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A CAPTURED ISLAND CHAIN IN THE COAST RANGE OF OREGON AND WASHINGTON

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Abstract. K-Ar and ^{40}Ar-^{39}Ar geochronologic data reveal the Paleocene to Eocene eruptive history of volcanic centers which produced the basaltic basement rocks of the Coast Range of Oregon and Washington. Volcanism was short lived at each center and migrated with time from the northern and southern ends toward the center, near the present mouth of the Columbia River. A plot of crystallization ages against geographic location produces a distinct V-shaped pattern. An origin by hot spot volcanism centered on or near a spreading ridge in early Tertiary time best explains the observed age distribution. Limited geochemical data support this model, as the basalts exhibit attributes of both spreading ridge and hot spot-related volcanism. Icelandic volcanism may be a present-day analog. Absolute motion modeling shows that the Yellowstone hot spot could have generated an island chain with approximately the correct paleoazimuth and volcanic propagation rate. Shortly after formation, this oceanic volcanic lineament collided with North America and rotated into its present marginal setting. The western edge of North America subsequently crossed over the hot spot, perhaps triggering late Eocene to Oligocene volcanism in the Coast Range, the Miocene Columbia River basalts in eastern Washington and Oregon and most recently, the basalts of the Snake River Plain and the Yellowstone area.

1. The Coast Range, Oregon and Washington

Recently much interest has focused on the tectonic history of the continental margin of western North America [e.g., Beck, 1980]. Field and laboratory studies have identified allocthonous terrains ('blocks' or 'microplates') which have been accreted to the North American plate during translation (right-lateral sense) and convergence with oceanic plates to the west [e.g., Simpson and Cox, 1977; Hillhouse, 1977]. The Coast Range of Oregon and Washington is one such terrain which is thought to have formed on the Farallon plate and, subsequently, rotated clockwise into its present position during collision with North America. This paper reports age determinations on basaltic samples from the basement rocks in the Coast Range which define a systematic progression most compatible with an origin by hot spot volcanism centered beneath a segment of the early Eocene Kula-Farallon spreading ridge.

The oldest rocks exposed in the Coast Range are tholeiitic submarine pillow lavas and breccias which grade locally into subaerially erupted alkalic basalts [Snavely et al., 1968; Cady, 1975]. These rocks crop out in a north-south linear swath from the southern tip of Vancouver Island to southern Oregon (Figure 1). From field relations and geophysical studies (gravity and aeromagnetic surveys [Bromery and Snavely, 1976; Couch and Braman, 1979] and seismic refraction [Berg et al., 1966; Langston, 1981]), the average thickness of this volcanic sequence has been estimated to be 3000 m [Snavely et al., 1968] but to exceed 6000 m at proposed eruptive centers. Younger lava flows of the Cascade Range cover the eastern boundary of the province, and the western boundary is thought to extend out to the edge of the continental shelf [Shor et al., 1968; Snavely et al., 1980]. From refraction studies the crust beneath the Coast Range has an estimated thickness of 15-20 km, intermediate between oceanic and continental crust. The estimated volume of erupted material is 250,000 km^3, which exceeds all other volcanic units in the Pacific Northwest, including the classic Columbia River Basalt province.

Thick sequences of continentally derived turbiditic sandstones and siltstones interfinger with and overlie the basement basalts, evidence indicating that the volcanic centers were formed close to a continental margin [Cady, 1975]. Current directions and lithologic characteristics of the sandstones of the middle Eocene Tyee Formation indicate a source region to the south, possibly the Klamath Mountains [Snavely et al., 1964]. The variable thickness of these sediments reflects the irregular volcanic topography on which they were deposited. Marine siltstones, sandstones, and conglomerates document an active continental margin undergoing vertical tectonics probably resulting from the overall convergent pattern. Large ash contributions to these sediments in Oligocene time correlate with the onset of volcanism in the ancestral Cascade Range [Snavely and Wagner, 1963]. Basaltic rocks manifest distinct pulses of volcanism in the late Eocene, middle Oligocene, and middle Miocene.

2. Geochronology Indicates Age Progressive Volcanism

The Tertiary and Quaternary sequences present in the Coast Range of Oregon and Washington occupy the forearc region in the generalized subduction model, overlying a low-angle, eastward dipping subduction zone that separates North America (above) from the Farallon plate (below). The presence of volcanic basement rocks in forearc regions is unusual (accreted sediments and their metamorphosed equivalents generally predominate), and various origins have been proposed for the Coast Range basalts:

1. The basalts accumulated in a eugeosynclinal trough that formed most of western Oregon and Washington after rising directly from the mantle through north-south fissures, perhaps

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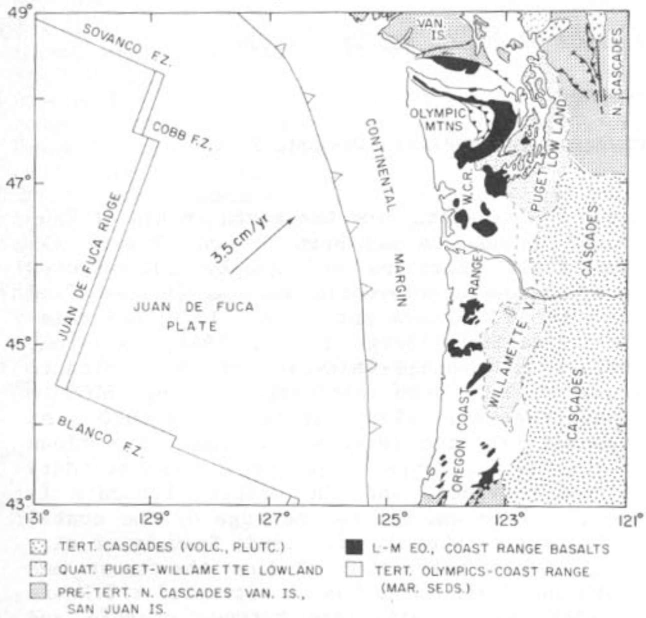

Fig. 1. Generalized geology and present plate boundaries in the Pacific Northwest. The basement rocks in the Coast Range (solid black) crop out in a north-south linear pattern from the southern tip of Vancouver Island to southern Oregon. These are tholeiitic submarine pillow lavas and subaerial alkalic basalts, which are thought to have been erupted as a line of islands at a segment of the early Tertiary Farallon-Kula plate spreading ridge.

following some differentiation in crustal magma chambers [Snavely and Wagner, 1963],

2. The basalts formed as a line of seamounts and islands on the Farallon plate, east of the proto-Juan de Fuca Ridge, followed by plate collision, which led to accretion of the volcanic lineament onto the North American plate [Snavely et al., 1968; Snavely and MacLeod, 1974; Cady, 1975],

3. The lower, submarine tholeiitic basalts formed as a piece of ocean floor [Snavely et al., 1980; McWilliams, 1980] upthrust during plate collision with North America into fault contact with the chemically distinct upper, subaerial, alkalic basalts of perhaps local continental origin [Glassley, 1974],

4. Island arc volcanism on the continental margin of western North America during Paleocene to early Eocene time produced this volcanic province, which was uplifted with further subduction [Lyttle and Clarke, 1974] and gave way to Cascade volcanism in Oligocene time.

5. The basalts formed by hot spot volcanism at the Farallon-Kula spreading ridge and rotated into their present position during subduction of the Farallon plate beneath North America [Simpson and Cox, 1977].

The age of the basement volcanic rocks has been previously estimated from the fossil remains of planktonic and benthic organisms preserved in sediments interbedded with the lava flows [Macleod and Snavely, 1973; Baldwin, 1974; Snavely et al., 1976; McWilliams, 1980]. These correlate with the Penutian and Ulatisian stages defined by Mallory [1959] or early to middle Eocene age. Paleocene sediments are interbedded with the Roseburg Volcanics in southern Oregon [Baldwin, 1974]. Whether all volcanism north to south was contemporaneous or age progressive has been a subject of debate. MacLeod and Snavely [1973] felt that volcanism throughout the province was contemporaneous in early to middle Eocene time. It is possible that lower, older sections are exposed in the north and south. McWilliams [1980] contends that basalts in the central portion of the province are younger (middle Eocene) than those at the northern and southern extremes (early Eocene), based on his interpretation of fossil evidence.

Radiometric dating (K-Ar, ^{40}Ar-^{39}Ar) was undertaken to clarify the age relationships within the volcanic basement rocks. These analyses define the absolute age of volcanism at the various centers of accumulation and its duration and measure any progression of volcanic activity with time within the province. With regard to the various origin models above, age progressive volcanism would support models 2 or 5, whereas synchronous or randomly distributed ages would suit models 1 or 4. A distinct age difference between the upper and lower units would support model 3. Brief cycles of voclanism at eruptive centers would be compatible with an oceanic island origin, 2, but extended activity might fit model 1 or 4 better.

Following thin section examination, selected samples were crushed, washed in distilled water, and sieved to 0.5-1 mm size. Argon isotopic compositions were determined using either a high-resolution Reynolds-type or AEI MS-10S mass spectrometer, each equipped with ^{38}Ar spike pipette systems (for conventional K-Ar analyses). Potassium concentrations were measured by atomic absorption spectrophotometry. For ^{40}Ar-^{39}Ar age work, split aliquants of crushed samples were irradiated at the U.S. Geological Survey's TRIGA Reactor in Denver, Colorado, for 4 hours at 1-MW power. Operating conditions and isotope interference corrections have been reported by Dalrymple et al., [1981a].

K-Ar ages (Table 1) reveal a clear and systematic age-space correlation. Specifically, there is a monotonic decrease in crystallization age from the southernmost center (Roseburg basalt) to the Grays River area of southwestern Washington (Figure 2). From there to the exposures in the Black Hills region of central western Washington, ages increase. Conventional K-Ar ages from samples from the Olympic Peninsula and southern Vancouver Island are scattered and appear to have suffered variable argon loss from low-grade metamorphism.

Stratigraphic position of samples is not always well known, especially in the more tectonically disturbed areas, and the extent of the volcanic section exposed varies from center to center. Nevertheless, ages at each center are closely grouped for samples collected from geographically separated sites. (Exceptions are samples suspected of argon loss, discussed below.) Potassium content (Table 1) of lavas may estimate the degree of fractionation, which is a rough guide to stratigraphic position in oceanic island evolution. If so, sampling at the Roseburg, Siletz River, Tillamook, and Grays River centers has been more comprehensive than at those farther north. The range in measured

TABLE 1. K-Ar Geochronology of Basalts from the Coast Range, Oregon and Washington

Sample	Location	Percent K	Radiogenic ^{40}Ar, x 10^{-6} cm^3/g	Percent Radiogenic Ar	Age,* m.y. ± 1σ
	Roseburg Volcanics				
D78-RB-15	SW¼ SE¼ sec. 24, T22S R6W Drain 15' Quad.	1.2054	2.9605	67.4	62.1± 1.0
D78-RB-20	NW¼ SE¼ sec. 10, T28S R12W McKinley 7½' Quad.	0.4128	1.0064	18.0	61.7± 3.6
D78-RB-21	SW¼ NE¼ sec. 26, T29S R12W Bridge 7½'Quad.	0.5157	1.2530	45.0	61.5± 1.6
D78-RB-24	SW¼ NE¼ sec. 11, T27S R12W McKinley 7½' Quad.	0.3160	0.7489	36.2	60.0± 1.7
D78-RB-25	SE¼ SE¼ sec. 22, T25S R12W Allegany 7½' Quad.	0.3157	0.7381	20.8	59.2± 2.8
D80-RB-31	Mobil Well site, Sutherlin, Oreg., 4500 m depth	0.1035	0.2149	29.6	52.7± 0.7†
	Siletz River Volcanics				
D78-SR-1	NE¼ SW¼ sec. 17, T14S R7W Alsea 15' Quad.	0.3654	0.7297	18.7	50.7± 3.1†
D78-SR-6	SW¼ SW¼ sec. 5, T8S R10W Euchre Mt. 15' Quad.	0.7267	1.5153	62.1	52.9± 1.0
D78-SR-7	NE¼ SW¼ sec. 5, T8S R10W Euchre Mt. 15' Quad.	0.4870	1.0514	48.2	54.7± 1.9
			1.1159	44.7	58.1± 1.5
D78-SR-10	NE¼ NE¼ sec. 3, T8S R9W Euchre Mt. 15' Quad.	0.3240	0.7272	87.0	56.9± 0.8
			0.7196	82.3	56.3± 0.9
D78-SR-11	NE¼ SE¼ sec. 27, T8S R9W Euchre Mt. 15' Quad.	0.2771	0.6073	40.5	55.5± 1.9
			0.5918	58.9	54.2± 1.2
	Tillamook Volcanics				
D78-TM-6	NW¼ NE¼ sec. 26, T1S R7W Blaine 15' Quad.	1.2016	2.5404	67.6	53.6± 1.0
D78-TM-8	NE¼ NW¼ sec. 26, T1S R7W Blaine 15' Quad.	0.1144	0.2527	43.8	56.0± 1.5
			0.2521	44.8	55.8± 1.6
D78-TM-11	SE¼ NW¼ sec. 33, T3S R8W Blaine 15' Quad.	0.5210	1.0611	57.7	51.7± 1.0
	Grays River Volcanics				
D78-GR-1	NE¼ NE¼ sec. 18, T12N R9W S Bend 15' Quad.	0.2852	0.5432	46.9	48.4± 1.2
D78-GR-2	Center Sec. 10, T12N R9W N Nemah 7½' Quad.	0.0755	0.1556	5.6	52.3±12.1
D78-GR-4	SW¼ NE¼ sec. 32, T13N R8W Raymond 15' Quad.	0.2403	0.4418	33.9	46.7± 1.8
D78-GR-5	NW¼ SW¼ sec. 35, T15N R9W S Bend 15' Quad.	0.6668	1.2672	43.3	48.3± 1.3
	Crescent Volcanics (Black Hills)				
D78-BH-6	NW¼ NW¼ sec. 14, T18N R3W Shelton 15' Quad.	0.3316	0.6768	48.8	51.8± 1.0
D78-BH-7	SW¼ NW¼ sec. 18, T18N R4W Shelton 15' Quad.	0.2551	0.5602	33.2	55.6± 1.2
D78-BH-18	SW¼ NE¼ sec. 15, T17N R4W Rochester 15' Quad.	0.2532	0.5315	53.5	53.3± 1.3
D78-BH-19	NE¼ SW¼ sec. 18, T17N R4W Rochester 15' Quad.	0.2761	0.5648	26.1	51.9± 2.3
D78-BH-23	SE¼ SE¼ sec. 7, T16N R4W Rochester 15' Quad.	0.2726	0.5525	17.7	51.4± 4.0
	Crescent Volcanics (Olympic Peninsula)				
D80-CV-24	NE¼ NW¼ sec. 33, T24N R1E Bremerton W 7½' Quad.	0.2348	0.4002	49.0	43.3± 0.5†
			0.4338	46.3	46.9± 0.6†
D80-CV-25	NE¼ NW¼ sec. 33, T24N R1E Bremerton W 7½' Quad.	0.2193	0.4243	55.9	49.2± 0.6†
D80-CV-26	NE¼ NW¼ sec. 33, T24N R1E Bremerton W 7½' Quad.	0.2288	0.4062	64.6	45.2± 0.5†
	Metchosin Volcanics				
D80-MT-2	Happy Valley Rd., 3 km S of Langford, B.C.	0.1782	0.3730	62.9	53.1± 0.7†
D80-MT-3	East Sooke Rd., @ Speyside Rd., Metchosin, B.C.	0.0561	0.0955	31.9	43.3± 0.8†
D80-MT-4	0.5 km E of Sooke Gabbro, East Sooke Rd.	0.0583	0.0960	40.2	41.9± 0.9†

*Ages calculated from the following decay and abundance constants: $\lambda_\varepsilon = 0.518 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol.

†Argon loss suspected.

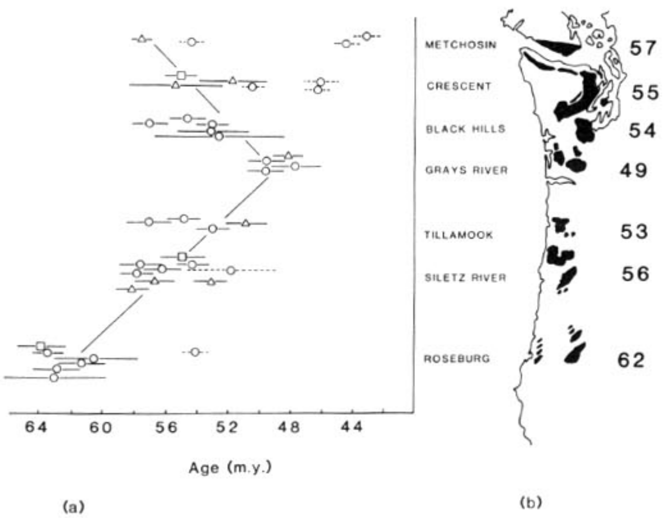

Fig. 2. (a)K-Ar and ^{40}Ar-^{39}Ar geochronology of basalts from the Coast Range, Oregon and Washington, reveals a V-shaped pattern when ages at various eruptive centers are plotted against distance. Open circles are conventional K-Ar age determinations, triangles are ^{40}Ar-^{39}Ar total fusion ages, and squares are ^{40}Ar-^{39}Ar incremental heating isochron ages. Horizontal bars show 1σ errors in measured ages. Dashed bars are samples suspected of argon loss. The rate of migration of volcanism (solid line segments connecting ages determined at individual eruptive centers, fitted by eye) is estimated to be 40 mm/yr. (b)Average ages are oldest at the northern and southern ends of the province, younging toward the center.

ages indicates that volcanism was of short duration at each center, up to 4 m.y.

For samples which were erupted in the submarine environment, difficulties in interpreting K-Ar age information may result from submarine weathering (radiogenic ^{40}Ar loss during alteration and K addition from seawater) and trapped (excess) argon. Regional burial metamorphism, particularly in the northern end of the province, may also have led to significant argon loss. Indeed, conventional K-Ar ages from the Crescent and Metchosin volcanics are scattered between 42 and 53 m.y. If the age lowering has resulted from a regional tectonic event, the ages grouped around 44 m.y. provide a maximum age estimate for the emplacement of the northern end of the Coast Range. To examine these effects, selected samples were chosen for ^{40}Ar-^{39}Ar study. Tables 2 and 3 and Figures 2 and 3 summarize these results which complement the conventional K-Ar age determination method.

As reported by Clague et al., [1975] and Dalrymple and Clague [1976], ^{40}Ar-^{39}Ar total fusion ages on whole rock basalt samples affected by submarine weathering are frequently consistent with ages determined from fresh mineral separates (primarily feldspar) and ages based on ^{40}Ar-^{39}Ar incremental heating experiments, while conventional K-Ar ages from the same rocks are lower. The reasons for the more reliable total fusion ages are unclear, but these authors propose that ^{39}Ar derived from K-bearing alteration minerals during neutron bombardment is lost from the sample prior to fusion, either during irradiation or extraction line bake out. Since this ^{39}Ar comes from alteration sites where radiogenic ^{40}Ar was previously lost (and/or unsupported K was added), the ^{40}Ar-^{39}Ar age commonly approaches the sample crystallization age. Experiments which employ break-seal vials to retain argon lost from the sample during irradiation confirm this explanation [Duncan, 1978, and unpublished data, 1981].

Samples selected from the Coast Range basalts show this effect: D78-SR-1, D80-CV-24, D80-CV-26, and D80-MT-2 all exhibit ^{40}Ar-^{39}Ar total fusion ages which exceed their conventional K-Ar ages and more closely estimate the crystallization age. The new age estimate for D78-SR-1, for example, is indistinguishable from the bulk of K-Ar ages from the Siletz River eruptive center. The other ^{40}Ar-^{39}Ar total fusion ages in Table 2 confirm previous conventional K-Ar age determinations and indicate that alteration was not a serious problem in those samples.

The ^{40}Ar-^{39}Ar incremental heating experiments done on four samples of Coast Range basalt (Table 3) are illustrated as isochron plots in Figure 3. Dalrymple et al., [1981b] have re-

TABLE 2. The $^{40}Ar/^{39}Ar$ Total Fusion Age Data on Basalts from the Coast Range, Oregon and Washington

Sample	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$	$^{37}Ar/^{40}Ar$*	Percent Radiogenic ^{40}Ar	Age, m.y. $\pm$ 1σ
D78-SR-1	19.339	360.92	0.1162	18.1	56.7±1.3
D78-SR-6	10.222	495.14	0.1574	40.3	52.9±1.0
D78-SR-10	6.398	775.61	0.4172	61.9	58.1±1.0
D78-TM-11	41.138	960.94	0.1638	69.2	50.7±1.2
D78-GR-5	33.269	1587.00	0.1652	81.4	48.1±1.0
D80-CV-24	385.48	323.57	0.0499	8.7	51.7±2.4
D80-CV-26	319.07	319.07	0.0484	7.4	55.3±3.1
D80-MT-2	181.92	372.00	0.1504	20.6	57.8±0.8

*The ^{37}Ar corrected for decay.

TABLE 3. The $^{40}Ar/^{39}Ar$ Incremental Heating Data on Basalts From the Coast Range Oregon and Washington

	Increment	$^{40}Ar/^{39}Ar$	$^{40}Ar/^{36}Ar$	$^{37}Ar/^{40}Ar$*	^{39}Ar (Percent of Total)	$^{40}Ar_{Rad.}$, %	Age, m.y. $\pm 1\sigma$
D80-RB-31	1	899.47	308.19	0.0329	3.6	4.1	55.3± 6.5
	2	2827.3	300.90	0.0069	13.1	1.8	65.7±16.8
	3	455.50	322.73	0.0291	22.6	8.4	58.5± 5.2
	4	355.84	330.20	0.0617	30.3	10.5	58.2± 1.4
	5	238.89	357.10	0.2484	17.0	17.3	68.9± 1.4
	6	171.14	374.79	0.4642	13.3	21.2	63.6± 0.7
Recalculated total fusion age							61.7± 2.6
Isochron age and intercept							63.9± 1.9
All increments							294.6± 1.4
SUMS/(N-2)†							0.5
D78-SR-1	1	16.457	395.08	0.0528	2.5	25.2	39.3± 1.4
	2	11.414	598.78	0.0687	3.4	50.6	54.3± 0.9
	3	8.006	1253.9	0.0876	8.9	76.4	57.3± 0.7
	4	6.795	2473.2	0.1097	13.9	88.0	56.1± 0.6
	5	6.141	2860.6	0.0283	19.7	89.7	52.5± 0.6
	6	6.301	1146.1	1.5760	51.6	74.2	51.2± 0.6
Recalculated total fusion age							52.5± 0.4
Isochron age and intercept							54.9± 1.7
Increment 1 omitted							265.2± 6.5
SUMS/(N-2)							33.7
D78-SR-10	1	593.18	1574.6	0.0187	<1	81.2	(2365 ±18)
	2	10.866	274.19	0.4197	2.6	0.0	(-4.9± 1.3)
	3	7.485	417.25	0.5262	6.3	29.2	25.0± 0.7
	4	6.258	938.44	0.6541	12.1	68.5	45.9± 0.6
	5	5.801	1951.48	0.6718	46.1	84.9	53.6± 0.6
	6	6.073	924.87	2.1346	33.0	68.0	51.6± 0.6
Recalculated total fusion age							48.8± 0.6
Isochron age and intercept							55.4± 1.0
Increment 1 omitted							130.4± 6.0
SUMS/(N-2)							6.2
D80-CV-25	1	14905	298.10	0.0048	<1	<1	48.4±18
	2	105.48	412.31	0.0714	47.4	28.3	54.9± 1.3
	3	118.35	386.54	0.1080	31.2	23.6	51.8± 2.0
	4	104.24	443.87	0.1624	10.4	33.4	64.8± 1.9
	5	128.93	379.79	0.3645	6.9	22.2	57.0± 3.6
	6	132.70	356.22	0.8067	4.1	17.0	52.7± 2.4
Recalculated total fusion age							55.0± 0.9
Isochron age and intercept							55.4± 3.2
All increments							286.1±14.9
SUMS/(N-2)							3.8

*The ^{37}Ar corrected for decay.
†Weighted least squares fit index [York, 1969].

viewed the interpretation of age data derived from such experiments, and this discussion follows their recommendations. In Figure 3, $^{40}Ar/^{36}Ar$ is plotted against $^{39}Ar/^{36}Ar$ for the individual temperature steps reported in Table 3. The slope of the weighted least squares line through the data from each sample determines the age, and the intercept gives the $^{40}Ar/^{36}Ar$ composition of nonradiogenic Ar.

Sample D80-RB-31 yields an isochron age of 63.9 ± 1.9 m.y. and a $^{40}Ar/^{36}Ar$ intercept of 295 ± 2. This age agrees with the 'plateau' developed by the five highest temperature steps and with the total fusion age recalculated from all increments. In addition, the intercept is indistinguishable from the atmospheric value (295.5), and the regression fitting index, SUMS/(N-2) [York, 1969], is acceptably low at 0.5. By all criteria this age is reliable and reassuringly similar to the conventional K-Ar ages (Table 1) from the Roseburg Volcanics. The K-Ar age for this sample, however, is 10 m.y. lower, which is attributable to argon loss resulting from burial metamorphism (4500 m well depth).

Samples D78-SR-1 and D78-SR-10 fail to meet

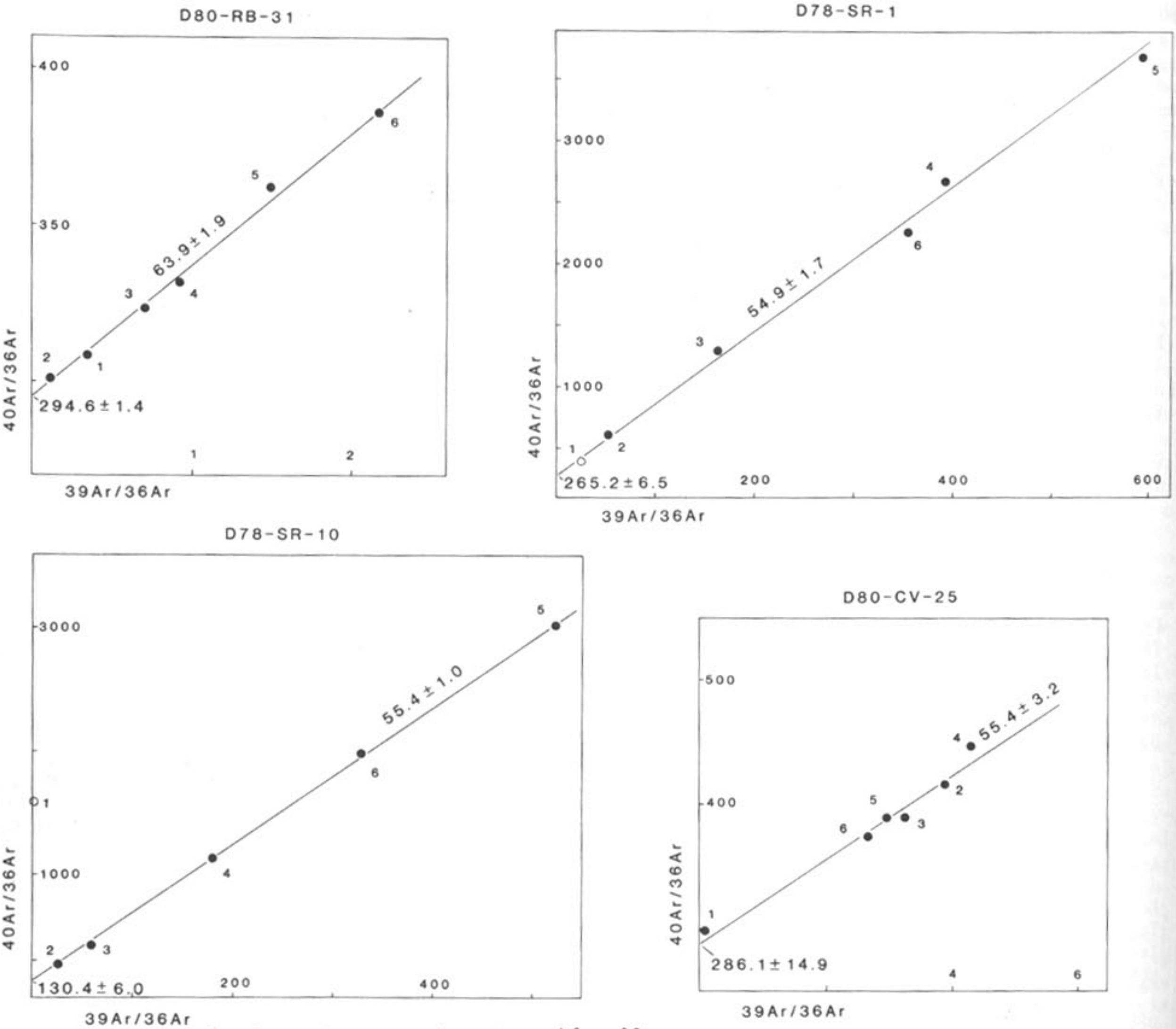

Fig. 3. Isochron diagrams for four $^{40}Ar-^{39}Ar$ incremental heating experiments on tholeiitic basalts from the Coast Range. Increasing temperature steps are numbered as in Table 3. Those used in the weighted least squares fits are indicated by solid circles. Isochron ages and nonradiogenic $^{40}Ar/^{36}Ar$ intercepts are shown. Only D80-RB-31 and D80-CV-25 meet all reliability criteria.

certain criteria and should be interpreted cautiously. A well-defined plateau is established by the five highest temperature steps of D78-SR-1, but the $^{40}Ar/^{36}Ar$ intercept is just under 295.5, and the fit index is much higher than the proposed cutoff of 2.5. The isochron age agrees well with the total fusion age (Table 2), however, and falls within the range of other Siletz River Volcanics K-Ar ages (Table 1). Age spectra from sample D78-SR-10 are too disturbed to yield a reliable crystallization age. The $^{40}Ar/^{36}Ar$ intercept falls far below the atmospheric value, and the scatter about the fitted line is somewhat greater than acceptable. The isochron age is lower than those calculated by conventional K-Ar analyses or the total fusion method, and the older estimates are preferred.

The isochron age derived from sample D80-CV-25 appears to be a good estimate of the crystallization age. The fit index is slightly higher than acceptable, but the $^{40}Ar/^{36}Ar$ intercept is appropriate, and the isochron age (55.4 ± 3.2) agrees well with the recalculated total fusion age (55.0 ± 1.3). The K-Ar age for this sample (49.2 ± 0.6) has been affected by argon loss, so the $^{40}Ar-^{39}Ar$ estimates are preferred.

The $^{40}Ar-^{39}Ar$ analyses show that except for samples from the northern exposures (Olympic Peninsula and southern Vancouver Island), conventional K-Ar ages from Coast Range basalts are close estimates of crystallization age which varies systematically along the volcanic lineament. Argon loss is identified in the Crescent and Metchosin volcanics (and occasional samples from the southern Coast Range), which yield older and more reliable ages by the $^{40}Ar-^{39}Ar$ total fusion and incremental heating methods. The spatial distribution of preferred ages produces the V-shaped pattern seen in Figure 2.

3. Ridge-Centered Hot Spot Volcanism

Both the short duration of volcanism and the systematic progression of age of eruptive activity from center to center are suggestive of an oceanic island/seamount lineament. Neither island arc volcanism nor rift volcanism (ocean floor or continental margin) would explain the observed systematic age distribution. The peculiar younging of ages from the ends of the province to the center can be modeled by a spreading ridge segment centered on or near a hot spot (Figure 4). A present example of such a feature would be the Iceland hot spot with the paired volcanic ridges east to the Faeroe Islands and west to Greenland. From the age-distance relationship (Figure 2), the rate of propagation of volcanism in the southern Coast Range must have been close to 40 mm/yr, and somewhat faster in the northern Coast Range.

Geochemical data support this hybrid origin, exhibiting aspects of both spreading ridge and hotspot volcanism [Snavely et al., 1968; Loeschke, 1979; Globerman and Babcock, 1980; Muller, 1980]. Because of submarine weathering, major element concentrations alone are unlikely to distinguish between possible eruptive environments, although the transition from submarine tholeiites to subaerial alkalic basalts is suggestive of oceanic island volcanism [Snavely et al., 1968]. Using various discrimination diagrams, such as Figure 5, immobile trace elements [Pearce and Norry, 1979] indicate an origin by intraplate (oceanic island) or mid-ocean ridge volcanism. Rare earth element patterns [Glassley, 1974; Hill, 1975; R. Duncan, unpublished data, 1981] show mildly light rare earth element enriched profiles, generally characteristic of oceanic islands or island arc tholeiites but which could match some spreading ridge tholeiites [Wood et al., 1979].

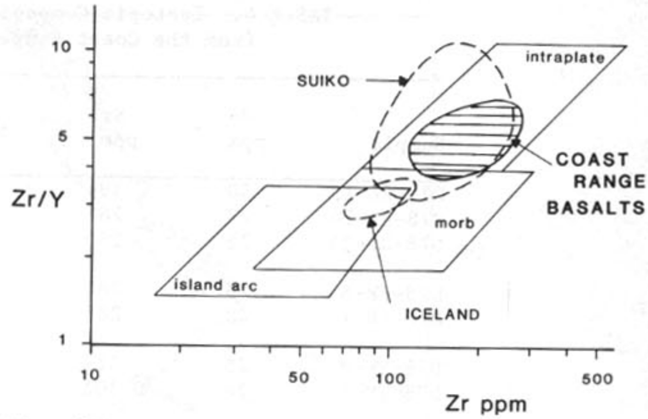

Fig. 5. Trace elements have been used to distinguish the tectonic environment of eruption of otherwise similar basalts. Here Zr and Y are used to characterize basalts from the Coast Range [Loeschke, 1979; Globerman, 1980] as intraplate to ocean floor origin. For comparison, analyses from Suiko Seamount [Kirkpatrick et al., 1981] and eastern Iceland [Wood, 1978] are illustrated.

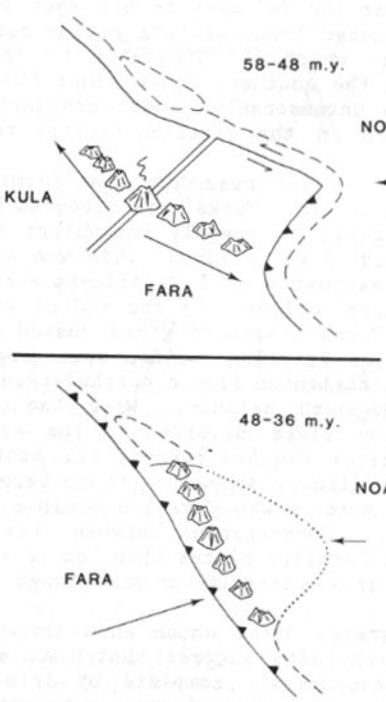

Fig. 4. (top) The distribution of ages within the early Tertiary eruptive centers favors an origin by hot spot volcanism underlying a spreading ridge segment. Seamounts and islands so generated would have been carried away from the hot spot in two directions, on the Kula (northern Coast Range) and Farallon (southern Coast Range) plates. Calculated absolute plate motions are shown as solid arrows. (bottom) As part of a major plate motion reorganization, this ridge segment stopped spreading, succeeded by Farallon-Pacific spreading farther north, by magnetic anomaly 21 (~48 m.y.) time. The subduction zone between the Farallon and North America plates then moved to the west, capturing this island lineament against North America.

New isotopic measurements of initial strontium ($^{87}Sr/^{86}Sr$) compositions range from 0.7028 to 0.7036 (Table 4) for samples from eruptive centers within the Oregon Coast Range and from the Grays River area of southwestern Washington. Globerman [1980] has reported a somewhat narrower range (0.7028 to 0.7032) for basalts from the Black Hills section of the Washington Coast Range. These $^{87}Sr/^{86}Sr$ values are consistent with an origin by ridge-centered hot spot volcanism, being transitional between spreading ridge and oceanic island compositions and similar to those measured in Icelandic lavas [Hart et al., 1973]. There does not appear to be any significant regional variation of $^{87}Sr/^{86}Sr$ within the Coast Range basalts, but there are very few measurements at each eruptive center.

4. Absolute Motion Modeling

Absolute plate motions for the North America, Pacific, Kula, and Farallon plates can be determined from the geometry and distribution of ages within hot spot lineaments on the Pacific and North America plates [Duncan, 1981; Morgan, 1981], coupled with relative motions across the Farallon-Pacific and Kula-Pacific spreading ridges. Since seafloor on the Farallon plate older than magnetic anomaly 5 (about 12 m.y.) has been subducted beneath North America, symmetric spreading must be assumed in order to calculate relative motions from Pacific plate magnetic anomalies and transform faults. This

TABLE 4. Isotopic Composition of Strontium in Basalts from the Coast Range, Oregon and Washington

Sample	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$* (± 2σ)	$^{87}Sr/^{86}Sr$ t = 0
D78-RB-15	30	594	0.146	0.70368±10	0.70355
D78-RB-24	27	282	0.277	0.70356± 4	0.70332
D78-RB-25	26	280	0.268	0.70336± 7	0.70313
D78-SR-6	23	282	0.236	0.70361± 6	0.70342
D78-SR-7	28	288	0.281	0.70352± 8	0.70330
D78-TM-8	25	219	0.330	0.70303± 8	0.70280
D78-TM-11	24	302	0.317	0.70327± 7	0.70305
D78-GR-2	22	191	0.333	0.70301± 5	0.70278
D78-GR-4	29	219	0.383	0.70305± 5	0.70279
D78-GR-5	27	254	0.307	0.70354± 7	0.70333

*Normalized to $^{86}Sr/^{88}Sr$ = 0.1194, E & A $SrCO_3$ $^{87}Sr/^{86}Sr$ = 0.70792, NBS 987 $^{87}Sr/^{86}Sr$ = 0.71023 (analyses performed at U.S. Geological Survey, Menlo Park, California).

is probably justified, since Farallon-Pacific spreading was rapid (40 to 50 mm/yr, Pacific half spreading rate, see Atwater [1970]) through the Tertiary. A similar plate motion analysis has been proposed by Engebretson et al. [1981].

Figure 6 illustrates a possible plate reconstruction for 60 m.y. B.P. based on the hot spot reference frame. The Kula-Pacific-Farallon triple junction is restored to a position considerably east and south of its present location in the north-central Pacific basin, and continental North America moves back to the east. If hot spot volcanism, located beneath a segment of the Kula-Farallon spreading ridge, produced the volcanic basement rocks in the Coast Range, then the azimuth of that lineament and the rate of propagation of volcanism within it should be predicted by Kula and Farallon plate absolute motions.

Considerable paleomagnetic data now support and document Tertiary clockwise rotation of the Coast Range basement rocks with respect to the North America craton, with negligible translatitudinal motion [Magill et al., 1981]. The magnitude of rotation varies from as much as 75° in the southern Coast Range [Simpson and Cox, 1977] to perhaps 25° in the north [Globerman and Beck, 1979], but rotation is uniformly clockwise. These data imply an original northwest-southeast orientation. Since the northern and southern sections of the Coast Range are proposed to have formed on separate plates (Kula and Farallon, respectively), different original azimuths are permissible, and the southern Coast Range may have rotated a greater amount than the northern. Considering presently active hot spots in this region, Figure 6 shows that only Yellowstone would generate the required lineament orientation. Additionally, coarse turbiditic sandstones and conglomerates that immediately overlie the basalts indicate that eruptions occurred fairly close to the margin of North America. So Yellowstone would be appropriately located relative to Paleocene North America to have generated the volcanic chain now seen as the basement rocks in the Coast Range. The Farallon plate velocity over the Yellowstone hot spot at this time, calculated from absolute motion modeling, is 37 mm/yr, which is comparable to the rate observed in the southern Coast Range (40 mm/yr) and perhaps unreasonably close considering the uncertainties in the Farallon-Pacific relative motions.

The islands and seamounts now forming the Coast Range basement rocks were produced between 62 and 48 m.y., or roughly equivalent to magnetic anomaly 25 to 21 time. This was a period of major readjustment of Pacific-Kula-Farallon plate relative motions. By the end of this period, Kula-Pacific spreading had ceased [Byrne, 1979] and the Farallon-Pacific spreading ridge had become reoriented from a northwest-southeast to a north-south azimuth. With the end of Kula-Farallon plate divergence, the spreading segment astride the Yellowstone hot spot froze or, more precisely, jumped north to become part of the new north-south Farallon-Pacific spreading ridge. Convergence between the North America and Farallon plates then led to emplacement of the stranded Coast Range island lineament.

Paleomagnetic data, which show large clockwise rotation, also suggest that this emplacement was essentially complete by late Eocene time. In particular, volcanic and sedimentary rocks younger than about 42 m.y. have been rotated much less than older rocks in the southern Coast Range [Magill et al., 1981]. Snavely et al. [1980] have suggested that during emplacement of the Coast Range volcanic lineament, the subduction zone between the North America and Farallon plates must have moved to the west of the Coast Range either by gradual overriding and scraping off of the oceanic islands or in a distinct jump (Figure 4). If the latter occurred, the oceanic lithosphere beneath the islands would have been preserved in the basement structure and could possibly be identified with seismic refraction and magnetic studies.

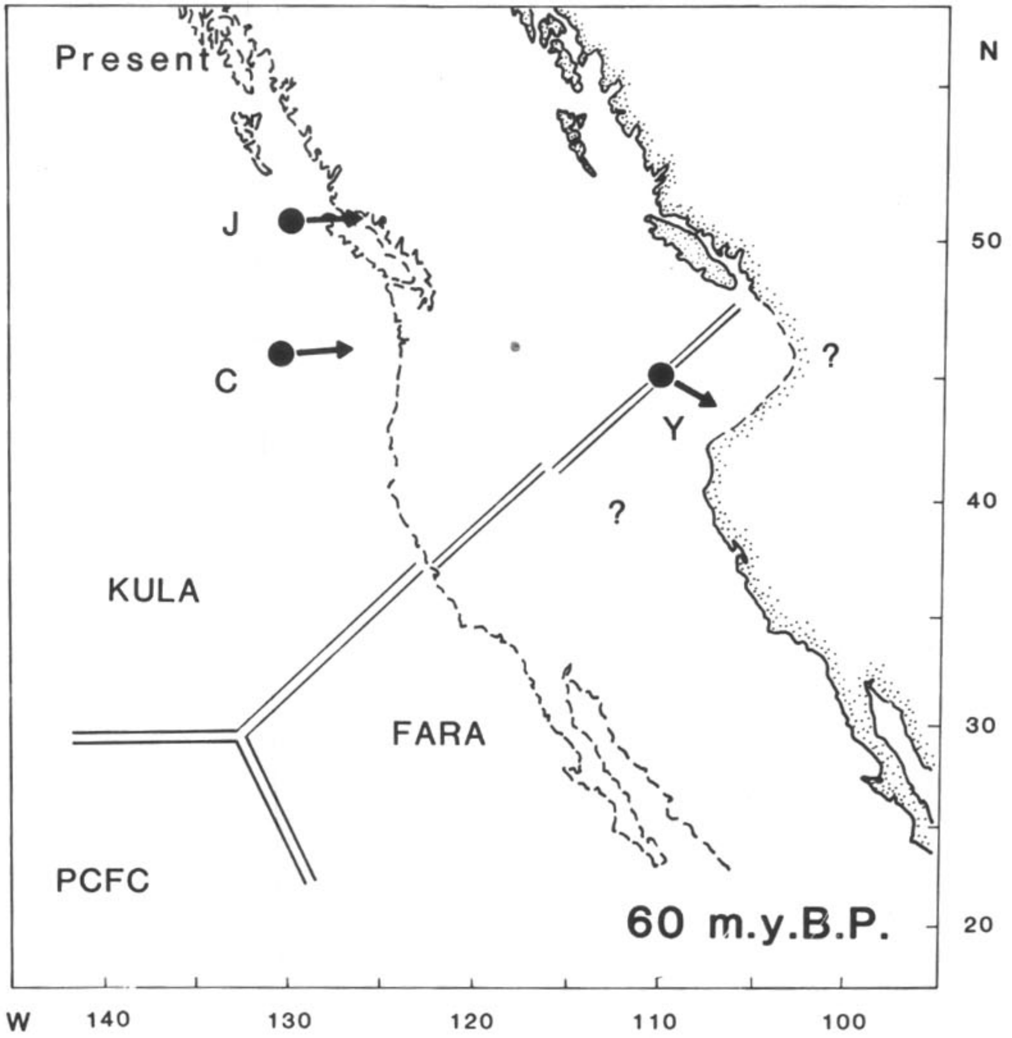

Fig. 6. This 60 m.y. B.P. plate configuration for the northeast Pacific is derived from the hot spot reference frame and relative plate motions calculated from magnetic anomalies recorded on the Pacific plate. The solid arrows show the azimuth of volcano propagation which would be left on the Farallon plate from each of three proposed hot spots: J. Tuzo Wilson (J), Cobb (C), and Yellowstone (Y). Only Yellowstone would have been appropriately close to North America to receive the coarse conglomerates and turbidites which interfinger with and overlie the Coast Range basalts.

North America has moved from east to west at about 20 mm/yr since the beginning of the Tertiary, relative to the mantle (i.e., the fixed hot spot reference frame [Morgan, 1981]). Figure 7 illustrates the hypothetical path left by a stationary hot spot at the latitude and longitude of Yellowstone during this period. Volcanic units along this swath that cannot otherwise be related to regional tectonic events, such as subduction or basin and range extension, and that were erupted at times appropriate for the westward passage of the North American plate may have a circumstantial association with the Yellowstone hot spot. We may dismiss, for instance, subduction-related volcanism in the Cascades and in eastern Oregon (late Eocene-early Oligocene Clarno and John Day formations [Enlows and Parker, 1972; Taylor, 1977]) and Washington-Idaho (Eocene Challis-Absaroka volcanics [Snyder et al., 1976; Armstrong, 1978]). Also, Miocene and younger basaltic and rhyolitic volcanic rocks in central and eastern Oregon [Watkins and Baksi, 1974; MacLeod et al., 1975] exhibit age patterns which may be more reasonably related to the northern limit of basin and range extension.

The suggestion that the Yellowstone hot spot has stimulated certain centers of the Tertiary and Quaternary volcanism of the Pacific Northwest of the United States is not new [Morgan, 1972; Suppe et al., 1975]. The data presented in this paper suggest that the Yellowstone hot spot was active in Paleocene to Eocene time, when it produced the islands and seamounts which form the basement basalts in the Coast Range of Oregon and Washington. If it is assumed that this hot spot remained active as a thermal anomaly throughout the Tertiary, the massive eruptions of Columbia River Basalts from feeder dikes in eastern Oregon and Washington [e.g., Watkins and Baksi, 1974; Swanson et al., 1979] may have been triggered. Other flood basalt

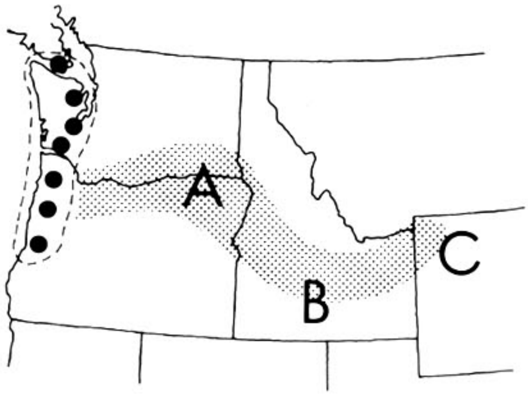

Fig. 7. Following eruption and emplacement of the Coast Range Basalts (dashed line is inferred extent, solid circles are eruptive centers), North America moved westward over the Yellowstone hot spot along the stippled path. Dike swarms which fed the Miocene Columbia River Basalts (A), basaltic volcanism in the Snake River Plain (B), and the current geothermal anomaly at Yellowstone (C) may all be manifestations of this hot spot.

provinces have been related to hot spot activity at the edges of continents [Morgan, 1981] but always at the inception of continental rifting. Volcanism intermediate in space and time (i.e., of Oligocene age) between the Coast Range and the eruptive fissures for Columbia River Basalts may be covered by later Cascade lavas and westward flowing Columbia River Basalt lavas. Alternatively, the subducting slab of the Farallon plate perhaps shielded the Yellowstone hot spot during this period, preventing magmas from reaching the surface until the Miocene. The most recent manifestation would then be the Snake River Basalts which began erupting in mid-to-late Miocene time [Armstrong et al., 1975], culminating in volcanism at Yellowstone today.

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References

Armstrong, R. L., Cenozoic igneous history of the U.S. Cordillera from lat. 42 to 49 N., Cenozoic Tectonics and Regional Geophysics of the Western Cordillera, edited by R. B. Smith and G. P. Eaton, Mem. Geol. Soc. Am., 152, 263-282, 1978.

Armstrong, R. L, W. P. Leeman, and H. E. Malde, K-Ar dating, Quarternary and Neogene volcanic rocks of the Snake River Plain, Idaho, Am. J. Sci., 275, 225-251, 1975.

Atwater, T., Implications of plate tectonics for the Cenozoic tectonic evolution of western North America, Geol. Soc. Am., Bull., 81, 3513-3536, 1970.

Baldwin, E. M., Eocene stratigraphy of southwestern Oregon, Oreg. Geol., 83, 1-40, 1974.

Beck, M. E., Jr., Paleomagnetic record of plate-margin tectonic processes along the western edge of North America, J. Geophys. Res., 85, 7115-7131, 1980.

Berg, J. W., Jr., et al., Crustal refraction profile, Oregon Coast Range, Bull. Seismol. Soc. Am., 56, 1357-1362, 1966.

Bromery, R. W., and P. D. Snavely, Jr., Geologic interpretation of reconnaissance gravity and aeromagnetic surveys in northwestern Oregon, U.S. Geol. Surv. Bull., 1181-N, N1-N13, 1964.

Byrne, T., Late Paleocene demise of the Kula-Pacific spreading center, Geology, 7, 341-344, 1979.

Cady, W. M., Tectonic setting of the Tertiary volcanic rocks of the Olympic Peninsula, Washington, J. Res. U.S. Geol. Surv., 3(5), 573-582, 1975.

Clague, D. A., G. B. Dalrymple, and R. Moberly, Petrography and K-Ar ages of dredged volcanic rocks from the western Hawaiian Ridge and southern Emperor Seamount chain, Geol. Soc. Am., Bull., 86, 991-998, 1975.

Couch, R., and D. Braman, Geology of the continental margin near Florence, Oregon, Oreg. Geol., 41, 171-179, 1979.

Dalrymple, G. B., and D. A. Clague, Age of the Hawaiian-Emperor Bend, Earth Planet. Sci. Lett., 31, 313-329, 1976.

Dalrymple, G. B., E. C. Alexander, Jr., M. A. Lanphere, and G. P. Kraker, Irradiation of samples for $^{40}Ar/^{39}Ar$ dating using the Geological Survey TRIGA Reactor (GSTR), U.S. Geol. Surv. Prof. Pap., 1176, 1981a.

Dalrymple, G. B., M. A. Lanphere, and D. A. Clague, Conventional and ^{40}Ar-^{39}Ar ages of volcanic rocks from Ojin (site 430), Nintoku (site 432), and Suiko (site 433) seamounts and the chronology of volcanic propagation along the Hawaiian-Emperor Chain, Initial Rep. Deep Sea Drill. Proj., 55, 659-676, 1981b.

Duncan, R. A., ^{40}Ar-^{39}Ar geochronology of basalts from ocean basins--Some successes with samples from aseismic ridges, U.S. Geol. Surv. Open File Rep., 78-701, 100-103, 1978.

Duncan, R. A., Hotspots in the southern oceans--An absolute frame of reference for motion of the Gondwana continents, Tectonophysics, 74, 29-42, 1981.

Engebretson, D., A. Cox, and R. G. Gordon, Relative motions between oceanic and continental plates in the northern Pacific Basin since the early Jurassic (abstract), Eos, Trans. AGU, 62, 1034, 1981.

Enlows, H. E., and D. J. Parker, Geochronology of the Clarno igneous activity in the Mitchell quadrangle, Wheeler County, Oregon, Oreg. Geol., 34, 104-110, 1972.

Glassley, W., Geochemistry and tectonics of the Crescent volcanic rocks, Olympic Peninsula, Washington, Geol. Soc. Am., Bull., 85, 785-794, 1974.

Globerman, B. R., Geology, petrology and paleomagnetism of Eocene basalts from the Black

Hills, Washington Coast Range, M.S. thesis, Western Wash. Univ., Bellingham, 1980.
Globerman, B. R., and R. S. Babcock, New geochemical data and their significance from the Washington Coast Range, Geol. Soc. Am., Abstr. Programs, 12, 107-108, 1980.
Globerman, B. R., and M. E. Beck, Jr., Cenozoic tectonic rotations in the western cordillera: New evidence from the Washington Coast Range (abstract) Eos Trans. AGU, 60, 816, 1979.
Hart, S. R., J.-G. Schilling, and J. L. Powell, Basalts from Iceland and along the Reykjanes Ridge: Sr isotope geochemistry, Nature Phys. Sci., 246, 104-107, 1973.
Hill, D. W., Chemical composition studies of Oregon and Washington coastal basalts, M.S. thesis, Oreg. State Univ., Corvallis, 1975.
Hillhouse, J. W., Paleomagnetism of the Triassic Nikolai Greenstone, McCarthy Quadrangle, Alaska, Can. J. Earth Sci., 14, 2578-2592, 1977.
Kirkpatrick, R.J., D.A. Clague, and W. Freissen, Petrology and geochemistry of volcanic rocks, DSDP Leg 55, Emperor Seamount Chain, Initial Rep. Deep Sea Drill. Proj., 55, 509-557, 1981.
Langston, C. A., Evidence for the subducting lithosphere under southern Vancouver Island and Western Oregon from teleseismic P wave conversions, J. Geophys. Res., 86, 3857-3866, 1981.
Loeschke, J., Basalts of Oregon (U.S.A.) and their geotectonic environment: I, Petrochemistry of Tertiary basalts of the Oregon Coast Range, Neues Jahrb. Mineral Abh., 134, 225-247, 1979.
Lyttle, N. A., and D. B. Clarke, New analyses of Eocene basalt from the Olympic Peninsula, Washington, Geol. Soc. Am., Bull., 86, 421-427, 1974.
MacLeod, N. S., and P. D. Snavely, Jr., Volcanic and intrusive rocks of the central part of the Oregon Coast Range, Oreg. Geol., 77, 47-74, 1973.
MacLeod, N. S., G. W. Walker, and E. H. McKee, Geothermal significance of eastward increase in age of upper Cenozoic rhyolite domes in southeastern Oregon, U.S. Geol. Surv. Open File Rep., 75-348, 1-22, 1975.
Magill, J., A. Cox, and R. Duncan, Tillamook volcanic series: Further evidence for tectonic rotation of the Oregon Coast Range, J. Geophys. Res., 86, 2953-2970, 1981.
Mallory, V. S., Lower Tertiary Biostratigraphy of the California Coast Range, American Association of Petroleum Geologists, Tulsa, Okla., 1959.
McWilliams, R. G., Eocene correlations in western Oregon-Washington, Oreg. Geol., 42, 151-158, 1980.
Morgan, W. J., Deep mantle convection plumes and plate motions, Am. Assoc. Pet. Geol. Bull., 56, 203-213, 1972.
Morgan, W. J., Hotspot tracks and the opening of the Atlantic and Indian Oceans, The Sea, 7, 443-488, 1981.
Muller, J. E., Chemistry and origin of the Eocene Metchosin volcanics, Vancouver Island, British Columbia, Can. J. Earth Sci., 17, 199-209, 1980.
Pearce, J. A., and M. J. Norry, Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks, Contrib. Mineral Petrol., 69, 33-47, 1979.
Shor, G. G., P. Dehlinger, H. K. Kirk, and W. S. French, Seismic refraction studies off Oregon and northern California, J. Geophys. Res., 73, 2175-2194, 1968.
Simpson, R. W., and A. V. Cox, Paleomagnetic evidence for tectonic rotation of the Oregon Coast Range, Geology, 5, 585-589, 1977.
Snavely, P. D., Jr., and N. S. MacLeod, Yachats Basalt--An upper Eocene differentiated volcanic sequence in the Oregon Coast Range, J. Res. U.S. Geol. Surv., 2,(4), 395-403, 1974.
Snavely, P. D., Jr., and H. C. Wagner, Tertiary geologic history of western Oregon and Washington, Wash. Div. Mines Geol. Rep. of Invest., 22, 1-25, 1963.
Snavely, P. D., Jr., H. C. Wagner, and N. S. MacLeod, Rhythmic-bedded eugeosynclinal deposits of the Tyee Formation, Oregon Coast Range, Kans. Geol. Surv. Bull., 169, 461-480, 1964.
Snavely, P. D., Jr., N. S. MacLeod, and H. C. Wagner, Tholeiitic and alkalic basalts of the Eocene Siletz River volcanics, Oregon Coast Range, Am. J. Sci., 266, 454-481, 1968.
Snavely, P. D., Jr., N. S. MacLeod, H. C. Wagner, and W. W. Rau, Geologic map of the Cape Foulweather and Euchre mountain quadrangles, Lincoln County, Oregon, U.S. Geol. Surv. Misc. Invest. Ser., Map 1-868, 1976.
Snavely, P. D., Jr., H. C. Wagner, and D. L. Lander, Interpretation of the Cenozoic geologic history, central Oregon continental margin: Cross section summary, Geol. Soc. Am., Bull., 91, 143-146, 1980.
Snyder, W. S., W. R. Dickinson, and M. L. Silberman, Tectonic implications of the space-time patterns of Ceonzoic magmatism in the western United States, Earth Planet. Sci. Lett., 32, 91-106, 1976.
Suppe, J., C. Powell, and R. Berry, Regional topography, seismicity, Quaternary volcanism, and the present day tectonics of the western United States, Am. J. Sci., 275A, 397-417, 1975.
Swanson, D. A., T. L. Wright, P. R. Hooper, and R. D. Bentley, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group, U.S. Geol. Surv. Bull., 1457-H, 1979.
Taylor, E. M., The Clarno Formation: A record of early Tertiary volcanism in central Oregon, Geol. Soc. Am. Abstr. Programs, 9, 768, 1977.
Watkins, N. D., and A. K. Baksi, Magnetostratigraphy and oroclinal folding of the Columbia River, Steens, and Owyhee Basalts in Oregon, Washington, and Idaho, Am. J. Sci., 274, 148-189, 1974.
Wood, D. A., Major and trace element variations in the Tertiary lavas of eastern Iceland with respect to the Iceland geochemical anomaly, J. Petrol., 19, 393-436, 1978.
Wood, D. A., J. Tarney, J. Varek, A. D. Saunders, H. Bougault, J.L. Joron, M. Treuil, and J. R. Cann, Geochemistry of basalts drilled in the North Atlantic by IPOD Leg 49: Implications for mantle heterogeneity, Earth Planet. Sci. Lett., 42, 77-97, 1979.
York, D., Least squares fitting of a straight line with correlated errors, Earth Planet. Sci. Lett., 5, 320-324, 1969.

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