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CENOZOIC PLATE MOTIONS AND THE VOLCANO-TECTONIC EVOLUTION OF WESTERN OREGON AND WASHINGTON

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Abstract. A refined northeast Pacific plate-motion model provides a framework for analysis of the Tertiary volcanic and tectonic history of western Oregon and Washington. We examine three possible models for the origin of the allochthonous Paleocene and Eocene oceanic basalt basement of the Coast Range: (1) accretion to the continent of hot spot generated linear seamount chains; (2) accretion of thick oceanic crust and seamounts generated during Farallon-Kula spreading reorganizations between 61 and 48 Ma; and (3) eruption of basalt during oblique rifting of the continental margin as it overrode an active Yellowstone hot spot on the Kula-Farallon ridge. The plate model suggests that microplate rotation and accretion of hot spot generated linear aseismic ridges cannot be easily reconciled with rapid northeast motion of the Kula and Farallon plates and the well-established paleomagnetic rotations. Following emplacement of the Coast Range basement, changes in the character of forearc, back arc and Cascade arc volcanism correlate with a marked decrease in the rate of Farallon-North America convergence between 43 and and 28 Ma. This slowdown may be responsible for (1) westward stepping of the volcanic arc front from the Challis axis to a Cascade axis at about 42 Ma; (2) a subsequent episode of increased ash flow tuff volcanism and extension in the Cascade arc between 37 and 18 Ma that correlates with the "ignimbrite flare-up" in the Basin and Range; and (3) a period of extensional basaltic and alkalic volcanism and intrusion in the Coast Range between 44 and 28 Ma. Reduction of the convergence rate and westward stepping of the flexure in the subducted slab may have reduced the horizontal compressive stress on the continent, allowing increased injection of magma into the crust, development of large, shallow magma chambers, and the outbreak of extensional volcanism over a large area behind the Farallon-North America subduction zone.

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INTRODUCTION

The extensive record of Cenozoic volcanism preserved in the Pacific Northwest provides an excellent opportunity to compare the geologic

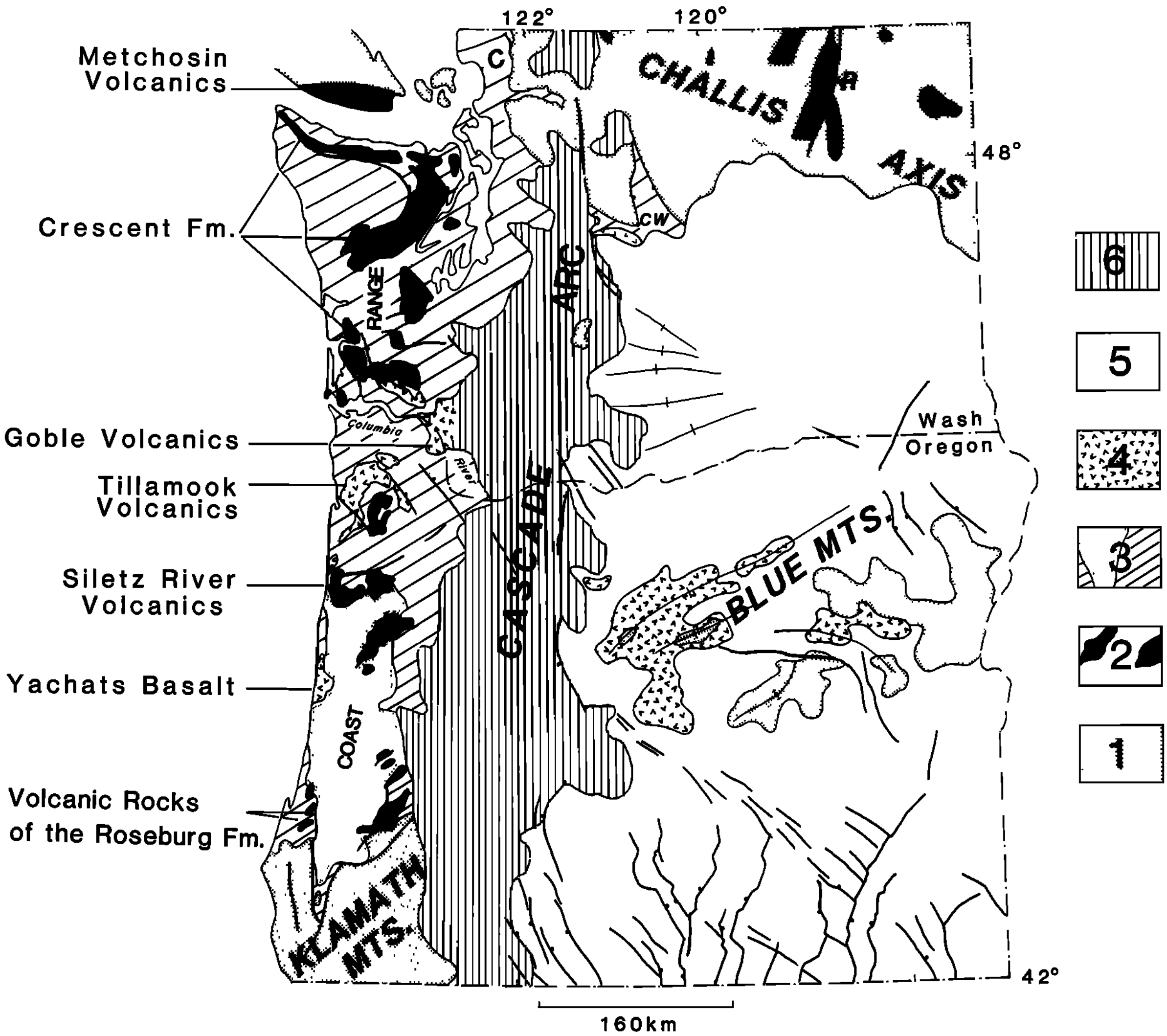

Fig. 1. Geologic and tectonic map of the Pacific Northwest after King and Beikman [1974]; 1 = pre-Tertiary rocks; 2 = Paleocene to middle Eocene volcanic rocks; includes oceanic basalt of Coast Range basement and volcanic rocks of Challis axis; 3 = mostly marine Tertiary sedimentary rocks, as mapped includes Quaternary in Puget Sound area; outline of the Eocene Tyee Formation stippled; 4 = Eocene and Early Oligocene volcanic rocks, includes basaltic rocks of the Coast Range and andesitic Clarno Formation in central Oregon; 5 = mostly Oligocene and Miocene volcanic rocks of the Columbia Plateau and Oregon Basin and Range; 6 = Tertiary and Quaternary volcanic rocks of the Cascade Range; C, CW and R = Chuckanut, Chiwaukum and Republic grabens; heavy lines are faults, ball on downthrown side; fine lines with crossbar are fold axes.

evolution of the area with plate tectonic models for Cenozoic interactions between the continent and oceanic plates to the west. Although our present understanding of Pacific Northwest volcanism is largely based on reconnaissance geologic mapping and radiometric dating, a preliminary evaluation of the data indicates spatial, temporal, and compositional trends that may correlate with plate motions. These correlations can provide clues to the thermal and mechanical processes operating in the upper plate above changing subduction regimes.

In this paper we examine the nature of volcanism in western Oregon and Washington and consider two major tectonic problems: (1) the origin of the early Tertiary oceanic basalt basement of the Coast Range, and (2) the timing and character of subsequent Coast Range volcanism and its relationship to the development of the main Cascade arc to the east (Figure 1). The plate motions impose some constraints on the origin of the Coast Range basalt basement, but considerable freedom still exists in the details of the plate geometry. We take this opportunity to speculate on several possibilities for the origin of the basalts and expand on the possible consequences of an active Yellowstone hot spot in the vicinity, as suggested by earlier workers [Simpson and Cox, 1977; Duncan, 1982]. Following emplacement of the Coast Range basalts, the change in location and character of continental volcanism appears to correlate in time with changes in plate motions. We suggest that these changes in volcanism reflect changing stress regimes in the overlying plate which are controlled by variations in the convergence rate and age of the subducting slab.

PLATE MODEL

The essentials of plate motion models for the northeast Pacific were developed initially by Atwater [1970] and Francheteau et al. [1970], with additional refinements by Atwater and Molnar [1973], Jackson et al. [1978], Byrne [1979], and Coney [1972, 1978]. A new analysis of the relative motion model for the northeast Pacific by Engebretson [1982] provides a detailed geometric framework in which to consider the volcanic and tectonic evolution of western Oregon and Washington. The primary assumption of the model is that hot spots which produce linear volcanic chains on the plates provide a nearly fixed reference frame in which to consider the relative plate motions. This postulate seems reasonable in light of recent analyses that indicate motion between hot spots of less than 5 km per million years [Morgan, 1981; Duncan, 1981; Gordon and Cape, 1982]. The plate model is also dependent upon the assumption that the anomaly pattern on the Pacific plate is the product of symmetrical spreading, because most of the Farallon and all of the Kula plate have been consumed. Additional assumptions must be made regarding the location of the Kula-Farallon spreading ridge prior to its reorganization between 61 and 48 Ma [Byrne, 1979; Engebretson, 1982]. An orientation for the Kula-Farallon ridge can be calculated from the Kula-Pacific and Farallon-Pacific relative motion poles, but there is little control on the location of the ridge with respect to North America because evidence for possible transform offset of the ridge has been subducted. We have assumed a relatively simple configuration for the Kula-Farallon ridge as a starting point at 65 Ma. The location of the ridge is constrained to run through the fixed Yellowstone hot spot to produce a stable and energetically reasonable geometry for that time period (Figure 3 and later discussion). The northward limit of the ridge with respect to North America is determined by the requirement that the northward moving Kula Plate be offshore during Late Cretaceous and early Tertiary right-lateral faulting in the northern Cordillera [see Davis et al., 1978; Plumley, 1980; Ewing, 1980], although it is possible that the ridge could have been further south at an earlier time (Page and Engebretson, 1984].

Reconstructions of Kula-Farallon-Pacific-North America positions at 65, 48, 37, and 16 Ma illustrate several important stages in the evolution of the plate geometry (Figure 2). The reconstructions, along with the velocity triangles of Figure 3, show three things:

1. The Kula and Farallon plates moved northeast with respect to both North America and hot spots during the entire Tertiary.
2. Rapid Farallon-North America convergence velocities slowed greatly between 43 and 28 Ma. The slowdown occurred in several stages; the major decrease at 43 Ma was coincident with a change in the absolute motion of the Pacific plate relative to the hot spots; the second at 37 Ma coincided with a reduction of the westward motion of North America with respect to hot spots and a reduction in the Pacific-Farallon spreading rate.
3. The Kula-Farallon ridge reorganized at least 3 times between 61 and 43 Ma in response to changes in spreading rates or directions on the other two spreading systems. Note that the demise of the Kula-Pacific spreading ridge at 56 Ma suggested by Byrne [1979] does not occur

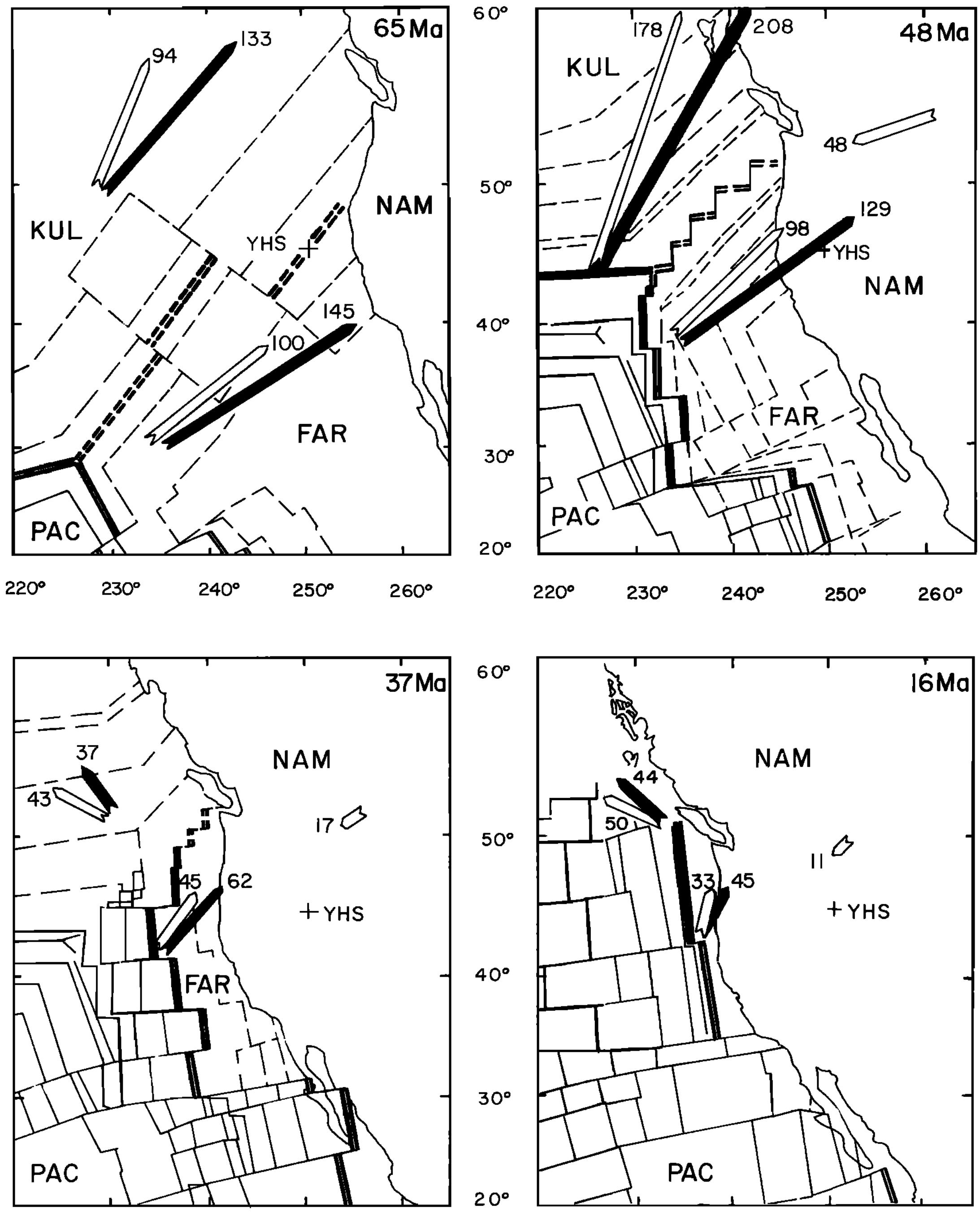

Fig. 2. Northeast Pacific plate geometry at 65, 48, 37 and 16 Ma modified from Engebretson [1982]. Relative motions of Kula (KUL), Pacific (PAC) and Farallon (FAR) plates with respect to Pacific Northwest continental margin of North America (NAM) shown by solid arrows, in km/Ma; open arrows show motion of plates with respect to hot spot; spreading ridges shown by double heavy line; fine lines are magnetic lineations, dashed where reconstructed.

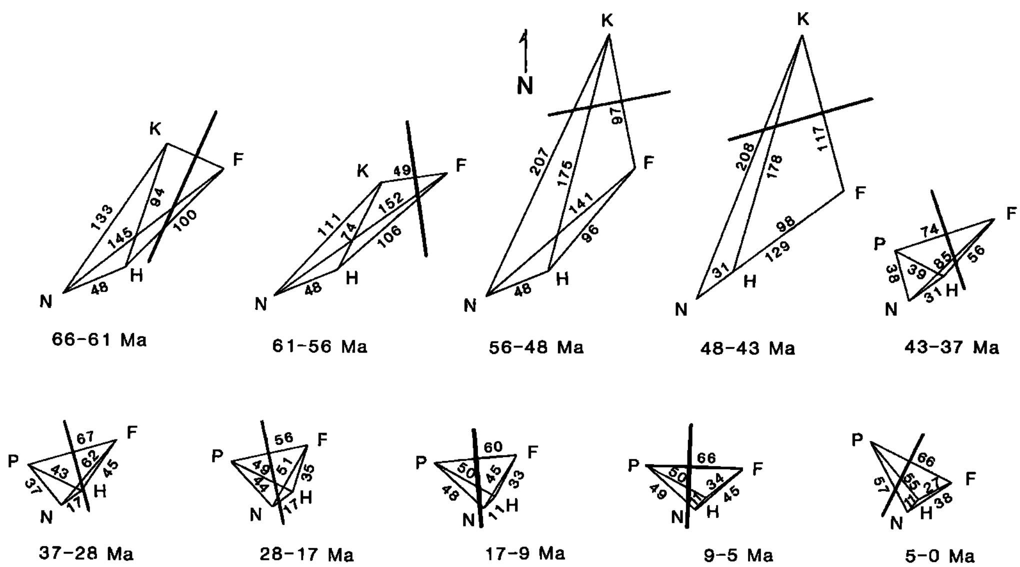

Fig. 3. Velocity triangles showing Cenozoic relative plate motions in km/Ma for Kula (K), Farallon (F), Pacific (P), North America (N) and hot spots (H) calculated for the Pacific Northwest continental margin (45°N, 124°W); heavy solid line shows stable orientation of Kula (or Pacific) - Farallon spreading ridge.

until 43 Ma in this model [Engebretson, 1982].

In the next two sections we discuss the timing and character of western Oregon and Washington volcanism in the context of this plate motion model.

ORIGIN OF THE COAST RANGE BASEMENT

The Paleocene to middle Eocene, mostly submarine tholeiitic basalts forming the basement of the Oregon-Washington Coast Range (Figure 1) may comprise one of the younger allochthonous terranes that make up the "collage" of the North American Cordillera [Coney et al., 1980]. Geologic, geochemical, and geophysical evidence summarized by Snavely et al. [1968], Simpson and Cox [1977], Magill et al. [1981] and Duncan [1982] shows the Coast Range basement to be fundamentally oceanic in character. The submarine tholeiitic basalt locally forms thick sequences that grade upward into subaerial basalt, which in places, is overlain by a cap of alkalic basalt suggestive of an oceanic island origin [Snavely et al., 1968]. The Coast Range basement has been interpreted as seamounts on oceanic crust that were tectonically accreted to the continental margin in Eocene time [Snavely and MacLeod, 1974; Dickinson, 1976; Simpson and Cox, 1977; Duncan, 1982].

Radiometric ages for the Coast Range basalts range from 49 to 62 Ma with the oldest ages at the northern and southern ends and the youngest near the Columbia River [Duncan, 1982]. Continent-derived conglomerate interbedded with the basalt at the northern and southern ends of the Coast Range suggests eruption of the basalt relatively close to the continental margin [Cady, 1975; P. D. Snavely, Jr., unpublished mapping, 1980]. In most places the age of basalt emplacement is not well documented because younger rocks cover the tectonic boundary, but at the southern end of the Coast Range, lower middle Eocene turbidite sandstone of the Tyee Formation laps across the exposed tectonic boundary and requires suturing by about 50 Ma [Magill et al., 1981; Heller and Ryberg, 1983]. At the north end of the Coast Range, suturing probably predates 42-Ma quartz diorite, andesite and dacite plugs and dikes, which we interpret to be related to the development of the Cascade arc, intruding the much older basalts [Tabor and Cady, 1978; P. D. Snavely, Jr., unpublished data, 1976].

Paleomagnetically determined clockwise rotation of about 75° for the Oregon Coast Range basalts contrasts markedly with the more moderate rotations of similar rocks in the Washington Coast Range and requires independent kinematic histories for the two areas [Globerman et al., 1982; Wells, 1982]. The large Oregon Coast Range rotation has been interpreted as the microplate rotation of an originally northwest trending oceanic ridge, either during oblique collision with the continent, or during asymmetric back arc spreading after collision [Simpson and Cox, 1977]. Magill et al. [1981] suggest that both processes have acted in sequence to produce the tectonic rotations. However, stratigraphic relationships require that most of the rotation occurred following suturing of the basalts to the continental margin in middle Eocene time. The overlying postaccretion sandstones and younger, late Eocene Coast Range volcanic rocks are rotated nearly as much as the older basalts, thus limiting the amount of preaccretion rotation to less than 20°. This places firm constraints on possible geometric relationships during accretion of an oceanic microplate to the continental margin and suggests that rotations are mostly due to asymmetric back arc spreading and superimposed dextral shear from the oceanic plates following accretion [Wells, 1982; Heller and Ryberg, 1983].

These geologic data, along with the plate motions, are used to constrain three possible tectonic models for the origin of the Coast Range basalts: (1) hot spot generation of linear seamount chains on the Kula and Farallon plates followed by accretion to North America; (2) generation along leaky fractures during multiple reorganizations of the Kula-Farallon ridge, perhaps near a hot spot, followed by accretion; and (3) eruption during oblique continental rifting of outboard allochthonous terranes as North America overrode an active Yellowstone hot spot.

Hot Spot Model

Simpson and Cox [1977] and Duncan [1982] have proposed models in which the submarine basalt basement of the Coast Range was erupted on an oceanic plate as it moved over the Yellowstone hot spot. The model is attractive for two reasons: (1) plate reconstructions show the Yellowstone hot spot to be approximately in the right place just offshore of Oregon during the Paleocene and early Eocene; and (2) the large volume of some of the volcanic edifices, with compositions ranging from mid-ocean ridge to oceanic island tholeiite, strongly suggests an island chain origin for the basalts [Snavely et al., 1968; Duncan, 1982].

Duncan [1982] has reported numerous conventional potassium argon and $^{40}Ar/^{39}Ar$ ages that on the average show a progressive younging of the Coast Range basement from 57 and 62 Ma at the north and south ends, respectively, to about 49 Ma just north of the Columbia River. Duncan envisions this symmetrical age progression to be the result of a hot spot on the Kula-Farallon spreading center producing seamount chains at about 40 km/Ma on each of the Kula and Farallon plates, somewhat analogous to Iceland today. In this model, the seamount chain on the Farallon plate would have originally trended southeast and subsequently rotated clockwise during collision to form the Oregon Coast Range basement, while seamounts on the Kula plate would have had a more northerly trend and rotated less upon accretion to form the Washington Coast Range basement.

We have recast the ridge-centered hot spot hypothesis in our plate motion geometry in Figure 4. The rapid northeast motion of the Kula and Farallon plates with respect to both hot spots and North America produces a geometry of island chain growth and accretion significantly different from those previously suggested. Our plate motion geometry seems to require the following:

1. Seamount chains trend northeast on both the Kula and Farallon plates; this is incompatible with the idea of oblique collision of an Oregon Coast Range microplate to produce the observed 75° clockwise rotation.
2. Hot spot volcanism propagated at about 100 km/Ma on both the Kula and Farallon plates. In 13 Ma each seamount chain would be twice the 600 km present length of the Coast Range, requiring subduction of the majority of the seamounts while retaining the age progression in the accreted remnants.
3. The range in age of the basalts requires the hot spot to be at least 600 km offshore to allow for eruption of the entire Coast Range sequence before overriding of the hot spot by North America. This requires an alternative explanation for the apparently continent-derived boulders interbedded in older basalt in the Olympic Mountains.

If our assumptions are correct, these

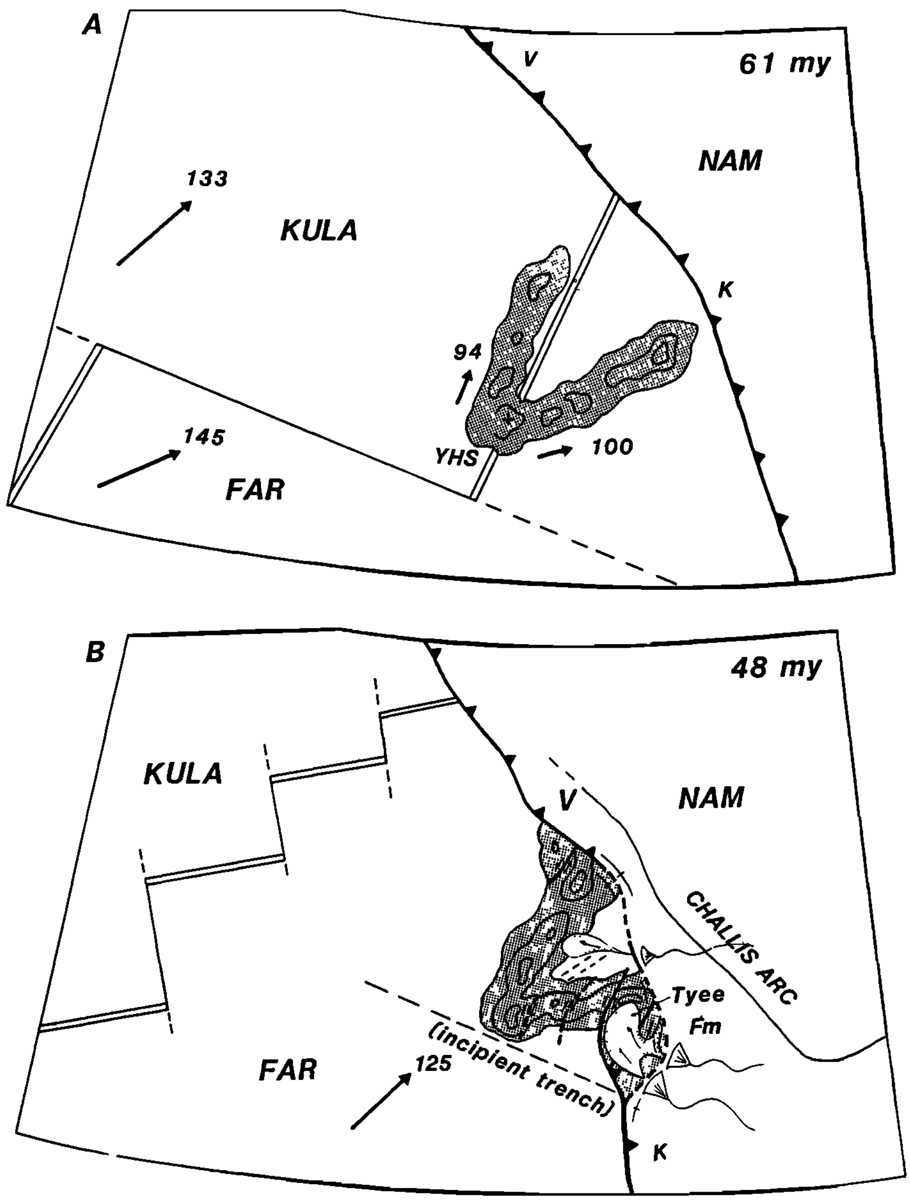

Fig. 4. Hot spot on a ridge model for origin of Coast Range basalt basement; conventions as in Figures 1 and 2, K = Klamath Mountains, V = Vancouver Island, YHS = Yellowstone hot spot, teeth on upper plate of convergent margin: (a) Geometry of volcanic ridges prior to plate reorganization at 61 Ma. (b) Long volcanic ridges must telescope to fit into Coast Range embayment during accretion. See text for discussion.

results do not support simple microplate accretion to the continent of hot spot generated aseismic ridges from the Kula or Farallon plates. Instead, rather complex accretion geometries seem to be required in which telescoping and dismemberment of the aseismic ridges occur during accretion to the continent. The plate motions with respect to hot spots are, of course, dependent on the perceived stability of the hot spot reference frame in the Pacific basin and assumption of normal spreading behavior on the northeast Pacific spreading ridges.

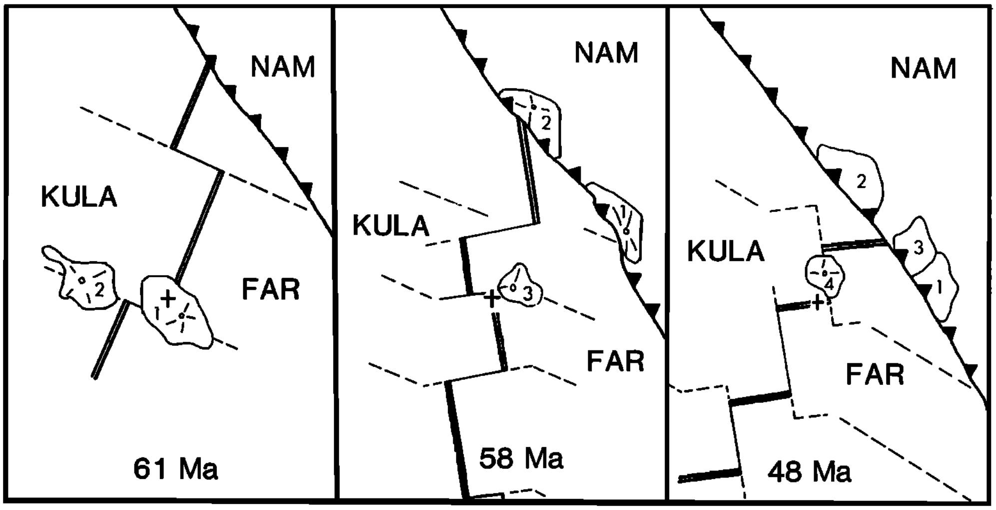

Fig. 5. Leaky fracture model for origin of the Coast Range basalt basement. Kula-Farallon ridge reorganizations at 61, 56 and 48 Ma break up plates and allow seamounts and islands to form along fracture zones. Hot spot fixes position of ridge and provides sources for large volcanoes; cross is location of Yellowstone hot spot.

Spreading Ridge Reorganization Model

A modification to the hot spot model is suggested by the correlation of 62- to 49-Ma Coast Range basement ages with periods of reorganization of spreading on the Kula-Farallon ridge at 61, 56, and 48 Ma (Figure 3). It seems likely that each reorganization would produce leaky transforms, ridge jumps, propagating rifts and cracks, and small plates as preexisting structures adjust to the new spreading direction (Figure 5). Such a terrane, perhaps analogous to the present situation at the north end of the East Pacific Rise [Klitgord et al., 1982], would have been fertile ground for the production of seamounts. The Coast Range basalts could have erupted as seamounts and volcanic ridges along leaky transforms [see Menard and Atwater, 1968; Plumley, 1980] or fracture zones during the readjustment of spreading directions. Although most fracture zone seamounts are ordinarily of small size [Batiza, 1982], the nearby presence of an active Yellowstone hot spot would have provided a magma source for production of larger volcanic edifices. Thin lithosphere near the hot spot may have controlled the location of successive ridge reorganizations through ridge jumping to accompany the unstable geometry after 61 Ma (compare Figures 3 and 5). In this model, an explanation of the symmetric age progression in the basalts must require successive accretion of episodically erupted basalt packages formed during each ridge reorganization.

Continental Rifting Model

Another model for the origin of the Coast Range basement involves generation of the basalt during oblique continental margin rifting. This idea is based on the paleomagnetic and geologic evidence that requires large-scale northward transport of some northern Cordilleran terranes during the Late Cretaceous and early Tertiary [Beck, 1980; Davis et al., 1978; Coney et al., 1980]. Some of these terranes, for example the Prince William and Chugach terranes of southern Alaska, may have been adjacent to Oregon and Washington at the beginning of the Tertiary [Moore et al., 1983; Plumley et al., 1983]. The Prince William and Chugach terranes comprise a Late Cretaceous and Paleogene accretionary complex stitched together by 60- to 62-Ma plutons. Paleomagnetic data from basalt and andesite interbedded in the Paleocene melange indicate formation at a paleolatitude of $40.3^{\circ} \pm 6.2^{\circ}$ N [Plumley et al., 1983].

The preferred reconstruction by Moore et al. (1983) places the composite Prince

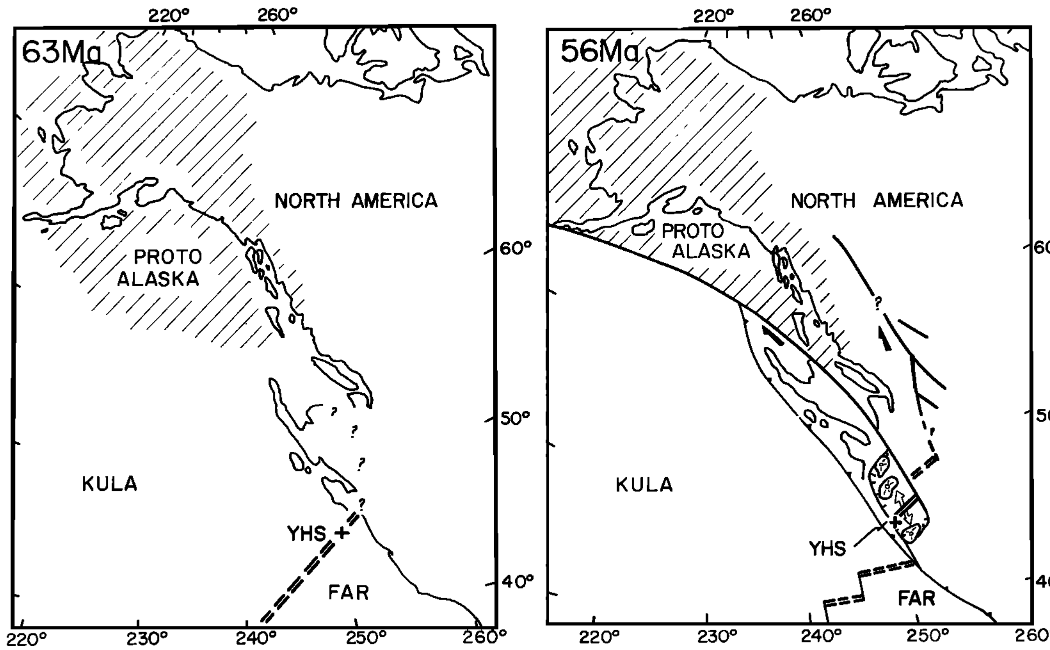

Fig. 6. Continental rifting model for the origin of the Coast Range, figure modified from Moore, et al. [1983]. Left: 63-Ma reconstruction--preferred paleolatitude of southern Alaska allochthonous terrane from Moore et al. [1983]. YHS is Yellowstone hot spot. Right: 56-Ma reconstruction--oblique rifting follows overriding of hot spot by North America. Alaskan terrane transported northward by fast moving Kula plate; Coast Range basalts erupted in its wake. Possible contemporaneous dextral slip on interior faults modified from Davis et al. [1978] and Ewing (1980).

William-Chugach terrane along with the adjacent, older Peninsular terrane offshore of Oregon and Washington at 62 Ma to provide a sediment source for the turbidites of the accretionary complex. It is possible that this superterrane was attached to the continent near Oregon and was subsequently rifted away as North America overrode the Kula-Farallon ridge and an active Yellowstone hot spot at that same location (Figure 6). Our proposed Kula-Farallon ridge geometry incorporates the fact that the Yellowstone hot spot lies close to the great circle between the Paleocene Kula-Farallon pole of rotation and the Kula-Farallon-Pacific triple junction. This coincidence suggests the Kula-Farallon ridge was tied to an active Yellowstone hot spot until about 61 Ma. Subsequent spreading ridge reorganizations at 61 and 56 Ma may reflect the eclipse of the hot spot by overriding North America and the beginning of rifting.

We envision an oblique rifting geometry perhaps analogous to the Gulf of California or the Andaman Sea north of Sumatra [Curray et al., 1979] where large components of transcurrent motion are evident in the rifting process (Figure 6). The highly oblique northward convergence of the Kula plate provided tectonic transport for the northbound Prince William, Chugach and Peninsular(?) terranes [Moore et al., 1983] away from the zone of rifting in Oregon and Washington. Some of the northward motion may have been accommodated inboard of the continental margin along dextral slip faults of the Rocky Mountain-Tintina-Pasayten-Straight Creek fault systems. Davis et al. [1978] and Ewing [1980] have summarized arguments requiring as much as 500 km dextral slip across the northern end of this system during the Late Cretaceous and early Tertiary. These faults would have terminated southward in zones of extension, a geometry similar to that postulated by Davis et al. [1978]. The Eocene Chuckanut, Chiwaukum and Republic grabens were in part contemporaneous with the formation of the Coast Range basalts and are geometrically compatible with oblique rifting during dextral slip faulting [Ewing, 1980; Tabor et al., 1984; Johnson, 1982; Gresens, 1982]. These basins may represent inboard extensions of the continental margin rifting event.

The Paleocene and early Eocene basalts of the Coast Range basement could have been generated by the hot spot in the extensional basin behind the northward moving terranes. This model has some advantages over the earlier models. It eliminates many of the geometric problems that are associated with eruption and accretion of linear seamount chains on the fast, northeast moving Kula and Farallon plates. Generation of the basalt by rifting of a slow-moving North American plate is more compatible with the observed moderate rate of age progression in the basalt and could allow a symmetrical age progression to develop.

One difficulty with this model involves explanation of strong compressional deformation of the Coast Range basement basalt and overlying early Eocene turbidites at the south end of the Coast Range [Baldwin, 1974]. This isoclinal folding and shearing in the Roseburg Formation of Baldwin [1974] is most commonly ascribed to collision of a Coast Range microplate with North America during early Eocene time [e.g., Heller and Ryberg, 1983]. Alternatively this deformation could record the northward passage of the Kula-Farallon ridge and the initiation of more orthogonal convergence. A push from the Farallon plate could have partially closed the marginal basin and caused incipient subduction of its eastern edge beneath the continent.

VOLCANIC HISTORY OF WESTERN OREGON AND WASHINGTON FOLLOWING ACCRETION OF COAST RANGE BASEMENT

Late Eocene and Oligocene

Following accretion of the Coast Range basement, the period 44 to 35 Ma was characterized by diminished volcanism along the Challis volcanic axis to the east and the beginning of Cascade volcanism parallel to the new continental margin (Figures 1 and 7). This change may have occurred as a progressive southwestward migration of the volcanic front or as a discrete step from the Challis axis to the Cascade axis [Snyder et al., 1976; Dickinson, 1976; Armstrong, 1978; Dickinson and Snyder, 1979]. The Challis volcanic episode lasted from 55 Ma to perhaps 43 Ma [Armstrong, 1978] and mostly predates the beginning of Cascade arc volcanism at about 42 Ma [Priest et al., 1982; Lux, 1982; Turner et al., 1983]. In the North Cascade Range, calc-alkaline volcanism and plutonism were essentially continuous during this time period [Tabor et al., 1984] where the later Cascade volcanism overlapped the more north-westerly Challis axis [Vance, 1982]. In western Washington, early andesitic and dacitic intrusive and volcanic rocks [Tabor and Cady, 1978; P. D. Snavely, Jr., unpublished data, 1976] erupted through and onto the Coast Range basement at about 42 Ma, effectively establishing a minimum age of Coast Range tectonic accretion.

East of the Cascade axis, 47- to 35-Ma arc volcanic rocks of the Clarno Formation [Enlows and Parker, 1972] lie geographically and temporally between the Challis and Cascade volcanic rocks (Figure 1), although a few scattered ages as old as 54 Ma are reported in Fiebelkorn et al. [1982]. The significance of the Clarno Formation is not well understood. It may represent an intermediate position in the migration of the volcanic front, or it may be a remnant arc fragment separated from the main arc by subsequent rifting [Vance, 1982]. A regional unconformity throughout much of the Pacific Northwest at about 38 to 35 Ma marks the end of the initial Cascade magmatic pulse and may record widespread subsidence in the arc, back arc, and forearc [Gresens, 1982; Tabor et al., 1984; Snavely and Wagner, 1963].

In the western Cascade Range of Oregon, regionally extensive rhyodacitic ash flows dated at about 35 Ma overlie the earliest Cascade volcanic rocks [Smith et al., 1980, 1982; N. S. MacLeod, personal communication, 1983]. This marks the base of a thick Oligocene and lower Miocene sequence of silicic ash flow tuffs and lavas in the Cascade arc that is correlative with the 34- to 17-Ma Basin and Range ignimbrite flare-up described by Lipman et al. [1972], Noble [1972] and Stewart et al. [1977]. This sequence includes the Ohanapecosh (dated at 36- to 30-Ma) and the Stevens Ridge (dated at 29- to 22-Ma) Formations of Washington [Fiske, et al., 1963; Hammond, 1979; Vance, 1982], and the mostly Oligocene Little Butte

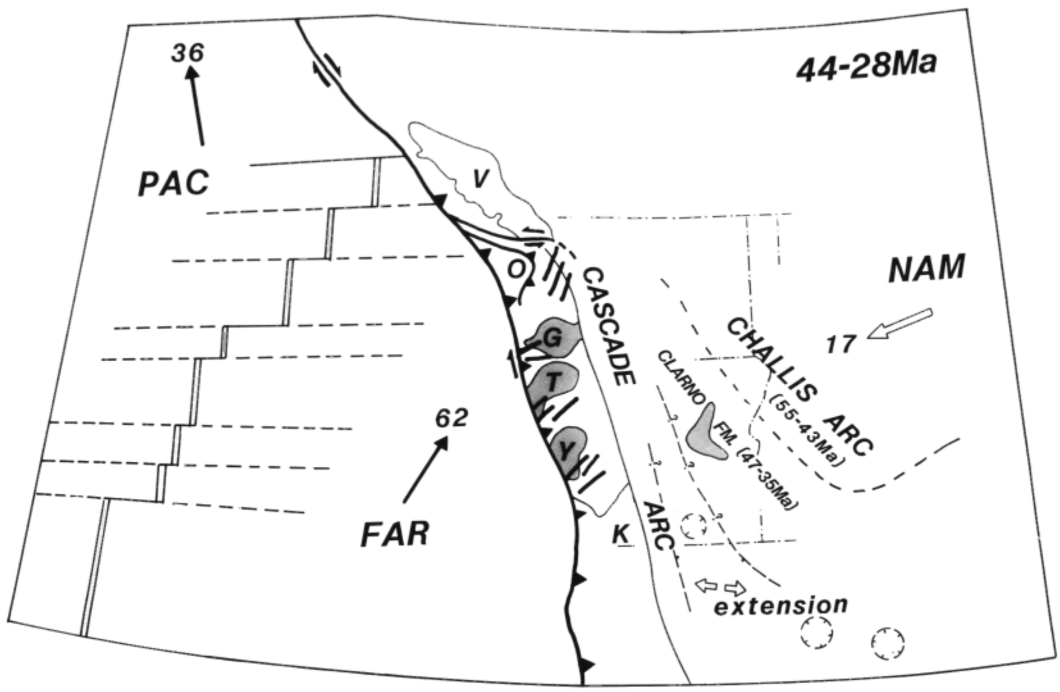

Fig. 7. Pacific Northwest patterns of volcanism 44 to 28 Ma; conventions as in earlier figures. Eruption of the Tillamook Volcanics, (T), Goble Volcanics, (G) and Yachats Basalt (Y) from regional dike swarms (short solid lines) is contemporaneous with westward step of volcanic front to Cascade axis and subsequent "ignimbrite flare up." Initial Cascade volcanism on Coast Range crust at 42 Ma represented by dikes on Olympic Peninsula (O). Dextral shear along coast drives clockwise tectonic rotations. Circular depressions schematically represent Cascade arc ignimbrite volcanism and its sources; dashed lines represent boundary of inferred interarc extension.

Formation and its equivalents in Oregon [Peck et al., 1964; Smith et al., 1980, 1982]. It consists primarily of silicic to intermediate pyroclastic and epiclastic tuff, breccia, ash flow tuff and andesite, with locally important accumulations of arc tholeiite in Oregon. Time-equivalent ash flow units also make up a significant part of the 37- to 18-Ma John Day Formation of eastern Oregon [Robinson and Brem, 1981] and abundant unnamed tuff units in south central and southeastern Oregon [Walker, 1960, 1977; Wells, 1979]. In the Coast Range, the pyroclastic activity is marked by a thick sequence of Oligocene tuffaceous siltstone containing abundant tuff and pumice lapilli tuff interbeds [Snavely and Wagner, 1963]. This Pacific Northwest episode of ash flow volcanism indicates shallow crustal emplacement of magmas, and it implies significant extension within the arc [see Hildreth, 1981].

In the Coast Range, the period 44-35 Ma is marked by several petrologically complex volcanic and intrusive episodes contemporaneous with initial Cascade arc magmatism [MacLeod and Snavely, 1973] (Figure 7). At about 44 Ma, the subaerial basalts of the Tillamook Volcanics in northwest Oregon were erupted [Magill et al., 1981; Wells et al., 1983; Snavely et al., 1970]. They were followed closely by the Goble Volcanics of southwest Washington around 40 Ma [Livingston, 1966; Beck and Burr, 1979; Wells, 1981, and unpublished data, 1980] and the upper Eocene Yachats Basalt of Oregon, dated at 37 to 35(?) Ma [Snavely and MacLeod, 1974; McElwee and Duncan, 1982]. These volcanic rocks are primarily basalt, although small amounts of andesite and dacite occur near the tops of the sequences. Chemically analyzed basalts from the Yachats and Goble Volcanics are high in titania, alumina, alkalies, and phosphate and range

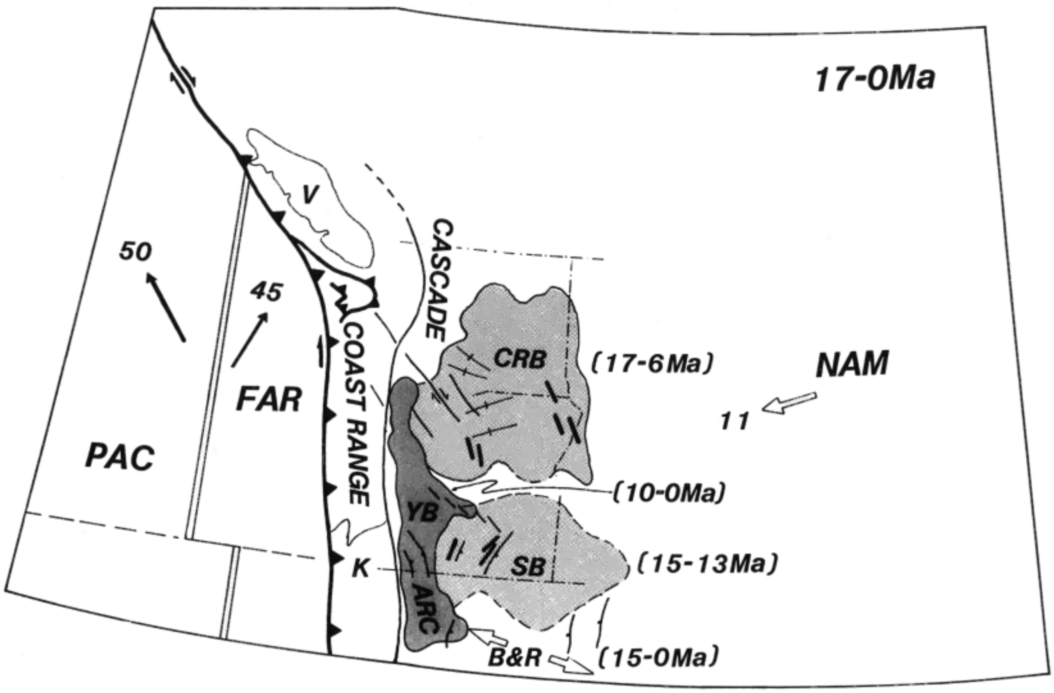

Fig. 8. Neogene extension and fundamentally basaltic volcanism in the backarc region; conventions as in earlier figures; CRB = Columbia River Basalt Group; SB = Steens Basalt and correlatives; YB = younger basalts of Cascade arc and Basin and Range; B & R = Basin and Range extension.

from quartz-normative tholeiite to alkali-olivine and high alumina basalt [Snavely and MacLeod, 1974; Wolfe and McKee, 1972]. The compositional heterogeneity suggests a mix of oceanic and magmatic arc sources. The high titanium alkalic basalts are especially unusual in a forearc setting [Gill, 1981]. The basalts were erupted from regionally extensive dike swarms that originally trended east-northeast, if we remove the subsequent clockwise tectonic rotation indicated by paleomagnetic studies [Simpson and Cox, 1977; Magill et al., 1981; Wells, 1982]. The abundant dike swarms indicate a period of north-northwest extension in the Coast Range, perhaps related to dextral shear along the coast driven by northeast directed oblique Farallon plate convergence during the late Eocene (Figure 7). Upper Eocene basaltic sandstone and deep water siltstone that overlie most of the volcanic centers record rapid erosion and subsidence of the volcanic rocks shortly after eruption [Snavely and MacLeod, 1974; Wells, 1981].

Between 35 and 30 Ma, igneous activity in the Oregon Coast Range was characterized by a suite of camptonite flows and intrusions and by sills and originally east-northeast dikes of syenite and ferrogabbro that suggests a continuation of the extensional environment [Snavely and Wagner, 1961; MacLeod and Snavely, 1973; Snavely et al., 1976a, b, c]. These extreme compositions are also very unusual in a forearc setting [Gill, 1981]. Similar Oligocene alkalic plugs can be found in coastal Mesozoic terranes as far south as Cape Mendocino, California [Meyer and Naser, 1970; Blake, 1977]. This unusual forearc magmatism may represent a local compositional perturbation of a regional extensional episode affecting the entire magmatic arc. In other arcs, sodic-alkaline lavas are associated with subduction of fracture zones normal to the trench [DeLong et al., 1975] and may reflect addition of a magmatic component from beneath the subducted slab. Several fracture zones subducting beneath Oregon at about 37 Ma may have provided a deeper source component to the Coast Range igneous rocks (Figure 2). Unequivocal Coast Range magmatism ended at about 30 Ma [Fiebelkorn et al., 1982; McElwee and Duncan, 1982], roughly concurrent with the cooling of low grade metamorphic rocks in the accretionary wedge of the Olympic Mountains at 29 Ma [Tabor, 1972].

Miocene to Present

The termination of the Oligocene and early Miocene pulse of ignimbrite activity in the central Oregon Cascade arc is marked by an unconformity at about 18 Ma [Priest et al., 1982]. Subsequent arc magmatism between 17 and 9 Ma consisted of pyroxene andesite, basaltic andesite, basalt and lesser dacite, with little of the ash flow volcanism characteristic of the previous episode [Peck et al., 1964; Priest et al., 1982]. These volcanic rocks are thin or absent in southern Oregon where a hiatus occurs between 15 and 8 Ma [Smith et al., 1982]. In the North Cascade Range of Washington, intermediate volcanism and plutonism were contemporaneous with ash flow volcanism of the Stevens Ridge Formation and continued until about 14 Ma when magmatism appeared to diminish [Hammond, 1979; Engels et al., 1976; Luedke and Smith, 1982].

The change to more abundant pyroxene andesite in the central arc at 17 Ma and the reduction in magmatism at the northern and southern ends of the arc after 15 Ma is roughly contemporaneous with deformation in the Coast Range and the beginning of major basalt volcanism and extension behind the arc. In the Olympic Mountains, a second deformation in the accretionary wedge is recorded by the formation of vein minerals at about 17 Ma [Tabor, 1972]. In the rest of the Coast Range, regional late middle Miocene deformation and uplift (about 14-12 Ma) was widespread [Snavely et al., 1980; Wells, 1981]. East of the Cascade arc, tholeiitic flood basalts of the Columbia River Basalt Group were erupted primarily between 17 and 13 Ma [Swanson et al., 1979], while coeval plateau basalts including the Steens Basalt and Owyhee Basalt were erupted in southeastern Oregon [Walker, 1977; Watkins and Baksi, 1974] (Figure 8). In the Oregon Basin and Range, the basalt volcanism continued into the Holocene, perhaps migrating northwestward toward the Cascade arc [Walker, 1977; McKee et al., 1983] possibly in step with the westward migration of silicic volcanism reported by MacLeod et al. [1976] for southeast Oregon.

Post 9 Ma mafic to silicic volcanism in the Oregon Cascade arc was marked by an apparent eastward shift of the volcanic front close to the High Cascade axis and the eruption of open textured olivine basalt, basaltic andesite, and locally abundant silicic ash flow tuff, possibly reflecting development of an extensional tectonic regime within the arc [Priest et al., 1982; Smith and Taylor, 1983]. In Washington, arc activity remained very sparse until the Pliocene when mafic and intermediate lavas erupted in southern Washington and were followed by localized Quaternary andesite and dacite volcanism along the High Cascade axis [Luedke and Smith, 1982]. In Oregon, mafic High Cascade lavas predominated after 5 Ma and were accompanied by extensional faulting and possible formation of localized grabens at about 4.5 Ma [Taylor, 1981; Smith and Taylor, 1983]. In the southern Cascade arc the Klamath graben plunges beneath Quaternary Cascade lavas and suggests migration of Basin and Range extension into the arc [Magill et al., 1982].

Discussion

The timing of Coast Range, Cascade arc, and back arc volcanic events suggests a relationship to the rapid decrease in the convergence rate between the Farallon plate and North America during the Tertiary (Figure 9). Between 43 and 28 Ma, Farallon convergence rates decreased from an average 150 km/Ma between 80 and 43 Ma to less than 40 km/Ma during the Neogene. The transition period (43-28 Ma) correlates very well with the major episode of Coast Range basaltic and alkalic volcanism (44-30 Ma), the westward step of the volcanic front to the Cascade axis at about 42 Ma, and increased ignimbrite activity in the Cascade arc (37-18 Ma). The contemporaneous southwest sweep of ignimbrite volcanism across the Great Basin marks a fundamental change from earlier Laramide compressional tectonics and is thought to be related to a migrating flexure or increasing dip in the subducting plate [Stewart et al., 1977; Coney, 1979].

The drop in convergence rate since 43 Ma may be caused by subduction of increasingly younger and more buoyant Farallon plate [Engebretson et al., this issue], thus decreasing trench pull forces. Subduction of young buoyant crust

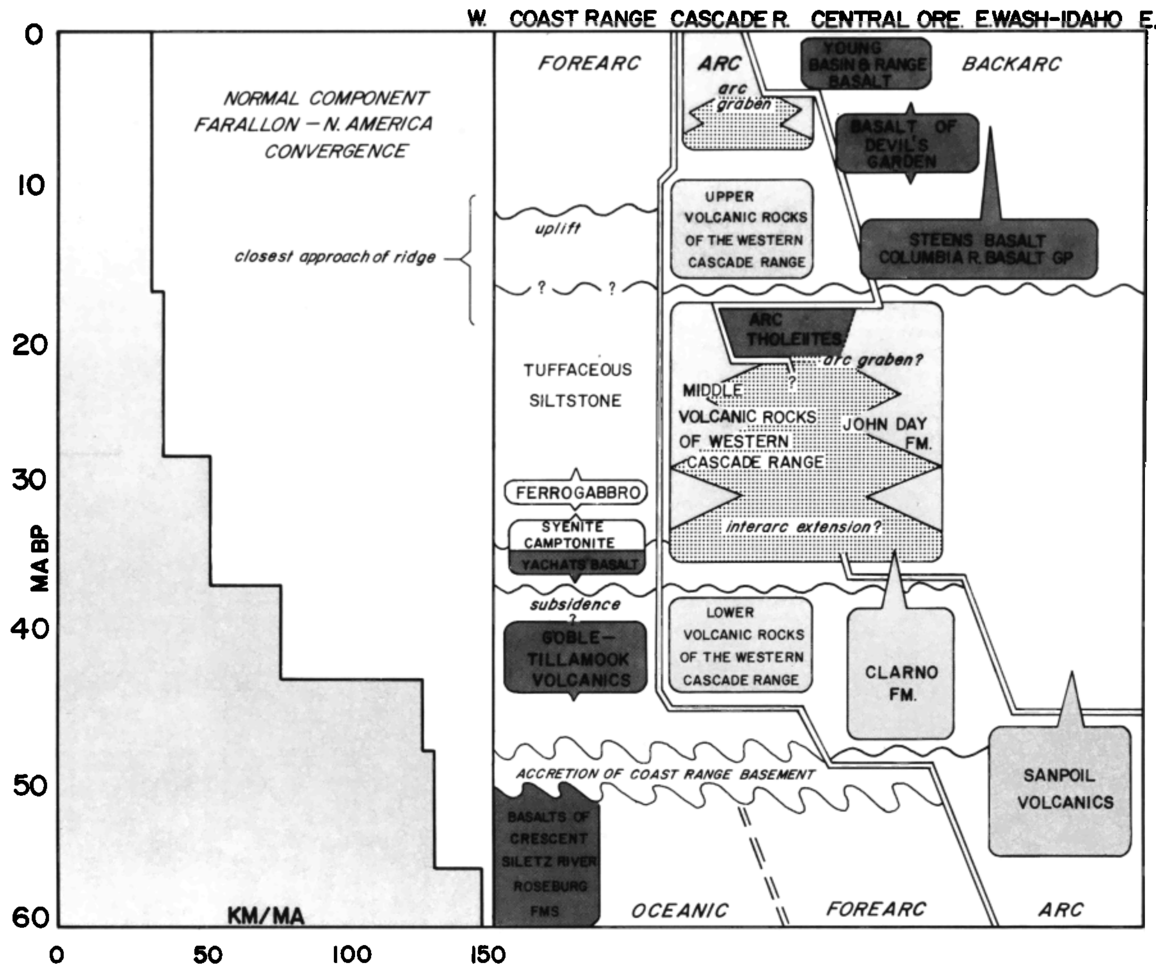

Fig. 9. Normal Farallon-North America convergence rate correlated with major volcanic events in the Pacific Northwest forearc, arc and back arc. Double lines are interpreted boundaries of tectonic environments; wavy lines are unconformities. Light-gray units are "typical" basalt-andesite-dacite-rhyolite arc volcanic rocks, dark- gray units are fundamentally basaltic volcanic rocks representing extensional regimes; stippled units are Cascade-derived tuffaceous rocks correlative with the Oligocene ignimbrite flare-up in the Basin and Range. Upper volcanic rocks of Western Cascade Range include the Sardine Formation of Peck et al. [1964] in Oregon and its Washington equivalents; middle volcanic rocks of Western Cascade Range include the Little Butte Volcanics of Peck et al. [1964] in Oregon and its Washington equivalents; lower volcanic rocks include volcanic rocks below the Little Butte in Oregon [N. S. Macleod, personal communication, 1983; Lux, 1982] and the Naches Formation and equivalents in Washington [Tabor et al., 1984]. Radiometric age control for Oregon units from compilation by Fiebelkorn et al. [1982]; for Washington units from Engels et al. [1976], Pearson and Obradovich [1977], Tabor et al. [1984] and Vance [1982]. See text for other sources of data.

is seemingly at odds with a progressive increase in the dip of the downgoing slab, but Furlong et al. [1982] have noted that the rigidity of the slab also decreases with decreasing age and convergence rate. They show the resistance to bending, and hence the radius of the zone of curvature in the slab, is greater in old, rapidly converging crust and smaller in young, slowly subducting crust. As a result, rapidly subducting old crust has a much larger contact area with the overlying continental lithosphere and should transmit greater compressive stress to the continent. This analysis is consistent with the patterns of magmatic activity and suggests that decreasing convergence rates caused a reduction in the horizontal compressive stress in the North American plate, thus allowing more magma injection into the crust and widespread volcanism behind the subduction zone. Several episodes of interarc extension may have occurred in the Cascade arc at this time, perhaps contemporaneous with each decrease in Farallon-North America convergence at about 43, 37 and 28 Ma (Figure 9). Basalt predominated in the thin basic crust near the continental margin, while more silicic volcanism was common to the east in areas underlain by continental crust.

During the Neogene, slow convergence rates were typical and no major changes in convergence direction occurred (Figure 3). The overall decrease in convergence rate may correlate with a decreasing volume of volcanic rocks erupted in the central Cascade arc during the same time period [White and McBirney, 1978], but the volume relationships are preliminary at this point. In contrast to earlier volcanic episodes, several major Miocene events occurred during this period of no major change in plate motion, including (1) deformation and uplift in the Olympic Mountains (17 Ma) and the Coast Range (14-12 Ma); (2) transition from mixed silicic ignimbrite, andesite and tholeiitic volcanism to more andesitic volcanism in the central Cascade arc (19-17 Ma); (3) temporary cessation of southern Cascade volcanism (15 Ma); and (4) tremendous flood basalt eruptions in the back arc region (17-13 Ma).

It is possible that some of these events are related to a very close approach of the Farallon-Pacific spreading ridge to the continent at about 16 Ma (Figure 2). At that time the ridge was probably less than 200 km offshore and may have produced compression and uplift in the continental margin as it overrode young crust (5-10 Ma) on the elevated ridge flank [DeLong and Fox, 1977]. The transition in the arc from a mixed assemblage containing ignimbrites to one of andesitic lavas, and the localized cessation of volcanic activity may reflect increased horizontal compression in the arc. Subsequent migration of the ridge away from the continent (after 12 Ma) and further reductions in the convergence rate mark a return to extensional, primarily mafic volcanism in the arc and the accompanying migration of back arc volcanism toward the arc. In contrast, the middle Miocene Columbia River Basalt Group and the Steens Basalt have no obvious connection to Farallon plate motions, other than their location east of the subducting slab. Their eruption during the close approach of the ridge suggests a tectonic control other than passive back arc spreading.

CONCLUSIONS

Detailed plate motion models for the northeast Pacific provide a useful framework for analysis of Tertiary patterns of volcanism in western Oregon and Washington, although the degrees of freedom in most tectonic models remain high. Our analysis of possible origins for the early Tertiary Coast Range submarine basalt basement suggests the following:

1. Microplate rotation and accretion of linear aseismic ridges are inconsistent with our plate model which indicates rapid northeast motion of the Kula and Farallon plates during the Tertiary. Accretion of hot spot island chains would be complex, requiring dismemberment and telescoping of the ridges during accretion.
2. Multiple Kula-Farallon ridge reorganizations between 61 and 48 Ma suggest a modification to the hot spot model in which the basalts are episodically generated along leaky fractures and transforms during changes in spreading directions. Proximity to an active Yellowstone hot spot would help produce large edifices on the fracture zones.
3. Alternatively, the proximity during the Paleocene in the position of the Coast Range and the preferred paleolatitude of allochthonous Paleocene terranes of southern Alaska suggests possible eruption

of the basalt in the wake of oblique continental rifting of North America. This may have occurred as the marginal terrane overrode an active Yellowstone hot spot and the nearby Kula-Farallon ridge.

Subsequent continental magmatism in the Pacific Northwest shows good temporal correlation to changes in plate motions. A marked decrease in Farallon-North America convergence rates between 43 and 28 Ma correlates with (1) a westward step in the volcanic front to the Cascade axis; and (2) widespread extensional volcanism in the arc and forearc, possibly related to decreasing horizontal compressive stresses in the North American plate. Middle Miocene Coast Range deformation and partial choking of the arc may have resulted from continental margin compression during the very close approach of the Pacific-Farallon ridge to the continent during the middle Miocene.

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