its present position. Blue-Ochoco Mountains are dragged behind the Cascade arc along dextral-slip faults. Patterns as in Figure 1.

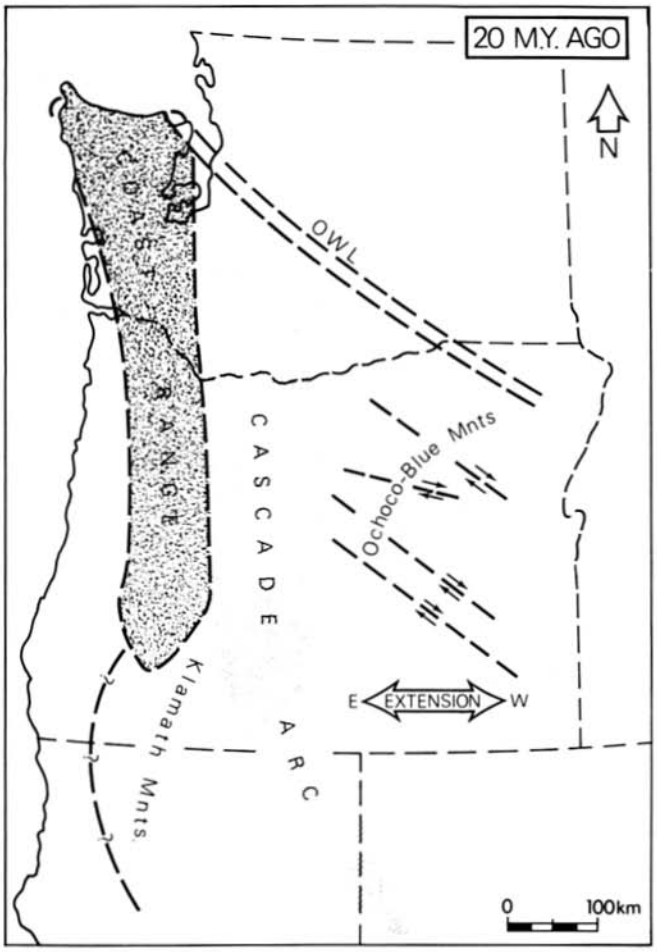


Figure 9. Idealized paleogeologic map of Pacific Northwest about 20 Ma, after coastal block has rotated about 60°, nearing its north-south position. Middle Western Cascade volcanism of episode 2 is also near completion. Blue-Ochoco Mountains are close to their present positions, dragged into place along northwest to west-trending faults. Southernmost fault bordering Ochoco-Blue Mountains may be a forerunner of the Brothers fault zone. East-west extension (backarc spreading) occurred in region south of Ochoco-Blue Mountains.

east-west extension. Extension on the north-south faults accommodates dextral displacement on the northwest-trending faults which penetrate the eastern slope of the range.

14. The volume of basaltic rocks, number of centers, and width of the High Cascade belt decreases northward in Washington. Maximum development of the belt occurs in southern Oregon, suggesting greater east-west extension in the range here.

These features can be accommodated in the second model of Simpson and Cox (1977). This model is elaborated in the following discussion.

The Coast Range-Klamath Mountains, forming a coastal block, rotated as a unit after rifting from the continent along the OWL about 50 Ma (Fig. 6). Shortly thereafter the Cascade Range began to form as a volcanic arc in the rift zone on the back (eastern) side of the coastal block (Fig. 7). During rotation, between about 50 and 15 Ma, the Cascade arc and the coastal block moved together, the point of rotation being the Olympic Mountains, and the OWL becoming the transition zone between rotating Cascade arc and stationary North Cascades (Figs. 7-9). These maps show the probable positions of the coastal block about 45, 30, and 20 Ma, after rotation of about 10°, 40°, and 60°, respectively, assuming a steady rate of rotation of about 2°/m.y. based on the paleomagnetic determinations in Simpson and Cox (1977). Between 50 and 15 Ma the lower and middle parts of the WCG were deposited, completing the first two episodes in the evolution of the Cascade Range. The coastal block and the Cascade arc rotated westward against a subduction zone, overriding the Juan de Fuca oceanic plate, and causing differential stresses along the length of the Cascade arc, in which compression caused folds in the northern part and extension permitted subsidence of the volcanic belt in its southern part. During active subduction the Olympic Mountains, as well as the northern end of the Cascade arc, were pressed against the continental margin at the OWL and subjected to continuous compression. As the Cascade arc rotated, segments of the Blue-Ochoco Mountains were dragged northwestward and westward, first along the OWL, and subsequently along other northwest- to west-trending faults, possibly the Mitchell and John Day faults (Simpson and Cox, 1977; compare Figs. 1, 8, and 9).

By 15 Ma the coastal block and the Cascade arc were approximately in their respective north-south positions and rotation had virtually ceased. The Blue-Ochoco Mountains were likewise in their positions. With the beginning of outpouring of Columbia River Basalt from north-northwest-trending feeder dikes (Swanson and others, 1975, 1978; McKee and others, 1977) and initial rifting of the western Snake River Plain 16½ to 15½ Ma (Armstrong and others, 1975), extension and rifting dominated the backarc region. Lavas of Columbia River Basalt flowed westward and became interstratified with Western Cascade strata of the arc in southern Washington and northern Oregon. Compressive folding continued in the northern part while extension and subsidence continued in the southern part of the arc. Final epizonal plutons were emplaced, culminating the formation of the WCG and completing episode 3 at about 5 Ma. Between about 12 and 5 Ma curvilinear Yakima folds were superimposed on the northern Cascade arc to the west and impinged on the continental margin at the OWL to the north and northeast. Uplift of the northern Cascade arc had been ongoing since perhaps as early as 20 Ma, and neared completion by about 5 Ma. By then the distribution of the tectonic elements and major volcanic units, with the exception of the HCG, were in their approximate present positions.

By about 5 Ma deceleration in the subduction rate of the Juan de Fuca plate caused a change in the style of volcanism and tectonism in the Cascade Range. Extensional faulting appears to have begun then to dominate the structural growth of the range. North-south faults and crater rows along fissure zones formed along the length of the range but are chiefly confined to the crest and eastern slope. Basaltic volcanism developed concomitantly with faulting. Scattered andesitic to dacitic volcanism occurred sporadically, principally along the crest of the range. Together these volcanic rocks form the HCG. Uplift was perhaps stabilized in the northern part of the range. No uplift has occurred in the range in northern California, but in southern Oregon the range continued to sag as previously, the rate of volcanic accumulation here exceeding the rate of subsidence to form a topographic barrier. North-south faults in the range are offset dextrally along the northwest-trending Brothers, Eugene, and McLoughlin faults, which penetrate from the east but do not transect the range. Extension appears greater in southern Oregon where the High Cascade belt is wider, diverging the projected southward trends of the plutonic belts and bowing the range westward. Episode 4, characterized by High Cascade volcanism and concurrent extension, continues in the Cascade Range.

DISCUSSION

This discussion concerns conditions affecting the model, problems in its realization, and possible interpretations of Pacific Northwest geology based on the model.

Conflicting arguments regarding the origin of the Coast Range and the position of the old subduction zone do not impair the proposed tectonic model. Snavely and others (1968), Glassley (1974, 1976), and Cady (1975) considered the early Eocene basalts of the range to have been oceanic ridge tholeiites or seamounts. Lyttle and Clarke (1975, 1976) maintained that the chemistry of the rocks signifies their magmatic arc origin. Dickinson (1976) believed the Coast Range to be seamount clusters or volcanic archipelagoes that were rafted against the continent when intervening oceanic lithosphere was consumed. The Coast Range block clogged the subduction zone, causing it to jump about 150 km westward to the seaward margin of the block. From this point on the proposed tectonic model is in operation.

If investigations demonstrate that the Eocene basalts of the Coast Range were indeed the products of a magmatic arc, then a three-segmented volcanic arc, according to the classification of arcs (Miyashiro, 1974), may have bordered the Pacific Northwest continental margin in the early Cenozoic. In the early formation of the Cascade arc but before its rifting from the continent, there existed an outer tholeiitic segment--the Coast Range, a middle calc-alkalic segment--the Cascade arc, and an inner, more alkalic segment--the Challis-Absaroka arc of Snyder and others (1976; Fig. 7). With rifting of the Cascade arc and ensuing rotation, the subduction zone rotated westward ahead of the coastal block. Consequently, volcanism shifted to the Cascade arc and ceased in the Challis-Absaroka arc by 41 Ma in northeastern Washington (Pearson and Obradovich, 1977) and by 38 Ma in Idaho (Armstrong, 1975).

Burr and Beck (1977) and C. D. Burr and M. E. Beck, Jr. (1978, personal communications) present evidence in support of rotation of the Cascade Range. They find that Goble volcanic rocks, of 32 to 45 Ma (Fig. 4), have rotated an average of 25°, and suggest that either the rate of rotation accelerated with time or the Cascade arc rotated separately at a slower rate or the arc rotated for a longer time than the Coast Range block. They argue that the Cascade arc, in particular the Goble rocks, rotated separately from the Coast Range because the crustal characteristics of the two blocks differ. This argument has been discussed in the introduction to this paper and is valid except that stratigraphic relationships indicate that the ranges had parallel development during late Eocene-middle Oligocene time. The 25° rotation is compatible with the uniform rate of rotation, 2°/m.y. (Simpson and Cox, 1977), which is used in plotting the positions of the coastal block in the maps (Figs. 7-9). In the model, the Cascade arc formed on the backside of the coastal block after the block had rifted and very likely began its rotation; therefore, the Cascade arc is assumed to have rotated somewhat less in a shorter time than the coastal block. The importance here is that paleomagnetic evidence indicates that rocks of the Cascade Range have rotated, how much and over what time span is yet to be determined.

The Roslyn, Guye, and thick sequences of the Puget Group and Naches formations, composed largely of sedimentary rocks derived from a plutonic-metamorphic provenance, lie in the northern part of the Cascade arc (Fig. 4), and indicate a proximity of the arc to continental terrain. To the south these formations are interbedded with the lower WCG (Hammond, 1979a). They were deposited chiefly in a forearc basin and were eventually overwhelmed by volcanic rocks. Near the southern end of the range a thin sequence of similar sedimentary rocks occurs in the lower part of the Colestin Formation (Wells, 1956), also part of the lower WCG (Fig. 4), indicating not necessarily a forearc basin but proximity to another continental provenance, here most likely the Klamath Mountains. Both occurrences of these non-volcanic sedimentary rocks are explained by the model: the north end of the arc remained adjacent to the continent in central Washington; the south end was marginal to the Klamath Mountains.

The Russell Ridge block of Mesozoic- Paleozoic rocks east of Mount Rainier (Hammond, 1979a) was possibly rifted from the OWL and rafted westward with the Cascade arc. Similarly, pre-Cenozoic rocks at the Pueblo Mountains, southeastern Oregon (Walker, 1977), form a detached block, which was possibly rafted in the lee of the Cascade arc or offset dextrally from the western end of the Blue-Ochoco Mountains. Other blocks may be buried beneath Cenozoic volcanic rocks in southeastern Oregon (Simpson and Cox, 1977).

To account for the position of the Blue-Ochoco Mountains in the backarc setting of the rotated Cascade arc is a problem in the model. Possibly the mountains were dragged into position by the arc, as a cluster of discrete blocks, each moving dextrally along northwest- to west-trending faults. As the Cascade arc rotated, the first translation in the Blue-Ochoco Mountains was along the OWL (Fig. 8) and in time translation shifted southward along additional northwest or westward shears (Fig. 9), and possibly the Mitchell and John Day faults (Simpson and Cox, 1977). Although no through-going faults show on the eastern Oregon map (Walker, 1977), a number of northwest-trending zones, separating areas of Mesozoic rocks, can be traced across the Blue-Ochoco Mountains. For examples, there are the zones southeastward through LaGrande, through Sumpter, along the Bates-Vale zone of Lawrence (1976), and through the Unity Reservoir. Several zones align with interruptions across trends in the Bouguer gravity contours (Berg and Thiruvathukal, 1967).

According to Simpson and Cox (1977), 41 m.y. old Clarno rocks of the western Blue Mountains (Fig. 4) show only 15° clockwise rotation, suggesting either very rapid rotation of the Coast Range-Klamath Mountains block or possible westward rafting of Clarno rocks and the mountains behind the coastal block without significant rotation. This amount of rotation may be caused by rotation of separate fault-bound blocks of the Blue-Ochoco Mountains as they were dragged westward by the Cascade arc. Also, the sigmoidal fold direction pattern within the Mesozoic strata of the Ochoco Mountains (Walker, 1977) may be caused by internal rotation of the block between the John Day and Brothers fault zones during westward translation.

The Brothers fault zone is the major tectonic break terminating the western end and southern side of the Blue-Ochoco Mountains (Lawrence, 1976). Movement on this zone has continued within the last 5 m.y. in response to extension and concomitant volcanism within the Basin and Ranges province immediately south (MacLeod and others, 1976; Fig. 1).

The southwestern Columbia Plateau is probably underlain by rafted blocks of Mesozoic rocks which extend as far as the eastern slope of the northern volcanic Cascade Range. Some are possibly similar to the rocks of the Russell Ranch block in the Cascade Range (Hammond, 1979a). Argillite of Jurassic age occurs in a deep well drilled below Columbia River Basalt north of Condon on the north slope of the Blue Mountains (R. D. Bentley, 1978, personal communication).

The OWL forms a narrow transition zone separating two distinctively different segments of a continuous volcanic arc. Compared with the southern volcanic Cascade Range, the North Cascades are distinguished by its breadth of Mesozoic rocks, amount of uplift (and depth of erosion), and lack of High Cascade basaltic rocks. The Bouguer gravity anomaly map of Bonini and others (1974) shows no essential crustal difference across the OWL. Yet, the overall stratigraphic relief across the OWL approaches the thickness of the WCG, here about 5 km. No early Cenozoic stratigraphic unit is recognized as extending across the OWL (Tabor and others, 1977; Hammond, 1979a). The significance of the zone in the Cascade Range, other than separating lithologically different parts, is yet to be understood. In the tectonic model, the OWL has been (1) a rift zone; (2) a strike-slip zone along which Mesozoic continental rocks have been rafted northwest and westward; (3) a possible zone of pre-middle Miocene volcanism; (4) a zone of westward extension; (5) a zone later transected by more northerly trending feeder dikes to Columbia River Basalt (Swanson and others, 1975, 1978); (6) a zone covered by flood lava flows and subsequently depressed; and (7) a zone, formerly a continental margin, against which the Columbia River basalts have been shoved northward during Yakima folding.

Inspection of Figure 6 will reveal that OWL does not lie exactly 70° but 65° with respect to the axis of the Coast Range. This slight infraction does not negate the rotation model. During Cenozoic westward extension the position of the OWL has likely moved westward as much as 5° from its former position. This interpretation is drawn into Figures 6 and 7; see also Figure 8.

Time of positioning the Blue-Ochoco Mountains is compatible with cessation of rotation of the Coast Range-Klamath Mountains block about 16 to 14 Ma (Choiniere and others, 1976). The Blue Mountains are cut by the north-northwest-trending Monument feeder dikes of the Columbia River Basalt (Fig. 1). These dikes are parallel to the regional trend of the feeder dikes (Swanson and others, 1975, 1978), which erupted as early as 16½ Ma (McKee and others, 1977), and to the rift faults marking the inception of downwarping of the western Snake River Plain at 15½ Ma (Armstrong and others, 1975).

The model is not affected by the arguments that rotation, or translation, has continued in the Blue Mountains since outpouring of Columbia River Basalt. Watkins and Baksi (1974) and Basham and Larson (1978) maintain that Columbia River Basalt in the Blue Mountains has rotated, in opposition to the evidence of no rotation in the feeder dikes cutting the mountains (Taubeneck, 1966) and in 14 m.y. or younger lava flows north of the Blue Mountains (Kienle and others, 1978b).

The difference is style of pre-Yakima folding along the length of the range--from partly closed, northwest-trending folds in Washington, to broadly open, north-south folds in northern Oregon, to a broad north-south trough in southern Oregon and California--is possibly explained by the distribution of stresses within the Cascade arc during its rotation. The northern end of the arc was repeatedly shoved against the rigid continent by the eastward moving Juan de Fuca plate and subjected to continuous compression. Southward along the arc the compressive stress diminished because (1) the arc was not backed against the continent, and possibly (2) the oceanic plate movement was oblique to the arc, causing extension across or oblique to the axis of the arc during its rotational translation. At the southern part of the arc, the trailing (eastern) side lagged, causing attenuation, and the gradually accumulating WCG sagged to form a broad depression. The Coast Range expresses a similar structural style along its length. The folds are northwest trending and closely spaced in southwestern Washington (Huntting and others, 1961) and northwestern Oregon, changing to a large north-south trough of chiefly Tyee Formation (Fig. 4) to the south (Wells and Peck, 1961).

The Yakima folds developed between 12 and 5 Ma in response to north-south compressive stress (Kienle and others, 1978a). The Columbia River Basalt was translated northward atop thin crust by mantle underflow to form a series of curvilinear folds with oversteepened north flanks. The northward convex fold pattern covers the region affected by the stress (Fig. 1). It is superimposed on the older northwest-trending folds of the northern Cascade arc as far south as Mount Jefferson. The fold pattern was also superimposed on the older northeast structure of the Strawberry Mountains (eastern part of the Ochoco Mountains), exposed in Ironside Mountain (Thayer and Brown, 1973). Final uplift of the Blue-Ochoco Mountains occurred during Yakima folding (Robyn and others, 1977). Warping in the Rattlesnake strata suggests that deformation in the mountains was diminishing 6 Ma (Fig. 4). To the north the translation abutted the old continental margin at the OWL, which largely absorbed the stress except for a few folds formed to the north, e. g., Frenchman Hills and Saddle Mountains.

The belts of Tertiary granitic plutons form a large volume of high-level low-density mass in the range and, therefore, may partly account for uplift of the range. In Washington the belts are closer together and underlie the crest of the range; only one belt continues southward into Oregon, lying west of the Cascade crest (Figs. 1, 2). Other plutons may underlie the range, very likely in southern Oregon and northern California, although their effect on uplift of the range appears negligible. The closer spacing of the belts in Washington and the correspondingly greater concentration of granitic mass here, as well as the adjacent pre-Cenozoic crystalline terrain of the North Cascades, probably accounts for isostatic uplift of the northern part of the range and not the southern part.

Evidence at least suggestive of extension in the Cascade Range is the abundance of north-south-trending faults and fissure zones or crater rows. These north-south structures occur throughout the length of the range from Mount Adams to Lassen Peak. Their association with abundant basaltic volcanic centers is suggestive of a broad rift zone. Although the faults and volcanic centers are generally concentrated along the crest and eastern slope of the range, the zone is irregular and extends well into the western slope locally. The maximum width of the zone within the range occurs in southern Oregon, where there are a greater number of basaltic volcanoes and a slightly greater thickness of the High Cascade rocks.

The widest zone of north-south structures occurs within the segment of westward bowing of the range in southern Oregon. The Brothers fault zone bounds the northern end and the McLoughlin fault zone terminates the southern end of the bow. No offset occurs along the projection of the Brothers fault zone into the Cascade Range (Hammond, 1976). Much of the westward displacement of the bow is attributable to offset of the Cascade crest along the Eugene and McLoughlin fault zones in the order of 10-15 km (Lawrence, 1976; Fig. 1).

Another indication of extension within the range is the southward divergence of the projections of the two plutonic belts. The eastern belt is also curved in conformity with the bow of the range. The divergence and curve indicate possibly several tens of kilometers of extension in the range in southern Oregon during the last 15 m.y. or less.

Extension across the Cascade Range and a change in style of volcanism from the WCG to the HCG is compatible with the interpretation that offshore subduction decreased markedly in the late Cenozoic (Atwater, 1970). By 8 Ma the distance between the leading edge of the oceanic plate and the Juan de Fuca spreading ridge had shortened considerably; therefore, the plate being "hot" (Dehlinger and others, 1971) was less likely to dive beneath the continent and, consequently, the Benioff zone became less steep. This flattening of the subduction zone and tendency of the downgoing slab to "float" slightly uplifted and extended the overlying crust. The formation of Newberry and Medicine Lake calderas east of the range (Fig. 1) may have been caused by this change in geometry of the subducting Juan de Fuca plate, by the leading edge of the consuming slab extending eastward of the Cascade Range. On the other hand, the calderas may have developed on youthful north-south extension faults just beyond the eastern margin of the Cascade Range.

Major problems in realization of the tectonic model are outlined as follows:

(a) Evidence for rotation of Cascade rocks younger than Goble, 32 m.y., is lacking. Data on paleomagnetic directions in strata of middle to upper WCG are necessary in order to substantiate rotation of the range until about 15 Ma. In addition, data are needed on the plutons in Oregon south of Mount Jefferson and on lower High Cascade volcanic rocks in order to delineate the amount of extension, and possible concomitant rotation, in forming the bow of the range.

(b) Evidence is lacking that the range south of the OWL rotated while the North Cascades remained stationary. Paleomagnetic direction studies are needed on Western Cascade rocks across the OWL.

(c) No evidence exists that tectonic zones with dextral slip transect the Blue and Ochoco Mountains. Mapping of possible northwest-trending zones in the mountains, followed by paleomagnetic studies, will be necessary to delineate transecting tectonic zones and to determine if the blocks rotated independently when being translated westward.

(d) Contrary evidence exists that movement at the south ends of the Klamath Mountains and Cascade Range blocks was sinistral with respect to the Sierra Nevada block during the Cenozoic 50 to 15 Ma (Wright, 1976; Simpson and Cox, 1977).

(e) Detailed mapping and stratigraphic correlation across the northwest-trending fault zones, i. e., the Brothers, Eugene-Denio, and McLoughlin (Lawrence, 1976), and the Honey Lake (Eaton, 1966; Wright, 1976), is necessary to determine their extent and rate of displacement.

SUMMARY

The model for tectonic evolution of the Cascade Range begins about 50 Ma when the Coast Range-Klamath Mountains (coastal) block rifted from the Mesozoic continental margin along the Olympic-Wallowa lineament. In the rift zone behind the coastal block the Cascade volcanic arc formed. The arc was concurrently rifted from the continent and rotated westward across Oregon on the back side of the coastal block about a pivot in the Olympic Mountains. Demarcation between stationary North Cascades and the Cascade volcanic arc was along the Olympic-Wallowa lineament. From 50 to 15 Ma the volcanic arc grew, forming the lower and middle parts of the Western Cascade Group. Rotation westward of the coastal block and Cascade arc was against an eastward subducting Juan de Fuca plate, which continually forced the north end of the rotating block against the continent. During rotation the Blue-Ochoco Mountains block was dragged behind the arc as a series of discrete blocks bound by northwest- to west-trending faults. These blocks were possibly also independently rotated clockwise. By about 17 Ma the Blue-Ochoco Mountains block arrived at its present position, and feeder dikes for Columbia River Basalt and rift faults of the western Snake River Plain began developing. At about the same time the coastal block and Cascade arc arrived at their present north-south positions. Volcanism of the arc climaxed between 15 and 5 Ma with deposition of the upper Western Cascade Group, locally interstratified with lava flows of the Columbia River Basalt, and final emplacement of epizonal granitic plutons. Between about 12 and 5 Ma the Yakima folds developed in response to north-south compressive stress and spread from the western Blue-Ochoco Mountains across the southwestern Columbia Plateau into the northern Cascade arc. Commencing about 50 Ma in the North Cascades, the northern part of the Cascade arc elevated isostatically in response to erosion of crystalline Mesozoic basement and emplacement of granitic plutons. Uplift climaxed about 5 Ma with formation of the Cascade Range. At about the same time north-south faults formed in the range, providing avenues for voluminous outpourings of High Cascade basaltic rocks. Sporadic andesitic-dacitic High Cascade stratovolcanoes also formed at the time from remnant magmatism in response to wanning subduction. Displacement along northwest-trending fault zones, which dextrally offset the crest of the Cascade Range, together with a wide belt of east-west extension, have caused the southern part of the range to bow westward.

As seen in the model, the Pacific Northwest is the product of Cenozoic crustal attenuation, in which rotation of Mesozoic terrains and Cenozoic volcanic arcs was followed by westward backarc extension of young Cenozoic volcanic terrains (Hamilton, 1966; 1969; Simpson and Cox, 1977). The evolution was not necessarily caused by a shallow subduction zone or fragmented subducted slab in order to account for a 1000-km wide magmatic arc (Lipman and others, 1972; Snyder and others, 1976; Dickinson, 1976). An active single subduction zone inclined beneath the westward rotating Coast Range-Klamath Mountains block and trailing Cascade volcanic arc produced the existing volume of volcanic rocks, and younger volcanism accompanying backarc attenuation account for the remaining distribution and volume of rocks.

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