Paleomagnetism and tectonic significance of Eocene basalts from the Black Hills, Washington Coast Range

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ABSTRACT

The Black Hills, located about 15 km west of Olympia, constitute one of several large basement uplifts in the Washington Coast Range. The oldest rocks exposed in this west-dipping homoclinal range consist of early to middle Eocene basalt flows and breccias with minor sedimentary interbeds, which are correlated with the Crescent Formation in the northern Olympic Peninsula. K/Ar geochronology of five basalt samples yields an average age of 53.1 ± 2.0 m.y. B.P., or early Eocene.

A total of 263 paleomagnetic cores were collected from 37 sites. All sites were cleaned using AF demagnetization, and 35 sites were corrected for measured and inferred tilt. The mean direction of these sites was virtually unchanged by applying tectonic corrections, although the precision was slightly improved. No flattening or steepening of inclination is apparent, although the mean declination of the 35 sites is easterly discordant with respect to the expected early Eocene declination for "stable" North America by 28.7° ± 15.4°. This discordance indicates that the Black Hills have rotated clockwise about 29° since early Eocene time.

The Black Hills basalts show significantly less rotation than Eocene rocks in the Oregon-Washington Cascade Range. Thus, the rotations of coastal Oregon and Washington, while identical in direction, differ significantly in amount, suggesting that the entire Coast Range block, from the Olympic Peninsula to north of the Klamath Mountains, has not been a coherent terrane since early Eocene time.

Several tectonic models are discussed that involve accretion and independent clockwise rotation of two or more Coast Range blocks, or "microplates," in response to episodic periods of underthrusting and extensive right-lateral shear along the Farallon-North America plate boundary during early and middle Tertiary time. The easterly discorances of declination that are observed in almost all tectonic terranes samples in the Oregon-Washington Coast and Cascade Ranges reflect a composite of differential rotation during accretion of the Coast Range seamount terrane, followed soon afterward by large-scale rotation of the western margin of the Pacific Northwest in response to oblique subduction and consequent distributed shear.

INTRODUCTION

Geologic and tectonic investigations in western North America during the last decade suggest that accretion, rotation, and possibly large-scale translation of continental and oceanic crustal fragments have been essential processes in the development of the western Cordillera during Mesozoic and Cenozoic time (Jones and others, 1977; Davis and others, 1978; Irving, 1979; Stone and Packer, 1979; Beck, 1980; Monger and Irving, 1980). Such studies have indicated that the Cordillera is an extensive composite of generally unrelated, accreted terranes (Davis and others, 1978; Jones and Silverling, 1979; Coney and others, 1980). The Cordillera thus may be envisaged as a "collage" (Helwig, 1974) into which crustal fragments, or "microplates" (Beck and others, 1980)—some apparently derived from distant sources—were emplaced by subduction processes and/or transient faulting. One probable microplate is the Oregon-Washington Coast Range, termed "Siletzia" by Irving (1979). It comprises a thick sequence of late Paleocene through middle Eocene submarine and subaerial lava flows (Fig. 1), with overlying marine sedimentary rocks, Oligocene dikes and sills, Miocene basalt flows, and coastal plain deposits (Snively and Wagner, 1963, 1964; Snively and others, 1968, 1980). This terrane has been interpreted as a large seamount province (Snively and others, 1968), which was accreted to the leading edge of North America during early Eocene (Snively and MacLeod, 1974, 1977; Magill and others, 1981), middle Eocene (Dickinson, 1976), late Eocene (Vance, 1977; Robinson and Brem, 1979), or early Oligocene time (Fairchild, 1980).

Cox (1957) first described an aberrant paleopole from the early to middle Eocene Siletz River Volcanics of the Oregon Coast Range, although he did not interpret this as evidence for tectonic rotation of the block. Simpson and Cox (1977) reported 58° to 78° of clockwise rotation since early Eocene time for the Siletz River Volcanics, the middle Eocene Tyee and Flournoy Formations, and late Eocene Yachats Basalt of coastal Oregon. The Coast Range block was thought by them to extend north through Washington to the southern tip of Vancouver Island—this distance of almost 600 km—rotated as a single, coherent terrane.

Subsequently, Beck and Burr (1979) demonstrated that the predominantly Oligocene Goble Volcanic Series of southwest Washington [apparently associated with early Cascade arc activity (Burr, 1978)] had rotated only 25° ± 13° clockwise since early Oligocene time, considerably less than the
GEOLOGY

The Black Hills constitute one of several large basement uplifts in the Washington Coast Range, comprising about 200 km of heavily forested uplands located about 15 km west of Olympia (Fig. 1). Elevations range from ~60 m along the Chehalis River to 800 m at Capitol Peak. Exposures are generally limited to roadcuts and quarries.

The oldest rocks exposed in the Black Hills constitute a >600-m-thick sequence of basalt flows and breccias, with minor interbeds of basaltic sandstone and siltstone that are correlated with the Crescent Formation in the northern Olympic Peninsula (Arnold, 1906; Weaver, 1937; Pease and Hoover, 1957; Snively and others, 1958; Brown and others, 1960). Petrochemical studies of the Black Hills basalts support this correlation (Globerman, 1979). The basalts are temporally and lithologically similar to the Metchosin Volcanics of southern Vancouver Island (Clapp, 1917; Muller, 1977, 1980); the Crescent Formation of the Willapa Hills in southwestern Washington (Wolfe and McKee, 1968; Wells, 1981); the Siletz River Volcanics (Snively and others, 1968); the lower part of the Tillamook Volcanics (Warren and others, 1945); and the lower part of the Roseburg Formation (Baldwin, 1974) of the Oregon Coast Range.

The dominant structures in the central Washington Coast Range are basement uplifts that expose Eocene basalts of the Crescent Formation; the Black Hills represent one of the largest of these features. Most uplifts existed as structural highs since middle or late Eocene time, as younger sedimentary units are generally observed onlapping or offlapping and thickening away from them. Northwest- and northeast-trending normal and reverse faults form the boundaries of most uplifts.

One of the most significant features in the Black Hills is the presence of K-Ar dates, which indicate that the rocks have not undergone significant tectonic movement since their formation. This is consistent with the lack of significant rotations reported for coastal Oregon. Recent studies by Bates and others (1981) in the Ohanapoco Formation of the southern Washington Cascade Range, Magill and Cox (1981) in the Western Cascades of Oregon, and Wells and Coe (1979, 1980) in the southwest section of the Washington Coast Range, indicate less rotation for these areas as well—about 34°, 25°, and 24°, respectively. Several preliminary studies have been conducted in the early to middle Eocene Crescent volcanic rocks of the Olympic Peninsula in the northern part of the Washington Coast Range, but most samples are altered and did not yield stable remanent magnetizations (Beck and Engebretson, 1982).

The structure of the Black Hills is relatively simple compared to that of the Olympic Mountains (Tabor and Cady, 1979) or the Willapa Hills (Wells, 1981). Globerman (1980) interpreted the Black Hills as a homocline dipping gently to the west. The marginal structures are obscured by younger cover, but geophysical data suggest that the Black Hills are fault-bounded on the north-
Eocene basalts from Black Hills, Washington Coast Range

Table 1. K/Ar geochronology of basalts from the Black Hills, Washington Coast Range

<table>
<thead>
<tr>
<th>Sample no.*</th>
<th>Lab no.</th>
<th>% K</th>
<th>Radiogenic 40Ar ( \times 10^{-9} \text{cc/st} )</th>
<th>% Radiogenic 40Ar</th>
<th>Age \pm 10 m.y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D78-CV-6</td>
<td>0.3316</td>
<td>0.6768</td>
<td>48.8</td>
<td>53.0 ± 1.0</td>
</tr>
<tr>
<td>2</td>
<td>D78-CV-7</td>
<td>0.2551</td>
<td>0.5119</td>
<td>33.8</td>
<td>52.1 ± 1.4</td>
</tr>
<tr>
<td>3</td>
<td>D78-CV-18</td>
<td>0.2532</td>
<td>0.5315</td>
<td>53.5</td>
<td>54.5 ± 1.3</td>
</tr>
<tr>
<td>4</td>
<td>D78-CV-19</td>
<td>0.2761</td>
<td>0.5648</td>
<td>26.1</td>
<td>53.1 ± 2.3</td>
</tr>
<tr>
<td>5</td>
<td>D78-CV-23</td>
<td>0.2726</td>
<td>0.5525</td>
<td>17.7</td>
<td>52.6 ± 4.0</td>
</tr>
</tbody>
</table>

*See Figure 1 for site localities.

AGE

Paleontological data from basalts of the Black Hills are scarce, owing to a paucity of interbedded sedimentary rocks. A poorly preserved foraminiferal assemblage collected from a siltstone interbed was referred to the early middle Eocene Ulatisian Stage by W. W. Rau, Washington Division of Geology and Earth Resources (December 1979, written commun.) and represents an opensea bathyal depositional environment. A Ulatisian foraminiferal assemblage also was collected by Rau from coquina-rich sandstone on the north side of Rock Candy Mountain in the Black Hills. This assemblage is more characteristic of a shallow-water (<50 m) littoral environment (W. W. Rau, June 1980, written commun.).

The uppermost flows of the volcanic sequence are locally interbedded with and conformably overlie by siltstone of the upper part of the middle to early late Eocene McIntosh Formation (Pease and Hoover, 1957; Snively and others, 1958). Deposition of these tuffaceous sedimentary rocks occurred during the waning stages of volcanism and apparently continued to be deposited after eruptions had ceased, into early late Eocene time.

K/Ar geochronology of five basalt samples (Table 1) yields an average age of 53.1 ± 2.0 m.y., or early Eocene. The ages are consistent over a range of K concentrations, which indicates that "excess" Ar and K addition in the marine environment was negligible.

Petrographically, the selected samples exhibit only small amounts of low-temperature secondary mineralization (zeolite minerals, saponitic clays), suggesting that the measured age reflects the crystallization age of these basalts. No magnetostatigraphic information is evident from these ages, as the duration of volcanism is probably within the reported error limits.

Paleomagnetism

A total of 263 basalt cores were collected from 37 sites, by procedures described by Doell and Cox (1965). At each site, six to eight oriented cores were obtained, using a portable rock drill. We used a magnetic compass to orient the samples, because weather conditions and forest cover did not permit orientation with a sun compass. As a result, spurious magnetizations of the outcrop, such as those resulting from lightning strikes, may have introduced error into some orientations.

Natural remanent magnetization (NRM) of each specimen was measured on a Schonstedt SSM-1A spinner magnetometer. Secondary components of magnetization were removed by alternating field (AF) demagnetization, using a Schonstedt GSD-5 AC tumbling-specimen demagnetizer. Optimum demagnetization field strength for each site was determined with two pilot specimens. The demagnetization level that resulted in the least angular divergence between two pilot specimens was the level selected for all other cores in the site. Most specimens were demagnetized at field strengths ranging from 10 to 40 mT.

In 11 sites, one or more specimens remained far outside unmistakable "clusters" following AF demagnetization. Specimens that diverged from the mean direction by at least twice the angular standard deviation were discarded. Generally, these aberrant samples were highly oxidized, cracked, or questionably oriented in the field, because they fragmented during drilling. A total of 25 samples were discarded using this criterion.

Two field sites were eliminated from the Black Hills population following demagnetization and the application of tectonic corrections. At one site, the six specimen directions failed to cluster (radius of 95% circle of confidence = 37°). The other site was rejected due to lack of knowledge of the structural setting at the sampling locality. Sampling and laboratory procedures followed in this study have been discussed by Globerman (1980).

Reliable structural measurements for tilt-correcting the paleomagnetic data were difficult to obtain, as sedimentary interbeds are scarce in the predominantly subaerial flow sequence in the Black Hills. In places where sedimentary interbeds were absent, we used breccia layers, sapatolite zones, and well-developed cross-jointing as provisional indicators of paleohorizontal. After all available attitudes were plotted on the base map, every sampling locality within a 2-km radius of each attitude was tilt-corrected. A sampling locality between two mapped attitudes was corrected using an interpolated attitude. It was possible to tilt-correct 17 of the 35 sites in this manner; these corrections resulted in a slight increase in the precision parameter (k), from 18.7 to 20.1 for the 17 sites with "known" attitudes. However, this increase is not significant at the 95% confidence level, using the test described by Cox (1968). The mean direction of these sites was virtually unchanged by correcting for tilt.

Applying tilt corrections to the remaining 18 sampling localities [termed "attitudes unknown" (AU) sites] was more difficult, as these sites are located >2 km from any mapped attitude. We tried three different bedding correction methods. (1) The AU sites were combined with the 17 tilt-corrected sites without correction. (2) The AU sites were eliminated entirely from the Black Hills population. (3) The AU sites were arbitrarily corrected using an estimated regional attitude of N10°E-10°NW, then combined with the remaining 17 sites that had been individually corrected.

We prefer the latter method, although the results of the three techniques are statistically indistinguishable, as indicated in Table 2. Furthermore, the small reduction in scatter that results from the application of tilt corrections suggests that tectonic deformation of the lava flows is insignificant between sampling sites. Since accurately measured attitudes are well distributed throughout the Black Hills area, and there is no steep regional dip, the paleomagnetic
TABLE 2. MEAN DIRECTIONS, PALEOPOLE POSITIONS, AND AMOUNTS OF CLOCKWISE ROTATION FOR THE BLACK HILLS VOLCANIC ROCKS, USING VARIOUS METHODS OF TECTONIC CORRECTION

<table>
<thead>
<tr>
<th>Description</th>
<th>N</th>
<th>D</th>
<th>T</th>
<th>k</th>
<th>α&lt;95</th>
<th>PLONG</th>
<th>PLAT</th>
<th>Rcw</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Early Eocene expected direction for stable North America</td>
<td>13</td>
<td>347.6 ± 7.9</td>
<td>67.8 ± 3.6</td>
<td>63.0</td>
<td>5.0</td>
<td>177.0 E</td>
<td>81.0 N</td>
<td>-----</td>
</tr>
<tr>
<td>2. Black Hills rocks: no demagnetization; no tilt correction</td>
<td>37</td>
<td>25.7 ± 23.0</td>
<td>68.9 ± 8.1</td>
<td>8.1</td>
<td>8.1</td>
<td>60.4 W</td>
<td>72.7 N</td>
<td>38.1 ± 24.3</td>
</tr>
<tr>
<td>3. Black Hills rocks: AF demagnetized; no tilt correction</td>
<td>35</td>
<td>32.1 ± 11.9</td>
<td>62.5 ± 5.5</td>
<td>18.7</td>
<td>5.5</td>
<td>36.7 W</td>
<td>67.4 N</td>
<td>44.5 ± 14.3</td>
</tr>
<tr>
<td>4. Black Hills rocks: AF demagnetized; tilt-corrected using method 1</td>
<td>35</td>
<td>25.3 ± 12.6</td>
<td>66.4 ± 5.0</td>
<td>22.4</td>
<td>5.2</td>
<td>48.6 W</td>
<td>73.0 N</td>
<td>37.7 ± 14.8</td>
</tr>
<tr>
<td>5. Black Hills rocks: AF demagnetized; tilt-corrected using method 2</td>
<td>17</td>
<td>18.8 ± 18.4</td>
<td>66.7 ± 7.3</td>
<td>21.5</td>
<td>7.3</td>
<td>50.3 W</td>
<td>77.3 N</td>
<td>31.2 ± 20.4</td>
</tr>
<tr>
<td>6. Black Hills rocks: AF demagnetized; tilt-corrected using method 3</td>
<td>35</td>
<td>16.3 ± 13.2</td>
<td>67.3 ± 5.1</td>
<td>22.9</td>
<td>5.1</td>
<td>55.0 W</td>
<td>78.8 N</td>
<td>28.7 ± 15.4</td>
</tr>
</tbody>
</table>

SYMBOLS

N = the number of sites used in calculating mean directions/paleopoles
D = mean declination, degrees
I = mean inclination, degrees, positive downward
k = precision parameter (Fisher, 1953)
α<95 = radius of circle of 95% confidence, degrees
Rcw = rotation (clockwise), degrees; easterly discordance of mean Black Hills direction from expected early Eocene direction for stable North America

Early Eocene pole position from Irving, 1979 Black Hills location: 47.0°N, 123.12°W

TILT CORRECTION

Method 1. Tectonic corrections are made on 17 sites where the attitudes of sedimentary interbeds, overlying clastic units, or horizontal cross-joints in basalt flow are reasonably well known. An additional 18 sites are included in this group for which no structural information is available. These latter sites have not been tectonically corrected.

Method 2. Tectonic corrections are applied to the 17 “attitudes known” sites. Only these sites are used in calculating the mean direction of the Black Hills volcanic rocks.

Method 3. Tectonic corrections are made on the 17 “attitudes known” sites. The remaining 18 sites have been arbitrarily corrected for tilt using the mean Black Hills attitude determined from 52 poles to bedding and cross-joints; the mean attitude is N(9°E, 10°NW). These 18 “attitudes inferred” sites have been combined with the 17 “attitudes known” sites in calculating the mean direction of the Black Hills rocks.

RESULTS

The mean directions are probably representative of the true direction of magnetization of the Black Hills basalts (Fig. 2). Most of the inter-site scatter is probably due to geomagnetic secular variation. The amount of angular dispersion in the paleomagnetic directions, at 16.7°, is probably due to geomagnetic secular variation (Fig. 2). Most of the intersite scatter is random undetected tilt may have decreased precision to a small degree.

In this study, we are fairly certain that the effect of secular variation on the paleomagnetic direction of the Black Hills basalts has been completely averaged out, because the presence of both polarities argues for magnetization over a long time span. The overlap of the circles of 95% confidence around the mean directions of the normal- and reversed-polarity groups (the latter plotted in the lower hemisphere) following tectonic correction suggests that the two groups are approximately antipolar (Fig. 2), and that the effect of secular variation is probably insignificant. Despite this slight overlap, the

two groups are not similar at the 95% confidence level, according to an F-test (Watson, 1956). The lack of antipolarity could be the result of incomplete magnetic cleaning. Furthermore, it is important to note that the direction of one reversed site (1028.781) is extremely discordant with respect to the other reversed sites (Fig. 2). If this site is eliminated, then the normal- and reversed-polarity groups are statistically similar and antipolar. An excursion of the Earth’s magnetic field, orientation error, or unrecognized structure at the outcrop may be responsible for this single aberrant direction.

Any north-south shift of the Black Hills would be recognized by a significant flattening or steepening of the observed inclination relative to the expected early Eocene inclination for stable North America, but none is apparent (0.5° ± 6.2°, Table 2). Rotation of the Black Hills about a vertical axis would result in its observed declination differing significantly from the expected early Eocene declination. As shown in Table 2, the expected declination is 347.6° ± 7.9° (Irving, 1979). Using our preferred tilt-correction technique (method 3), a declination of 16° ± 13.2° is obtained; this is easterly discordant with respect to the expected declination by 28.7° ± 15.4°.

DISCUSSION

Our paleomagnetic data are consistent with a clockwise rotation of about 29° for the Black Hills with respect to cratonic North America since early Eocene time (Fig. 2). This appears to be less than rotations reported for Eocene rocks in western Oregon, although almost identical to the rotations inferred for correlative basalts in southwestern Washington. For example, in the major portion of the Willapa Hills in the southeast part of the Willapa Range, early to middle Eocene submarine lavas of the Crescent Formation rotated 24° ± 10° clockwise (Wells and Cole, 1980). In coastal Oregon, however, the early to middle Eocene Siletz River Volcanics and
middle Eocene Tyee-Flournoy sedimentary rocks have undergone about 50° to 75° of clockwise rotation (Simpson and Cox, 1977).

In order to determine if two separate sampling regions (1 and 2) of similar age have undergone significant differential rotation (R), the following equation is used (Wilson and Cox, 1980):

\[
(1) R(2) = R(1) - R(2), \\
\n\nV(1) R(2) = [\sqrt{V(1)^2 + V(2)^2}]^2
\]

A value of \((1) R(2) > V(1) R(2)\) would indicate that the two sampling regions underwent differential rotation. Applying this equation to the rotations inferred for the Siletz River volcanics \(R(SRV) = 76.8° ± 15.7°\) and the Black Hills basalts yields the result \((S) R(BH) = 48° ± 22°\), indicating that the larger amount of rotation for the coeval Siletz River unit is significant at the 95% confidence level. The clockwise rotation of the middle Eocene Tyee and Flournoy Formations \([R(TF) = 70° ± 17°]\) is also significantly greater than that of the Black Hills basalts, by an angle 41° ± 23°. However, no differential clockwise rotation is indicated between the Crescent Formation lavas in the Willapa Hills of southwestern Washington \([R(WH) = 24° ± 10°]\) and the Black Hills basalts \([R(WH) R(BH) = 4.7° ± 18.4°]\).

**INTERPRETATION**

We conclude that the Black Hills basalts of the Washington Coast Range underwent significantly less clockwise rotation than rocks of similar age in the Oregon Coast Range (Fig. 3). Our data support previous suggestions that the entire Coast Range block, from the Olympic Peninsula to north of the Klamath Mountains, has not been a coherent terrane since early Eocene time (Wells and Coe, 1980; Magill and others, 1981). A tectonic model that is more consistent with available paleomagnetic data involves accretion and independent clockwise rotation of two or more Coast Range terranes, or "microplates," in response to episodic periods of underthrusting and extensive right-lateral shear along the Farallon-North America plate boundary during early and middle Tertiary time (Beck and others, 1979; Wells and Coe, 1979; Snively and others, 1980). This interpretation requires a re-evaluation of the model used by Simpson and Cox (1977) for the emplacement and rotation of the Coast Range.

The nature and tectonic history of the boundary between the Oregon and Washington coastal blocks is problematical. Middle Eocene basalts in the Tillamook Highlands of northwestern Oregon have rotated about 46° clockwise (Magill and others, 1981), while slightly older volcanic rocks in the Willapa Hills of southwestern Washington show only about 24° clockwise rotation (Wells and Coe, 1980). On the basis of paleomagnetic and geologic evidence, it is likely that the Oregon-Washington Coast Range is separated between these two areas, presumably in or near the Columbia River (Beck and Burr, 1979; Wells and Coe, 1979, 1980). Venkatkrishnan and others (1980) interpreted photolinears in the western Cascade Range southeast of Portland as dextral shear zones—in part, northwestern extensions of the Brothers and Eugene-Denio fault zones (Lawrence, 1976). Jones (1977) suggested that the northwest-trending Portland Hills fault west of Portland had as much as 20 km of right-lateral movement since late Eocene time. Perhaps these Neogene faults reflect older basement structures, which accommodated differential rotation between the Oregon and Washington Coast Range blocks. However, gravity and aeromagnetic surveys in northwestern Oregon (Bromery and Snively, 1964) show no evidence for a throughgoing northwest-striking fault.

In summary, the paleomagnetic data reported here provide additional evidence for separation of the Oregon-Washington Coast Range into two or more smaller blocks that have had independent rotational histories. The blocks are broadly coeval, and their stratigraphic frameworks are sim-
Figure 3. Diagram showing rotation versus age for various paleomagnetic study areas in the Oregon-Washington Coast Range (circles) and Cascade Range (squares). Closed symbols, Oregon localities; open symbols, Washington localities. Error bars give 95% confidence limits on rotation. Units shown: Siletz River Volcanics (SRV), Tyee-Flournoy Formations (TF), Yachats Basalt (YB), and Miocene flows (MF; Simpson and Cox, 1977); Goble Volcanic Series (GV; Beck and Burr, 1979); Eocene intrusions (E1), Oligocene intrusions (O1), and Miocene intrusions and flows (MIF; Beck and Plumley, 1980); basalts of Pack Sack Lookout (PS; Magill and others, 1982); Willapa Hills (WH; Wells and Coe, 1980); Tillamook Volcanics (TV; Magill and others, 1981); Oregon Cascade Range (OC; Magill and Cox, 1981); Oha- napecosh Formation (OF; Bates and others, 1981); Black Hills (BH; this study). El may include material as young as early Oligocene (Beck and Plumley, 1980).

Figure 4. Paleogene paleogeographic map of the northwestern United States. Arrows indicate relative directions of oceanic plate convergence. Modified from Nilsen and McKee, 1979.

POSSIBLE ROTATION MECHANISMS

We suggest that differential clockwise rotation of the Oregon-Washington Coast Range probably occurred during and/or after its accretion to western North America. This rotation may have been accomplished by one (or more) of six possible mechanisms, which are briefly summarized below.

1. The Coast Range blocks fragmented and underwent differential clockwise rotation in response to pivoting subduction of the Farallon plate, as first described by Menard (1978).

2. The configuration of the late Eocene coastline of northwestern North America controlled the kinematics of subduction of oceanic lithosphere and accretion of oceanic volcanic piles (D. C. Engebretson, 1981, personal commun.). Nilsen and McKee (1979) envisaged a concave-westward coastline for the Pacific Northwest during Paleogene time (Fig. 4). Given this paleogeography, the Oregon coastal block should have undergone considerably more clockwise rotation during accretion to the continental margin than coastal Washington, if the Oregon-Washington Coast Range had an initial northwest-southeast orientation during early Eocene time (Simpson and Cox, 1977; Hammond, 1979), and Farallon–North America relative plate motion was northeastward through early and middle Eocene time (Nilsen and McKee, 1979; Engebretson and others, 1980). Detachment of these thick volcanic piles from the subducting oceanic lithosphere (for example, Vogt and others, 1976) may have occurred along a basal sedimentary horizon (D. C. Engebretson, 1979, personal commun.), such as that which stratigraphically underlies the Crescent basalts of the Olympic Peninsula (Cady, 1975).

3. The thick late Paleocene to middle Eocene basalt accumulations of the Oregon-Washington Coast Range represent a chain of oceanic islands that erupted along the axis (Snavely and others, 1968, 1980; Globerman and Babcock, 1980). A similar origin for the early Eocene Metchosin Volcanics of southern Vancouver Island has been proposed by Muller (1980). Segmentation of the ridge by a transform fault could have separated the Oregon and Washington coastal blocks and enabled them to undergo differential clockwise rotation during accretion (R. E. Wells, 1981, personal commun.).

4. Rotation of rigid crustal fragments occurred in a broad right-lateral shear couple. These fragments, which may be visualized as roller bearings, rotated clockwise and translated northward as independent units (Beck, 1976). Clockwise rotation and possibly northward translation of large crustal regions within the northern Channel Islands in the southern California Borderland, and in the western Transverse Ranges (Kamering and Luyendyk, 1979; Kamering and others, 1980), are thought to have occurred between late Oligocene and late Miocene time within the Pacific–North America dextral shear couple (Luyendyk and others, 1980). Differential clockwise rotation of
small (<20 km) crustal blocks in the Morro Bay area of central coastal California (Greenhaus and Cox, 1979) apparently occurred in response to distributed right-lateral shear along the plate boundary. Crustal heterogeneities and an irregular initial pattern of crustal fragmentation may have produced local variations in amount of rotation within the shear couple (Greenhaus and Cox, 1979).

5. Rotation of small crustal blocks occurred behind the trench and was probably accompanied by development of a right-lateral strike-slip fault (Beck, 1980). Fitch (1972) proposed that recent crustal movements in the western Sunda arc region of Indonesia show coexistence of oblique convergence, active volcanism, and transcurrent faulting on the continental side of a zone of plate consumption. The development of a strike-slip fault along the axis of a volcanic arc is easily achieved, since it is a zone of crustal weakness (Fitch, 1972). Such structures presumably should exist in the western Cascade Range, since North America–Juan de Fuca plate convergence has been oblique for the past 8 m.y. (Riddihough, 1977). The earthquake focal mechanisms associated with the 1980 Mount Saint Helens eruption sequence suggest right-lateral strike-slip faulting on northwest-striking planes.

6. Extension of the Basin and Range province on the order of 80% may have produced about 30° of clockwise rotation during the past 20 m.y. (Magill and others, 1981). Rotation of the Cascade Range, Oregon-Washington Coast Range, Klamath Mountains, and northern Sierra Nevada occurred as linked terranes with little internal deformation, as envisaged by Heptonstall (1977). This mechanism permits differential rotation between blocks at their points of contact but requires relatively uniform amounts of rotation within each block (Magill and others, 1981).

Any one of the first three models, involving tectonic rotation during accretion of the seamount province, could have resulted in differential clockwise rotation of the Oregon and Washington Coast Range blocks. They do not adequately explain rotation of the Cascade Range nor the 15° clockwise rotation of middle Miocene basalts in the southwest Washington Coast Range (Simpson and others, 1980), which clearly postdates accretion. Models 4 and 5 are compatible with available paleomagnetic data, although they do not satisfactorily explain why the Oregon and Washington Coast Range blocks rotated by different amounts, while the entire Cascade Range and Washington Coast Range underwent nearly identical amounts of rotation. Model 6 precludes any relative motion within the Coast Range but is consistent with invariant clockwise rotation of the Cascade Range from at least southwest Oregon to southern Washington. The model requires a hiatus in rotation for the period 40 to 20 m.y. B.P., in contrast to Beck and Plumley's (1980) contention that rotation occurred at a constant rate from early Eocene to at least early Miocene time. Available paleomagnetic data do not preclude either of these possibilities. It is unlikely, however, that Basin and Range extension is a viable hypothesis for rotation of the Washington Coast and Cascade Ranges, since the northwest-trending Bakers and Vail fault zones in central and eastern Oregon define the northern limit of significant east-west extension (Lawrence, 1976). Bates and others (1981) have discussed other objections to this model.

Following Magill and others (1981), we propose that the easterly discordanacies of declination that are observed in almost all Tertiary rocks sampled in the Oregon-Washington Coast and Cascade Ranges reflect a composite of differential rotation during accretion of the Coast Range seamount terrane (models 1, 2, and 3), followed soon afterward by left-lateral shear of the western margin of the Pacific Northwest, perhaps in response to distributed right-lateral shear (models 4 and 5), or Basin and Range extension (model 6). The latter three mechanisms, we favor the first two, which involve monotonic regional rotation, beginning by late Eocene to Oligocene time, and continuing through late Miocene to possibly Holocene time, as a result of oblique convergence and dextral shear along the Farallon (Juan de Fuca)–North American plate margin. Local crustal heterogeneities and complex ancestral fracture patterns near the margin may have contributed to variable block rotations on an appreciably smaller scale, as in the Willapa Hills (Wells and Coe, 1980).

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