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Tillamook Volcanic Series: Further Evidence for Tectonic Rotation of the Oregon Coast Range

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Paleomagnetic directions from the Eocene Tillamook Volcanic Series of the Oregon Coast Range point 46° clockwise from the expected Eocene field direction. Potassium argon dating of six dikes and flows from this formation yields a mean age of 44.3 ± 0.6 m.y. These results establish that the Oregon coastal block of Simpson and Cox (1977) extends north to the Oregon-Washington border and that this block has rotated clockwise 46° ± 13° during the past 44 m.y. The block has undergone no detectable north-south translation. A two phase model is developed to explain the tectonic history and anomalous magnetic field directions of the Pacific northwest region. Phase I of the rotation, active between 50 and 42 m.y. B.P., results from fragmentation of the Farallon plate with rotation of a fragment during its accretion to North America. Phase II of the rotation, active between 20 m.y. b.p. and the present, occurs in association with extension in the Basin and Range province.

INTRODUCTION

Anomalous directions of magnetization in early Tertiary rocks of the Coast Range of Oregon (Figure 1), first reported by *Cox* [1957] and confirmed by recent paleomagnetic studies [*Simpson and Cox*, 1977], have established that lower, middle, and upper Eocene sedimentary and volcanic rocks have undergone clockwise rotations about vertical axes of from 50° to 75° (Figure 2). The area sampled in these studies is a block extending northward 225 km from the Klamath Mountains. The fact that similar clockwise rotations are recorded in rocks of varying Eocene age and as petrologically dissimilar as basalts and turbidites leaves little doubt that the anomalous paleomagnetic directions have recorded a true tectonic rotation. Having established this, however, a number of questions remain concerning the regional extent and timing of the rotations and the mechanisms responsible for them.

Where Are the Boundaries of the Rotated Region?

In southern Oregon the predominately Cenozoic terrane of the Coast Range meets the mainly Mesozoic terrane of the Klamath Mountains along a geologic boundary that may or may not be a Cenozoic tectonic boundary. The possibility that the Klamath terrane rotated with the Oregon Coast Range during the Cenozoic has not as yet been tested paleomagnetically. To the east, the early Tertiary rocks of the Coast Range pass beneath middle and late tertiary and Quaternary volcanics and sediments of the Cascades. If the Coast Range rotated into its persent position from a more seaward position to the west [*Simpson and Cox*, 1977], the presumed suture to the east is masked by younger deposits of the Cascades. *Magill and Cox* [1980] propose that the Cascades have undergone 25° clockwise rotation sometime between 25 m.y. B.P. and the present. In fact all the paleomagnetic data from the Cascades [*Beck*, 1962; *Beck and Burr*, 1979; *Bates et al.*, 1979; *Bates and Beck*, 1981; *Magill and Cox*, 1980] show remarkably consistent results yielding an average rotation of 27° ± 7 [*Magill and Cox*, 1980]. Depositional contacts linking the Coast Range and Klamaths to the Cascades require that these terranes have undergone the same post 25 m.y. B.P. rotation as the Cascades.

To the north of the Coast Range, early Tertiary rocks similar to those in the Oregon Coast Range extend all of the way to the Olympic Peninsula. The question of whether all of this terrane has undergone the same rotation as that recorded in the central and southern Oregon Coast Range is the subject of much current paleomagnetic research [*Wells and Coe*, 1979; *Globerman and Beck*, 1979]. The present study was undertaken to determine whether the rotation recorded in the southern part of the Oregon Coast Range extends northward to the Columbia River at the Oregon-Washington border.

When Did the Rotation Occur?

In attempting to incorporate the paleomagnetically observed rotation of the Oregon Coast Range into the geologic history of this region, it is important to know the timing of the rotation as precisely as possible. Did the rotation occur throughout the Cenozoic or was it completed by the Miocene or some earlier time? Recent paleomagnetic studies of mid-Oligocene dikes and sills within the southern Coast Range [*Clark*, 1969; *Beck and Plumley*, 1980] and Oligocene basalts from the Western Cascades [*Bates et al.*, 1979; *Bates and Beck*, 1981; *Magill and Cox*, 1980] show that a significant amount of clockwise rotation took place after the Oligocene. The present study of upper Eocene rocks helps establish the amount of rotation that occurred earlier in the Tertiary.

By What Mechanism Did the Rotation Occur?

As was first suggested by *Irving* [1964], the simplest explanation of the paleomagnetic data is some sort of regional tectonic rotation, as had been hypothesized for this region earlier by *Carey* [1958] and *Wise* [1963]. Most workers now agree with this. However developing a specific paleogeographic model that integrates the paleomagnetically observed rotations with the known geology of the Coast Range and adjacent regions has proven to be a challenging problem. The following is a brief summary of the relevant geology.

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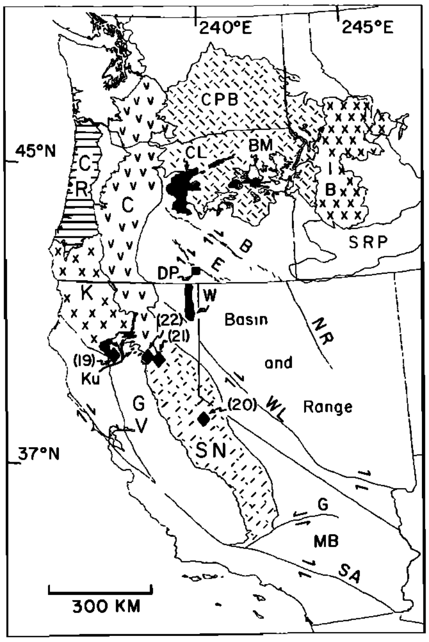

Fig. 1. Generalized geotectonic map of the western United States based on *Cohee* [1962] and *Lawrence* [1976]. C, Cascades; CR, Oregon Coast Range; CL, Clarno Formation; BM, Blue Mountains; CPB, Columbia Plateau Basalts; DP, Drake Peak; GV, Great Valley; IB, Idaho Batholith; K, Klamath Mountains; Ku, Upper Cretaceous sediments; MB, Mojave block; NR, Nevada rift; SN, Sierra Nevada; SRP, Snake River Plain; W, Warner Mountains. Fault Zones: B, Brothers; E, Eugene-Denio; G, Garlock; SA, San Andreas; WL, Walker Lane. The numbered locations refer to paleomagnetic sampling localities identified in Table 3.

The oldest rocks in the Coast Range (Figure 2), the lower and middle Eocene Siletz River volcanics and the correlative lower Eocene Roseburg formation, consist of tholeiitic pillow basalts, intercalated marine volcanic sediments and subaerial alkalic basalts [*Snavely and Wagner*, 1963; *Snavely et al.*, 1968; *Baldwin*, 1974, 1975]. The overlying middle Eocene Tyee-Flournoy formations are marine turbidite sandstones and siltstones [*Snavely et al.*, 1964; *Lovell*, 1969; *Baldwin*, 1974]. Flow structures and distinctive lithologies indicate that the main source of the middle Eocene sediments was to the south in the Klamath Mountains. Continued basaltic volcanism through the middle and late Eocene produced the Yachats basalt [*Snavely and MacLeod*, 1974] and the Tillamook Volcanic Series [*Snavely et al.*, 1970; *Beaulieu*, 1971; *Nelson and Shearer*, 1969].

Information about the original tectonic setting of the rocks of the Coast Range is provided by geologic, geochemical, and geophysical data. The lower Eocene Coast Range basalts are marine and are overlain by lower, middle and upper Eocene basalts with major element chemistry most similar to that of oceanic island provinces [*Snavely et al.*, 1968; *Glassely*, 1974]. Trace element data from the lower marine basalts [*Loeschke*, 1979] is supportive of formation as either an oceanic island or ocean ridge. The overlying basalts, the upper Siletz volcanics, the Yachats and the upper Tillamook basalts are all subaerial and therefore appear to cap an emergent island complex. Correlative (Eocene) pillow basalts to the north in the Olympic Peninsula [*Baldwin*, 1974; *Cady*, 1975] are associated with pelagic limestones [*Garrison*, 1973], consistent with an oceanic island setting. *Snavely et al.* [1968] have estimated the thickness of the Siletz basalts at 10,000 to 20,000 feet, clearly anomalously thick crust. This and an even greater crustal thickness of 15 to 20 km determined for the Coast Range from seismic data [*Tatel and Tuve*, 1955; *Berg et al.*, 1966; *Langston and Blum*, 1977] are consistent with a basement of oceanic crust anomalously thick due to the presence of oceanic islands. This model for the Coast Range basement is supported by the regional geology, by regional isotopic data and by seismic, gravity and resistivity data as summarized by *Simpson* [1977]. All appear to support the existence of oceanic crust beneath a large part of western Oregon and southwestern Washington [*Hamilton*, 1969, 1978; *Dickinson*, 1976; *Davis et al.*, 1978].

Two interpretative models were introduced by *Simpson* [1977] and *Simpson and Cox* [1977] to explain the inferred tectonic rotations and geology. In the first model, the present rocks of the Coast Range formed on a segment of oceanic plate and pivoted about a point near the southern end of the plate during subduction beneath North America. In an alternative second model, *Simpson and Cox* [1977] proposed an early Tertiary subduction zone extending southeast across what is now interior Oregon and Washington. This subduction zone was clogged in the early Tertiary by thickened oceanic crust including the thick sediments and seamounts which characterize the present Coast Range block. Subsequently, the trench jumped westward and the Coast Range block rotated clockwise, about a pivot at the northern end near the Olympic Peninsula. The seaward movement of the

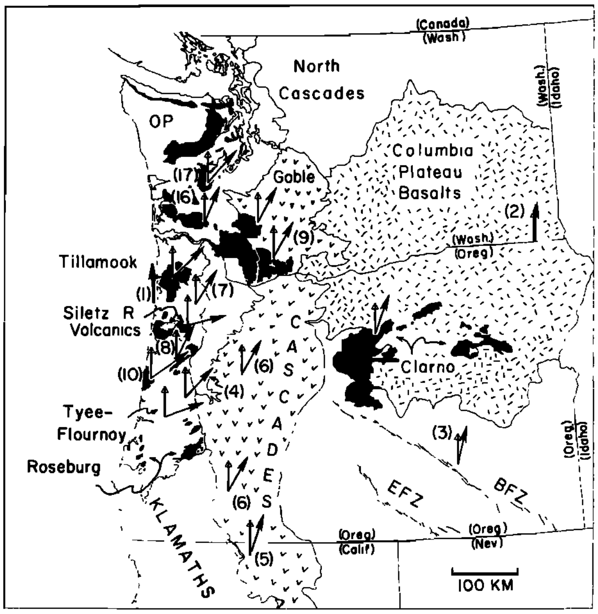

Fig. 2. Generalized geotectonic map of Oregon and Washington. Arrows indicate the mean paleomagnetic directions found for the respective geologic units. The open arrow marks the expected declination and the solid arrow the observed declination. The arrows have been adjusted so that the expected declinations point due north. An easterly directed solid arrow therefore indicates a 90° clockwise rotation. The arrows are labeled by geologic names or numbers listed in the rotation data summary of Table 3. A paleomagnetic direction for the Coast Range Eocene Instrusions ((12), Table 3) and outcrops of the Miocene Intrusions (4). Oligocene Intrusions (5) and the Blue Mountains (Figure 1) are not shown for simplicity. Map is based on *Huntting et al.* [1961], *Wells and Peck* [1961], *Cohee* [1962], *Lawrence* [1976], and *Walker* [1977].

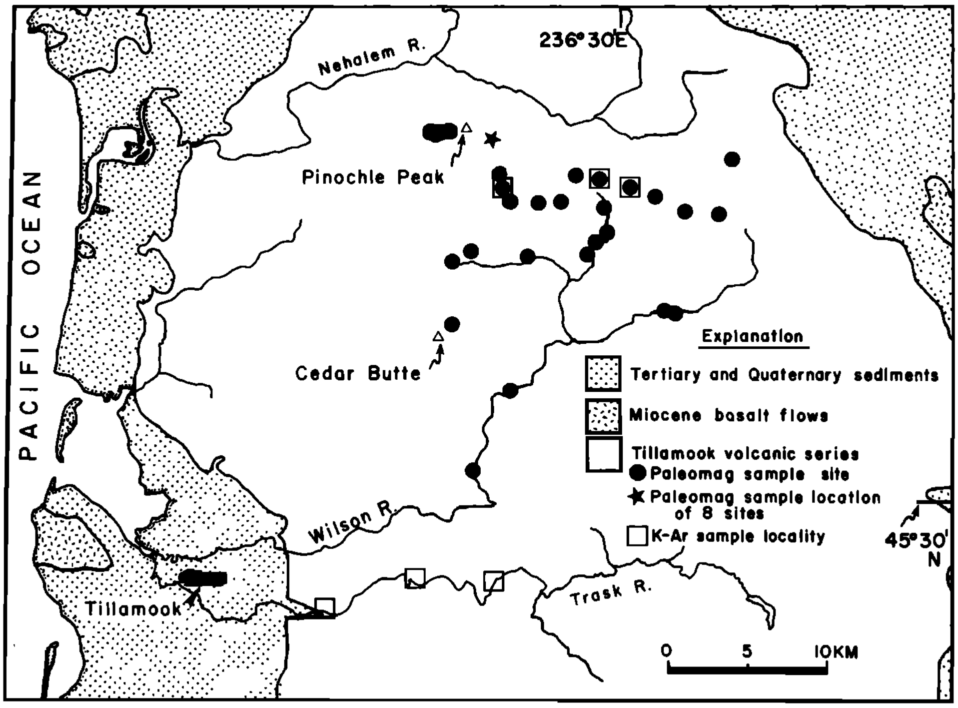

Fig. 3. Generalized geologic map of the paleomagnetic and K-Ar sampling locations within the Tillamook volcanics. The geologic boundaries and stratigraphy are from *Warren et al.* [1945].

southern end of the block was described as a type of back-arc spreading. Although the two models predict distinctly different regional geologic histories for the Pacific Northwest, our geologic and geophysical understanding of key areas such as the Klamaths and eastern Oregon is still not complete enough to determine whether either of the two models is correct. Later in this paper, we will return to the question of paleogeographic models.

PALEOMAGNETIC DATA AND AGE DETERMINATIONS FROM THE TILLAMOOK VOLCANIC SERIES

Although the Tillamook Volcanic Series have not been mapped in detail, *Snavely et al.* [1970] and *Nelson and Shearer* [1969] have described the general geologic history of this area. The oldest of the three units of the Tillamook Volcanic Series is marine in origin whereas the youngest unit is distinctly subaerial. The lower and middle units are submarine pillow basalts, tuffs, breccia and interbedded sediments. The lower pillow basalt unit of the Tillamook is correlative with pillow basalts of the lower Siletz River volcanics of central Oregon and the Roseburg Formation of southern Oregon, whereas the middle unit of the Tillamook is probably the equivalent of the uppermost Siletz River, Yamhill, and Tyee Formations to the south. Both in northern and central coastal Oregon these lower to middle Eocene marine formations are overlain by subaerial basalts.

The primary subject of this study was the uppermost unit of the Tillamook Volcanic Series, which consists of more than 1500 m of subaerial basalt flows, dikes, agglomerate, and pyroclastics. Individual flows 6 to 7 m thick typically have a rubbly

TABLE 1: K-Ar Geochronology of basalts from the Tillamook Volcanic Series, Oregon

Sample Number & Description	%K	Radiogenic ^{40}Ar (x 10^{-6} StP cc/g)	$\frac{\text{Radiogenic } ^{40}\text{Ar}}{\text{Total } ^{40}\text{Ar}} \times 100$	Age* ± 1 s.d. (m.y.)
Y027 flow (?)	0.758	1.3673	50.3	46.0 ± 0.9
Y051 flow	0.690	1.1674	31.4	43.2 ± 0.6
		1.2390	48.5	45.8 ± 0.5
Y106 flow (?)	1.283	2.1450	46.7	42.7 ± 0.5
D78-T-3 flow	0.921	1.5862	51.6	43.9 ± 0.5
D78-T-5 flow	0.470	0.8427	48.3	45.7 ± 0.5
D78-T-14 dike	0.791	1.3250	68.2	42.7 ± 0.4
Average				44.3 ± 1.3

*Ages calculated from the following decay and abundance constants: $\lambda_\varepsilon = 0.581 \times 10^{-10}\ \text{yr}^{-1}$; $\lambda_\beta = 4.962 \times 10^{-10}\ \text{yr}^{-1}$; $^{40}\text{K/k} = 1.167 \times 10^{-4}$ mol/mol.

Ages from the upper unit are defined by Y sample numbers and the lower unit by D78 sample numbers.

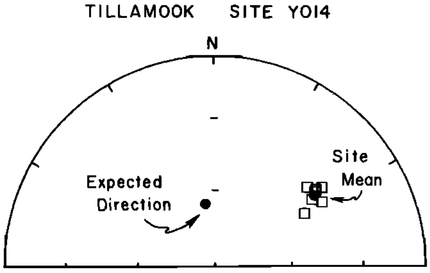

Fig. 4. Paleomagnetic field directions for the seven samples of site Y014 corrected for tectonic tilt. The rocks have been magnetically cleaned at a peak field of 20 milliteslas. All field directions are of reversed polarity and have been reflected through the origin to plot on the lower hemisphere of this stereographic polar plot.

brecciated base and an oxidized, brecciated upper surface. They are similar in physical appearance to the upper Eocene Yachats Basalt flows which cap the Eocene marine section in the central Coast Range [*Snavely and MacLeod*, 1974]. The only structural deformation in the area sampled is a shallow regional dip of 20° or less to the northwest, north, and northeast defining what appears to be a structural high centered somewhat to the south of our sampling area. Dike swarms trending west to northwest occur in the western part of the area (Figure 3) near Pinochle Peak and Cedar Butte, and are associated with agglomerate, tuff, and breccia. We interpret these dikes as feeders of the basalt flows.

Geochronology

K-Ar dating was done on three samples from the upper unit and on three samples from the lower unit of the Tillamook Volcanic Series (Figure 3). The selected samples were fine to medium grained basalts. Although the samples were the freshest available, all had undergone some low temperature alteration, as indicated by the presence of minor to modest amounts of calcite, zeolite, and smectite. Low temperature alteration of this type may result in the loss of argon or the addition of potassium from seawater, the latter being less likely in the upper unit of subaerial basalts. Both effects would produce K-Ar ages younger than the true crystalization ages of the basalts.

The range of K-Ar ages within both the upper and lower units is 43 to 46 m.y. (Table 1). The calculated ages of two specimens from one sample in the upper unit are 43 and 46 m.y. and since this spans the range of ages of all samples, the dating lacks the accuracy required to determine the duration of volcanism. The difference in ages of the two specimens from the one sample is entirely due to variations in argon content of the two specimens, suggesting that the younger age of 43 m.y. reflects argon loss due to diffusion or alteration and the older age of 46 m.y. is more reliable. Comparing the 43 and 46 m.y. ages of samples Y106 and Y027 from the upper unit (Table 1), again it seems likely that the younger age reflects argon loss and that the older age is the more reliable one. On the basis of these data 46 m.y. appears to be the best estimate of the minimum age of the upper unit. This age is in broad agreement with the paleontologically assigned age of upper Eocene [*Snavely et al.*, 1970]. If the geologic correlation of the lower unit with the lower Eocene pillow basalts of the Siletz River volcanics is correct, then the K-Ar ages of the lower unit are too young, suggesting that substantial argon loss or potassium addition has occurred. To test this future experiments are planned using the Ar^{40}-Ar^{39} method, a technique which has been used successfully to determine the ages of similarly altered Siletz River basalts further to the south [*Duncan*, 1978].

Paleomagnetism

A total of 4 to 9 samples were collected from each of 20 flows and 14 dikes from the uppermost unit and 2 flows from the lower unit of the Tillamook Volcanic Series (Figure 3). All samples were stepwise magnetically cleaned using alternating peak fields of 10, 20, and 30 milliteslas. To determine stability at higher fields, samples from five sites were subjected to stepwise demagnetization to fields ranging from 10 to 160 milliteslas. In all cases the extremely stable component left after demagnetization in these higher fields was found to be parallel to the component left after routine cleaning in fields of 20 or 30 milliteslas (Figures 4 and 5). Stepwise thermal demagnetization to 650°C of one to three samples from each of five sites produced similar results. The thermal demagnetization trend was parallel or subparallel to the magnetic vector remaining after 20 or 30 millitesla alternating field demagnetization, usually within 4° and in all cases less than 15° (Figure 6). After themal demagnetization to 600°C, all samples had only a small component of magnetization remaining (Figure 6) relative to the predemagnetization intensity (NRM). This indicates that the remanent magnetization resides in magnetite rather than hematite.

The directional stability and coercivity spectra of samples from a given site were analyzed to determine the optimum field for cleaning. In our final synthesis, site means from the upper unit were not included if their 95% confidence limit was greater than 7° because these data appeared to contribute more noise than signal to the final result (Table 2). Directions from 4 sites were rejected by this criterion. The 95% confidence limits of the two sites from the lower unit were 7° and 14°. The site with the 14° confidence limit was not rejected since this would result in the loss of half our data from the lower unit.

A summary of the magnetic data from the Tillamook volcanics corrected for tectonic tilt is shown in Table 2 and Fig-

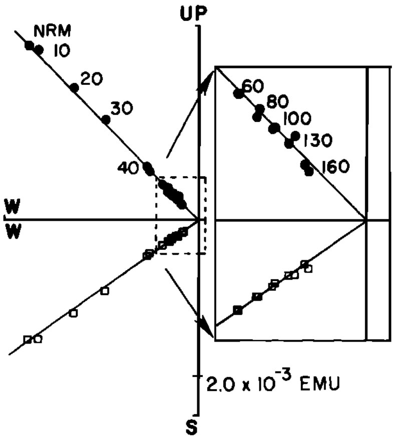

Fig. 5. Zijderveld component plot for sample Y018-1 of site Y014 during stepwise alternating field demagnetization. The open boxes represent the west and south components and the dots the west and up components of magnetization. The demagnetization field values are shown in milliteslas. The sample experienced the removal of only a single component of magnetization from the NRM up to peak fields of 160 milliteslas. Directions have been corrected for tectonic tilt.

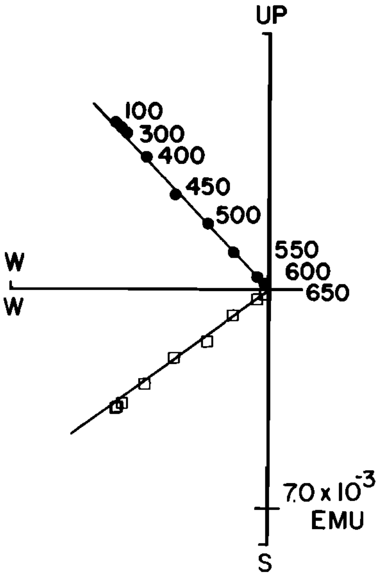

Fig. 6. Zijderveld component plot for sample Y018-2 of site Y014 during stepwise thermal demagnetization. Sample Y018-2 is a second specimen from the same sample core as Y018-1 of Figure 5. The open boxes represent the west and south components and the dots the west and up components of magnetization. The demagnetization temperatures in degrees centigrade are noted next to the appropriate points. The alternating field demagnetization trend of Y018-1 is shown by the plotted line segments.

ure 7. The measured field directions clearly show a significant clockwise rotation from the expected Eocene field direction for stable North America. Accounting for the dispersion in the measured and expected field direction, the clockwise rotation is found to be 46° ± 13° with 95% confidence.

Corrections for tectonic tilts up to 20° were made using the measured dips of the lava flows themselves except at the few localities where sediments were present. Errors are always introduced in such corrections because lava flows have an initial dip when they form which should not be corrected for, yet after deformation the measured dip is a composite of the initial dip and a tectonic tilt. On the Hawaiian Islands, which are a reasonable analogue for the original environment of the Tillamook volcanics, initial dips are generally less than 5° to 10°, so it seems likely that only small errors are introduced by using the present observed dips of the Tillamook volcanics for tilt corrections. If this conclusion is wrong and if, to consider an extreme case, the present dip of the flows is all initial dip, the result would be to increase the amount of inferred rotation by 19°. The inclination after tilt correction is 64°, which compares well with the expected inclination of 66° for the middle Eocene (Table 3). Without tilt correction the mean inclination is 78°, which would imply an unreasonably large southward translation of 2100 km. Because most the tectonic corrections reflect a regional northerly to northeasterly dip, there is no dramatic decrease in the amount of scatter in magnetic directions after tectonic corrections. However, the precision parameter for the site virtual geomagnetic pole increases from 9 to 14 upon correcting for tilt and this increase is significant at the 95% confidence level. We conclude therefore that correcting for the measured dips of the flows gives the best estimate of the mean Tillamook paleofield direction.

In tectonic studies like the present, the length of time represented by the units sampled is of particular importance because an underlying assumption is that bias introduced by geomagnetic secular variation has been removed by averaging over a time interval longer than the longest periods present in the geomagnetic field, which are probably less than 0.1 m.y. Although the K-Ar ages of the Tillamook lavas span 3.3 m.y., the true ages probably span a shorter time interval, as discussed earlier. The observation that all the polarities from the upper unit are reversed is consistent with all the lavas having been formed during one interval of constant reversed polarity, the one between 45 and 48 m.y. being the most probable (Figure 8). If this correlation with the magnetic time scale is correct, the upper Tillamook unit may span as much as 2.5 m.y. It seems unlikely on the basis of two geologic considerations that our samples span only an extremely small time interval. First, the stratigraphic thickness of flows present in the upper Tillamook section is about 1500 m and we sampled widely in this section, trying to avoid multiple sampling of the same flow. Our 20 flows and 14 dikes probably sampled a large fraction of the history of at least one shield volcano, a typical lifetime of which is 0.5 to 1.0 million years. Second, the observation that the magnetic directions of the two normal polarity sites from the lower unit are antiparallel to the magnetic directions of the reversed sites of the upper unit constitutes a positive reversal test and lends support to the interpretation that the range of ages was adequate to fully sample secular variation.

The amount of angular dispersion in the paleomagnetic directions further support such a conclusion. The amount of angular dispersion in virtual geomagnetic poles expected for a site at this latitude is about 15° [*Cox*, 1970]. Insufficient sampling of secular variation would be expected to yield a smaller angular dispersion. The angular dispersion observed in the Tillamook volcanics is 22°, which is consistent with a full sampling of geomagnetic secular variation with some additional dispersion due to inaccurate tectonic corrections.

TECTONIC INTERPRETATION

Amount of Rotation

The magnetic field directions from the Tillamook volcanics acquire tectonic significance through a comparison with the expected field direction which we have computed using the apparent polar wander curve of North America [*Irving*, 1979]. The computed expected paleofield directions are listed in Table 3. As noted above, the observed Tillamook direction is rotated 46° from the expected direction. The significant and consistent clockwise rotation is clearly seen in the measured versus the computed paleofield directions for the entire Oregon Coast Range. The agreement between the computed and measured magnetic inclinations indicates that the Coast Range has not undergone significant north-south translation, which suggests rotation about a local pivot [*Simpson and Cox*, 1977].

Northern Boundary of the Rotated Block

The paleomagnetic results from the Tillamook Volcanics clearly establish that the rotated terrane of the southern Oregon Coast Range [*Simpson and Cox*, 1977] extends northward to the Columbia River at the Oregon-Washington border. Although the amount of rotation recorded in the upper Eocene Tillamook volcanics is somewhat less than that recorded in the older formations of the southern Coast Range, we will see later that this probably reflects progressive rotation with time

TABLE 2. Summary of paleomagnetic data from the Tillamook Volcanic Series

	Site	F/D	Dec.	Inc.	α95	κ	N	Demag Field
Upper unit:	Y001	F	253.3	-58.7	4.4	187	7	30
	* Y008	F	219.2	-38.7	19.5	13	6	30
	Y014	F	234.8	-41.6	3.3	326	7	20
	Y021	F	233.6	-65.3	6.5	88	7	30
	* Y028	F	229.9	-55.1	33.4	3	9	30
	Y037	F	199.1	-63.5	6.2	80	8	20
	Y045	D	231.7	-54.0	5.1	176	6	30
	Y051	F	218.6	-50.4	6.3	77	8	30
	Y059	F	215.8	-47.5	4.2	259	6	30
	Y065	F	176.2	-64.7	4.1	266	6	30
	Y071	F	214.7	-43.2	5.3	163	6	20
	Y077	F	231.3	-53.4	4.6	173	7	30
	Y081	F	227.1	-66.0	2.6	649	6	30
	Y087	F	290.6	-68.1	6.7	101	6	30
	* Y093	F	250.3	-48.9	15.0	21	6	30
	Y101	F	152.1	-81.3	7.0	92	6	30
	Y107	F	156.0	-75.1	4.2	491	4	30
	Y111	D	212.8	-61.3	4.8	253	5	30
	Y116	D	210.0	-52.3	2.8	722	5	30
	Y126	D	209.6	-60.5	4.6	406	4	30
	Y130	D	198.1	-59.1	5.0	335	4	30
	Y134	D	200.0	-59.8	3.5	693	4	30
	Y138	D	203.1	-55.7	2.4	1517	4	30
	Y142	D	211.9	-49.0	5.8	251	4	30
	Y146	D	213.3	-55.1	4.9	347	4	30
	Y151	D	218.8	-73.4	5.4	154	6	30
	Y157	D	219.3	-72.6	3.0	501	6	20
	Y163	D	223.9	-70.4	4.5	420	4	20
	Y169	D	231.7	-71.8	5.5	282	4	20
	Y172	F	202.7	-74.1	5.9	128	6	30
	Y179	F	138.3	-60.0	4.2	251	6	20
	* Y185	F	223.6	-48.3	17.5	16	6	30
	Y191	F	234.6	-60.8	6.5	108	6	30
	Y197	D	216.0	-43.8	4.6	393	4	30
Lower Unit:	T3	F	49.9	68.4	6.9	178	4	10
	T4	F	42.4	63.0	14.3	30	5	20

F/D=flow or dike, Dec.=declination, Inc.=inclination, α_{95}=radius of 95% confidence in degrees, κ=precision parameter, N=number of samples, Demag Field=peak demagnetization field in milliteslas. The sites marked by an (*) were not included in the final synthesis due to a high α_{95} indicating poor grouping of the directional data.

rather than differential rotation between the southern and northern Oregon Coast Ranges. This is in accord with a considerable body of geologic observation which argues against the differential rotation of small independent blocks within the Oregon Coast Range. Of particular importance are: (1) the continuity of outcrop of middle Eocene Tyee and Flournoy formations along the entire Coast Range which define it as a single Eocene basin rather than a tectonic composite of several basins, (2) the absence of strong deformation in these formations, and (3) the internal consistency of current directions recorded in the turbidites of this formation throughout the Coast Range [*Snavely et al.,* 1964], including turbidites in the vicinity of the Tillamook volcanics. The structural continuity suggested by these observations is further supported by the presence of a pronounced gravity high [*Bromery and Snavely,* 1964] extending from the northern to the southern part of the Coast Range (Figure 9). The smooth gravity contours in western Oregon do not display the offsets or short wavelength features that are commonly associated with major tectonic structures. The available geophysical and geologic data are thus consistent with the Oregon Coast Range having rotated as one quasi-rigid block extending from the Klamath Mountains to the Columbia River.

Paleomagnetic studies to the north reveal a more complex pattern. In the lower and middle Eocene Willipa Hills basalts directly north of the Columbia River, the amount of clockwise rotation is approximately 22° based on preliminary results [*Wells and Coe,* 1979]. This rotation is significantly less than that recorded in the Tillamook or Siletz volcanics, indicating that the coherent rotated block does not extend farther to the north. Paleomagnetic results from the Black Hills basalts [*Globerman and Beck,* 1979], north of the Willipa Hills and south-

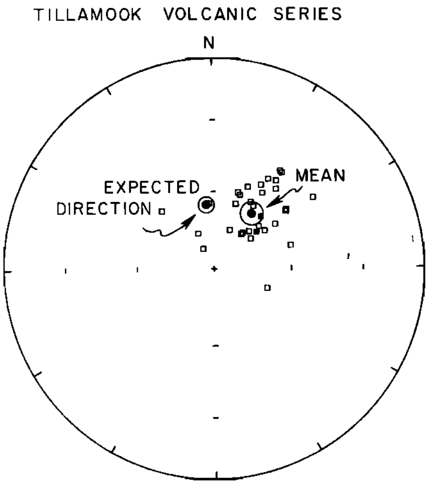

Fig. 7. Paleomagnetic field directions for the Tillamook volcanics (Table 2) corrected for tectonic tilt. The directions of normal polarity are plotted as filled boxes and reversed polarity as open boxes. Directions of reversed polarity have been reflected through the origin to plot on the lower hemisphere of this stereographic plot. The mean direction was computed from the mean pole of the 32 site VGP's. The circles about the expected and observed means are the 95% confidence circles (α_{95}).

east of the Olympic Peninsula, show a 40 degree clockwise rotation. Moreover, the gravity anomalies north of the Columbia River (Figure 9) have irregularities with sharp gradients suggestive of discrete tectonic blocks [*Fox,* 1981]. The emerging picture is one of different amounts of rotation in different tectonic blocks north of the Columbia River contrasted with the coherent rotations of the one block to the south. We will return to this point later.

Timing of Rotations

The amount of rotation recorded in the formations of the Coast Range (Table 3) decreases with decreasing age. To assess the uncertainty in these changes, we note that if the rotation and its uncertainty from one formation are $R_A \pm \Delta R_A$ and that from a second formation is $R_B \pm \Delta R_B$, then the difference ${}_{A}R_{B} \pm \Delta_{A}R_{B}$ in rotation between the two formations is

$${}_{A}R_{B} = R_A - R_B \qquad \Delta_{A}R_{B} = [\Delta R_A{}^2 + \Delta R_B{}^2]^{1/2}$$

where ΔR values are 95% confidence intervals. If the two formations are from the same region but are of different ages, then a value of ${}_{A}R_{B} > \Delta_{A}R_{B}$ would indicate that significant rotation had occurred between the ages of the two formations. Similarly, if the two formations are of the same age but from different regions, a value of ${}_{A}R_{B} > \Delta_{A}R_{B}$ would indicate that the two sampling regions had undergone differential rotation. Applying this to the rotations inferred for the Siletz River volcanics and the Tillamook volcanics yields the result ${}_{\mathrm{Siletz}}R_{\mathrm{Till}} = 28° \pm 18°$ indicating that the larger amount of rotation of the older Siletz River unit is significant at the 95% confidence level. The rotation of the Tyee is greater than that of the younger Tillamook by the angle 23° ± 21°, again a significant difference. If our interpretation is correct that these sampling localities are on the same quasi-rigid Coast Range microplate, these results establish that the microplate underwent significant rotation during the Eocene.

The Goble volcanics immediately to the northeast with ages in the range 45 to 32 m.y. were found by *Beck and Burr* [1979] to have rotated 28° ± 12°, so that ${}_{\mathrm{Till}}R_{\mathrm{Goble}} = 18° \pm 18°$. If we account for the uncertainty in age of the Goble volcanics, as seems appropriate, this difference becomes 18° ± 21°, which is not statistically significant. If future research establishes a significant difference between the Tillamook and Goble rotations, this might be due to the two regions being on separate microplates, as *Beck and Burr* [1979] suggested, or it might be due to their being of different ages and having formed on one microplate undergoing rotation during the Eocene. The former would be favored if the Goble volcanics are predominantly of an age near 45 m.y., the latter if the age of the Goble volcanics is predominantly 32 m.y. The presently known paleomagnetic and radiometric data thus do not require differential rotation between the Tillamook and Goble areas, but they also do not preclude it. If the two areas are on separate microplates, the present study narrows the range of possible locations of the tectonic boundary between the two (Figure 2) to a narrow zone near the Columbia River.

A plot of rotation versus age (Figure 10) with all the data from the Oregon Coast Range, Cascades, and Goble volcanics can be fit by several line segments. To the eye it might appear that the data in Figure 10 could be fit by a simple straight line corresponding to rotation at a constant rate. To test statistically whether the data are simply linear we fit the paleomagnetic rotation and age data with first, second and third order polynomials weighting the data by the 95% confidence limits of the respective rotations. The third order polynomial shown in the inset of Figure 10 fits the data significantly better than the linear (95% confidence) and second order curve (50% confidence) as determined by an F test of the chi square statistics. This analysis does not prove that the third order polynomial fit is correct but it does indicate that the best fit curve is more complicated than a simple linear trend corresponding to rotation at a constant rate. The heavy line of Figure 10 is similar to the fitted polynomial but is a more reasonable curve incorporating our interpretation of the regional geology described in the following section. The chi square of the interpreted curve is slightly less than that of the best fit third order curve and therefore must be considered an equally good fit to the data. The earlier rotation from 50 to 42 m.y. with rotation at a rate of 5° to 6° per million years is required by the trend in the rotations of the Siletz River, Tyee-Flournoy, Tillamook and Goble basalts described above. The later rotation as determined from the Coast Range Miocene basalts [*Simpson and Cox,* 1977; *Beck and Plumley,* 1980], the Oligocene Coast Range dikes and sills [*Clark,* 1969; *Beck and Plumley,* 1980] and paleomagnetic results from the Western Cascades [*Bates et al.,* 1979; *Bates and Beck,* 1981; *Magill and Cox,* 1980] require about 30° of post-Oligocene clockwise rotation of the Coast Range and Cascades [*Magill and Cox,* 1980]. Although the timing of this second rotational period is not well constrained by the paleomagnetic data, our preferred interpretation is one of rotation from 20 m.y. to the present at an average rate of 1.5 degrees per million years.

PALEOGEOGRAPHIC INTERPRETATION

Introduction

These results (Figure 10), combined with our knowledge of the regional geology, suggest to us that the rotation of the Oregon Coast Range took place in two phases, each due to a different geologic process. Phase I of the rotation occurred dur-

Table 3: Compilation of regional paleomagnetic results from Oregon, Washington and the Sierra Nevada regions

		Observed Data													
Name and Reference		Pole					Field Direction		Expected Field			Flattening		Rotation	
Oregon-Washington Region		Lat.	Lon.	α95	N	κ	Inc.	Dec.	Age	Inc.	Dec.	F	ΔF	R	ΔR
Miocene Basalts	(1)	77.0	80.0	29.0	8	4.6	52.0	354.0	20	63.8	356.0	11.8	31.3	-2.0	35.8
Columbia R. Basalt N	(2)	87.6	203.2	7.0	6	91.6	65.7	357.7	20	64.8	355.8	-0.9	6.6	1.9	12.8
Columbia R. Basalt S	(3)	84.2	315.8	5.9	14	45.9	62.8	7.8	20	62.4	356.0	-0.4	6.3	11.8	10.8
Miocene Intrusions	(4)	----	----	9.6*	8	----	67.5	29.5	20	63.5	357.5	-4.0	----	32.0	26.8
California Cascades	(5)	78.7	292.9	8.9	24	12.0	65.5	13.8	25	61.5	356.0	-4.0	7.6	17.8	14.4
Western Cascades	(6)	72.2	280.0	10.9	24	8.3	70.1	20.7	25	62.1	356.0	-8.0	8.1	24.7	19.7
Oligocene Intrusions	(7)	----	----	8.4*	14	----	56.0	39.0	30	63.5	354.5	7.5	----	44.5	16.7
Marys Peak	(8)	63.0	8.0	8.0	26	13.5	42.0	22.0	30	64.0	354.6	22.0	11.3	27.4	11.4
Ohanapecosh	(9)	71.3	320.7	4.4*	34	----	63.6	26.8	35	65.3	352.2	1.7	----	34.6	12.4
Yachats Basalt	(10)	58.0	308.0	20.0	8	8.6	64.0	46.0	40	64.4	350.3	0.4	16.3	54.7	30.2
Goble Volcanics	(11)	75.5	345.5	5.5	37	17.7	57.5	18.5	40	65.4	350.1	7.9	6.4	28.4	12.4
Eocene Intrusions	(12)	----	----	12.5*	10	----	62.0	44.5	40	64.5	353.0	2.5	----	51.5	28.4
Clarno Formation	(13)	80.5	274.0	11.3	13	14.4	67.5	9.5	45	65.0	349.1	2.5	9.0	20.4	19.4
Tillamook	(14)	65.5	312.7	7.0	32	14.0	64.2	35.5	45	66.2	349.1	2.0	6.7	46.4	12.7
Tyee-Flournoy	(15)	49.0	305.0	11.0	40	5.2	63.0	59.0	45	65.3	349.3	2.3	9.6	69.7	17.2
Willipa Hills	(16)	----	----	----	--	----	----	10.0	50	67.6	347.8	----	----	22.2	----
Black Hills	(17)	69.4	322.3	5.2*	35	----	63.2	29.6	50	67.9	347.6	4.7	----	42.0	14.0
Siletz River Volc.	(18)	45.0	307.0	8.0	33	10.7	61.0	63.0	55	67.4	346.2	6.4	8.4	76.8	15.7
Sierra Nevada Region															
Great Valley	(19)	72.0	181.0	5.4	17	44.0	65.7	337.4	70	67.6	339.0	1.9	6.5	-1.6	13.7
Cretaceous Granites	(20)	68.8	195.2	9.6	14	18.0	68.1	336.0	85	67.0	333.6	-1.1	8.9	2.4	19.9
Bucks Batholith	(21)	57.6	194.8	7.9	9	43.7	72.1	317.1	140	60.4	333.6	-11.7	12.4	-16.5	22.9
Reeve Formation	(22)	73.0	139.0	9.0*	40	----	54.8	339.3	150	53.9	341.1	-0.9	----	-1.8	17.3

α_{95} = radius of 95% confidence about the mean pole, an (*) denotes an α_{95} of the mean field direction where the mean pole α_{95} was not available, N = number of sites, κ = precision parameter, Inc. = inclination, Dec. = declination, Age = age of the pole of Irving (]979) used to compute the expected field direction, F = $\text{Inc.}_{\text{expected}} - \text{Inc.}_{\text{observed}}$, $\Delta F = [\Delta I^2_{\text{obs}} + \Delta I^2_{\text{exp}}]^{\frac{1}{2}}$ where $\Delta I = 2\alpha_{95}/1 + 3\cos^2 p$, $R = \text{Dec.}_{\text{observed}} - \text{Dec.}_{\text{expected}}$, $\Delta R = [\Delta D^2_{\text{obs}} + \Delta D^2_{\text{exp}}]^{\frac{1}{2}}$ where $\Delta D = \sin^{-1}[\sin\alpha_{95}/\sin p]$, p = colatitude, or $\Delta D = \sin^{-1}[\sin\alpha_{95}/\cos(\text{Inc.})]$ if an α_{95} for the mean field direction is only available. The Columbia R. Basalt N data is an average of stes SRC, LC, A, GR, M, and I of Watkins and Baski (1974), Columbia R. Basalt S data is an average of sites BC, CC, PG, OR, SM of Watkins and Baski (1974) and SA, SB, SC, SD, SE, SF, SG, SH, SI of Watkins (1965). Other references are (1), (10), (15), (18) Simpson and Cox (1977); (4), (7), (12) Beck and Plumley (1980); (5) Beck (1962); (6) Magill and Cox (1980); (8) Clark (1969); (9) Bates and Beck (1981); (11) Beck and Burr (1979); (13) Beck et al. (1978); (14) this study; (16) Wells and Coe (1979); (17) Globerman and Beck (1979); (19) Mankinen (1978); (20) Grommé and Merrill (1965); (21) Grommé et al. (1967); (22) Hannah and Verosub (1979).

ing the Eocene. The underlying geologic process was the breakup and clockwise rotation about a southern pivot point of a narrow offshore Eocene oceanic plate similar to the present Juan de Fuca plate. This is essentially model 1 of *Simpson and Cox* [1977]. Phase II of the rotation took place at a slower rate in post Eocene time and likely was predominantly a post Oligocene tectonic event. The underlying geologic process was differential extension in the Basin and Range province, with greater extension toward the southern end of the Coast Range producing clockwise rotation of the Coast Range and Klamath Mountains about a northern pivot point. This is essentially model 2 of *Simpson and Cox* [1977] and is vaguely similar to the oroclinal model of *Heptonstall* [1977]. At the beginning of Phase I the subduction zone was located to the east of the seafloor upon which Eocene strata that now comprise the Coast Range were forming. By the end of Phase I and prior to Phase II the subduction zone had completely shifted to the west and the strata of the present Coast Range had become part of the North American plate. We will now review the geologic information that points toward a two phase rotation of this type.

Phase I: Pivoting Subduction of Seafloor

Menard [1978] proposed that as the East Pacific rise approached North America at the beginning of the Tertiary, the narrowing Farallon plate [*Byrne*, 1978] broke up into fragments analogous to the present Juan de Fuca and Cocos plates. To understand Menard's model, consider a wedge shaped plate bounded by a ridge on the west and a trench on the east. If the ridge converges toward the trench at the north end of the plate, the lithosphere adjacent to the trench will be young, hot, and light and will not subduct easily—in Menard's words, it will be a drogue that slows the subduction of the plate at its northern end. The lithosphere being subducted at the south end of the plate will be older, cooler, thicker and denser and will subduct more readily causing the plate fragment to pivot in a counterclockwise sense about a northern pivot point. *Menard* [1978] proposes that this occurred be-

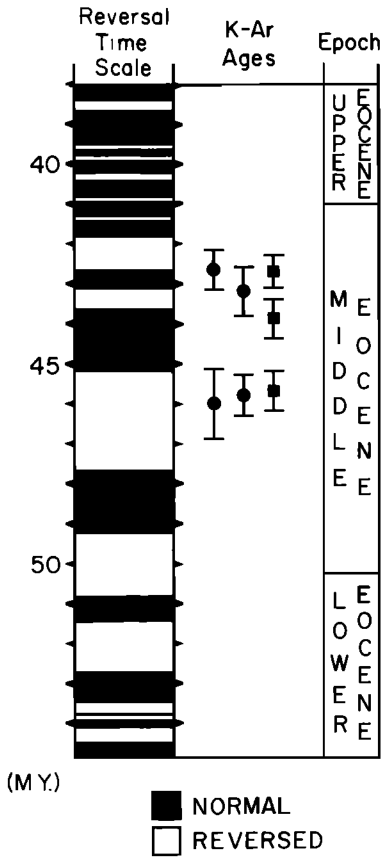

Fig. 8. Geomagnetic timescale of *Ness et al.* [1980] with the K-Ar dates from the Tillamook volcanics upper unit (dots) and lower unit (boxes). The error bars are ±1 s.d.

tween 50 and 35 m.y. B.P. and again between 33 m.y. B.P. and the present, fragmenting the Farallon plate into the hypothetical Vancouver, Cocos and Nazca plates. An important accompaniment of Menard's pivoting subduction is active volcanism along leaky transforms and elsewhere as the plate changes its direction of motion. *Menard* [1978] points out that the present small Juan de Fuca and Cocos plates which appear to be pivoting are, in fact, studded with seamounts.

If the northern Farallon plate did fragment during the early Eocene according to a Menard type model, the seafloor adjacent to Eocene North America should have been a seamount province similar to the present Juan de Fuca and Cocos plates. The geologic and geochemical evidence quite clearly suggests that it was [*Dickinson*, 1976]. The major element geochemistry of the lower and middle Eocene Siletz River Volcanics and the upper Eocene Yachats basalt very closely resembles that of oceanic islands like Hawaii and is quite distinct from that of arc basalts. The high TiO_2, and the high Na_2O/K_2O ratio, the low SiO_2, and the Fe/(Fe + MgO) ratio relative to SiO_2 [*Snavely et al.*, 1968; *Snavely and MacLeod*, 1974; *Jakes and Gill*, 1970] are especially diagnostic. Moreover, the CaO concentrations are too low relative to SiO_2 for the basalts to be of island arc origin (W. R. Dickinson, personal communication, 1980). The trace element geochemistry of the lower Eocene marine basalts [*Loeschke*, 1979] also shows these basalts to be unlike island arc rocks. The geochemistry, together with the geologic evidence that a substantial fraction of the lower and upper Eocene basalts formed as subaerial flows on oceanic islands [*Snavely et al.*, 1968] all are consistent with the interpretation that the Eocene basalts that now form the Coast Range were a seamount province.

The regional geology appears to indicate that this evolving seamount province collided with North America during the early Eocene and then became trapped between two active trenches. During the early Eocene, the Kula-Pacific ridge ceased spreading, which resulted in a reorganization of the Kula-Farallon and Pacific-Farallon ridges [*Byrne*, 1979]. This change in Farallon plate motion appears to have been accompanied by the middle Eocene formation of a second subduction zone seaward of the evolving Coast Range seamounts, possibly along an old Kula-Farallon transform. The seamounts were then trapped by two active trenches, one east and another to the west of the seamount province. Clockwise rotation resulted as this trapped wedge of oceanic crust was partially consumed by the eastern trench. We will now elaborate on this model and present the relevant geologic evidence.

Evidence for the early Eocene collision of the seamount province with North America is found in the geology of the southern Oregon Coast Range. At the extreme southern end of the range the presence of a subduction zone is recorded in the early Eocene Roseburg Formation [*Baldwin*, 1974, 1975]. The latter includes submarine basalts and marine sediments that are intensely thrusted and isoclinally folded, with late Cretaceous sediments being folded into the Roseburg during

Fig. 9. Complete Bouguer gravity anomaly map of western Oregon and Washington from *Berg and Thiruvathukal* [1967] and *Bonini et al.* [1974]. The dotted lines mark the coastal outline and the geologic boundaries of the Klamaths and Cascades (see Figure 1).

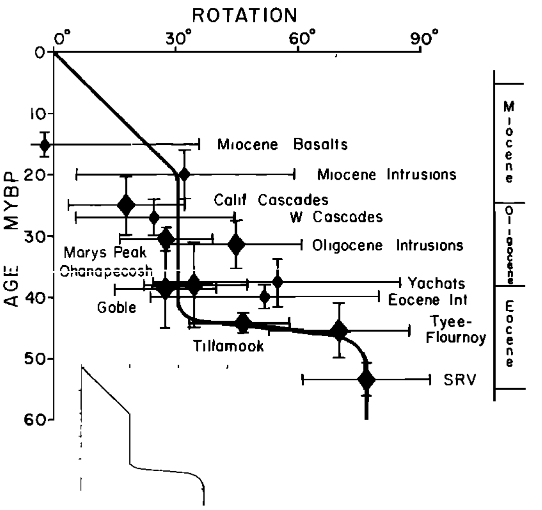

Fig. 10. Rotation versus age for geologic units in the Cascades and Oregon Coast Range. The data shown are described in Table 3. The rotation error bars are the ΔR values listed in Table 3. The inset shows a weighted least-squares fit of the data to a third order polynomial (dotted curve) superimposed on our suggested curve (solid) which is constrained by our interpretation of the regional geology.

an early Eocene episode of intense deformation. We interpret this deformation to mark a subduction zone. *Beaulieu* [1971, p. 30] notes that the Roseburg (lower Umpqua) has several features of a melange. Strong northwestward vergence of the folds in the lower Eocene strata of southern Oregon is suggestive of underthrusting from the northwest [*Baldwin,* 1964]. Some Roseburg strata were tectonically emplaced within the neighboring Jurassic Otter Point Formation of the Klamath terrane and the Roseburg contains exotic blocks of schist, greenstone and conglomerate, all derived from the Klamaths. This indicates the subduction zone at the southern end of the Coast Range was located near shore in the early Eocene. Subduction at this locality stopped abruptly at or near the end of the lower Eocene. The gently folded middle Eocene turbidites and conglomerates of the Tyee and Flournoy formations which overlie the Roseburg formation with an angular unconformity display none of the thrusting and telescoping of strata that characterized the underlying Roseburg formation. The simplest explanation is a westward jump of the subduction zone toward the end of the lower Eocene.

The location of the lower Eocene trench in the region north of Roseburg is uncertain on the basis of the available geologic information. Although the Siletz River Volcanics are correlative with the Roseburg Formation, the former have not undergone the intense deformation of the latter, indicating that the location of the early Tertiary subduction zone was probably considerably eastward of the northern part of the present Coast Range. The presumed suture between North America and the adjacent oceanic plate could be located beneath post Eocene Tertiary cover almost anywhere in the broad band between the Coast Range and the nearest Mesozoic rock outcrops several hundred kilometers to the east.

Additional evidence for the existence of an early Tertiary subduction zone to the east of the Coast Range is provided by the calcalkaline Eocene Challis and Absaroka volcanics (50 to 36 m.y. B.P.) of Montana, Wyoming, and Idaho [*Armstrong,* 1974, 1975, 1978; *Snyder et al.,* 1976]. This volcanism diminished greatly at the end of the Eocene, persisting only weakly in southwestern Montana and Wyoming into Oligocene time [*Armstrong,* 1978]. The location of the lower Eocene eastern trench shown in Figure 11 therefore is constrained by the Roseburg deformation, the trend of the Challis-Absaroka volcanics and evidence of subduction on Vancouver Island [*Muller,* 1977; *Davis,* 1977].

During the latter part of this period of active Challis-Absaroka volcanism, calc-alkaline volcanism began well to the west in the Western Cascades, pointing to a substantial westward shift of the subduction zone. Five observations suggest that both the eastern and western subduction zones were active during the middle and upper Eocene. The first is that assuming a reasonable delay time of 4 m.y. between the cessation of subduction and cessation of related volcanism, the Challis-Absaroka volcanism likely represents actual subduction until approximately 40 m.y. B.P. (late Eocene). Second, the paleomagnetic data establishes that the seafloor that now forms the Oregon Coast Range was rotating during the middle and early upper Eocene. This rotation is consistent with the presence of a subduction zone to the east through late Eocene time and requires that the rate of subduction was greatest at the north end of the subduction zone. The third observation is the occurrence of late middle Eocene and late Eocene basalts, andesites and pyroclastics (45 to 31 m.y.) in the Western Cascades of Washington [see *Hammond,* 1979] and of late Eocene andesite flows and pyroclastics in the Western Cascades of southern Oregon [*Peck et al.,* 1964]. Similar late Eocene (40 m.y.) andesite flows also are found in the Warner Mountains (see Figure 1) of extreme northern California [*Axelrod,* 1966] and in the Drake Peak area [*Wells,* 1979] of south-central Oregon (Figure 1). If we are correct in interpreting these rocks as early Cascade arc deposits, they indicate that a western subduction zone must have begun in the middle Eocene in order to produce late Eocene arc rocks.

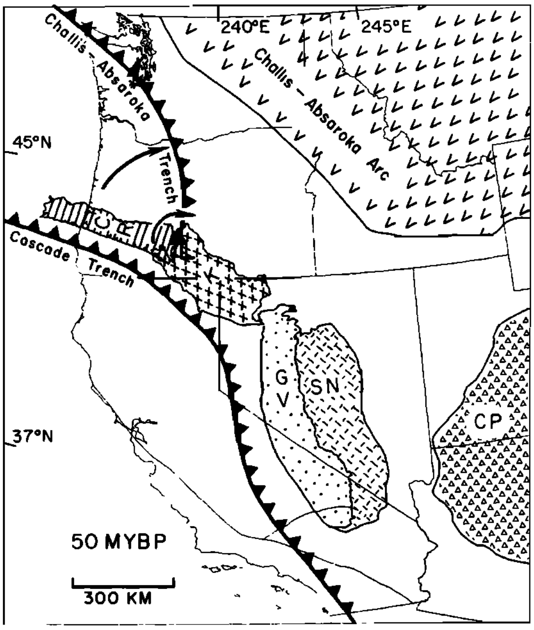

Fig. 11. Position of the primary blocks of the present western U.S. continental margin at the beginning of Phase I rotation. 50 m.y. B.P. See Figure 1 for the present-day position of these blocks. The rotation pivot at the southern end of the Coast Range block is shown by a triangle.

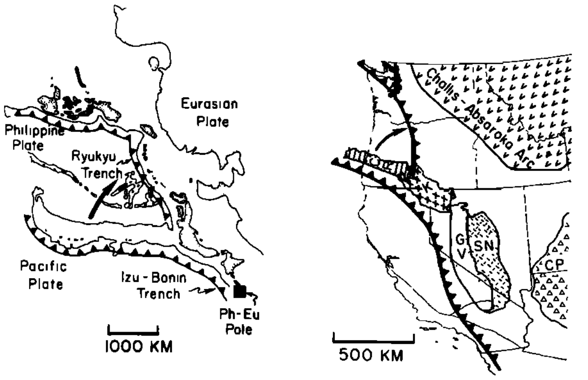

Fig. 12. A comparison of Phase I rotation (see Figure 11) with a modern-day analogue from the western Pacific. The Philippine plate and adjacent regions have been rotated to the Oregon-Washington area and plotted with the same map projection to minimize distortion. The Philippine-Eurasia relative motion pole of *Seno* [1977] is shown by a solid box (Ph-Eu).

Fourth, we note that middle Eocene sediments of the southern Coast Range received andesitic pumice blocks and mud flow debris from an arc located to the east of the basin [*Snavely and Wagner,* 1963; P. Snavely, personal communication, 1980]. This arc was likely the beginning western Cascade arc. Fifth, *Snavely et al.* [1980] interpret seismic profiles of the central Oregon continental margin as showing strike-slip faulting during late middle to early late Eocene time. They further suggest that middle Eocene underthrusting may have occurred on this margin west of the Coast Range. We and *Snavely et al.* [1980] interpret this possible underthrusting as that associated with a subduction zone which we shall label the Cascade trench. These five observations suggest that the Challis-Absaroka and Cascade subduction zones were both active during the period 50 to 40 m.y. B.P.

In addition to these observations, the undeformed character of the middle Eocene marine sediments of the Coast Range suggests that the Cascade trench must have been located to the west of the Coast Range. The picture that emerges during the middle and upper Eocene is one of a wedge shaped piece of seafloor bounded on the east and west by subduction zones narrowing to the south and rotating about a southern pivot. The pivot point was near the present location of the Roseburg formation, the volcanics and sediments of which jammed the trench at its southern end. Rotation and continued volcanism in the Coast Range occurred as the wedge shaped plate was consumed in the eastern trench and mildly deformed. Considering the size of this wedge shaped oceanic plate and a reasonable subduction velocity of 5 cm/yr, the Phase I rotation of 40° to 50° could have spanned as little as 5 to 6 m.y.

By the end of the Eocene the subduction zone to the east was no longer active and the marine oceanic rocks of the Oregon Coast Range had become part of the North American plate. This suturing of the Coast Range to North America appears to be the possible cause of the southeasterly compressional orogeny in the lower Clarno unit in central Oregon [*Taylor,* 1977]. K-Ar dating by *Swanson and Robinson* [1968] seems to place the orogeny during the period of 42 to 44 m.y. B.P. (J. B. Noblett, personal communication, 1980) in good agreement with the termination of Challis-Absaroka volcanism and our estimate of when Phase I rotation ended.

The formation of the Cascade trench and subsequent rotation of seafloor to the east was likely the result of several effects: (1) the subducting Farallon plate was young, thin, and hot and therefore relatively buoyant, (2) the low density basaltic seamounts riding on the Farallon plate accentuated the buoyancy of the plate [*Vogt,* 1976], (3) the Farallon plate changed its motion at about 55 to 50 m.y. B.P. in response to the cessation of spreading at the Kula-Pacific ridge [*Byrne,* 1979]. We propose that because of its buoyancy the eastern part of the Farallon plate became partially coupled to North America near the middle of the Eocene. The combined effect of this partial coupling and the change in motion of the Farallon plate forced the initiation of the Cascade trench to the west.

A modern analogue of the proposed rotation and subduction zone geometry would be the piece of seafloor (Philippine plate) bounded by the active Ryukyu and Izu-Bonin trenches in the western Pacific. Present-day motion of the Philippine plate relative to Eurasia [*Seno,* 1977] indicates that the Philippine plate is rotating clockwise into the Ryukyu trench about a local pivot (Figure 12) similar to the proposed Eocene rotation of the Oregon Coast Range. *Uyeda and Ben-Avraham* [1972] and *Matsuda* [1979] propose that the seaward Izu-Bonin trench formed as a result of an Eocene change in Pacific plate motion. This converted a former transform to a trench, thereby trapping a wedge shaped piece of seafloor. We speculate that a similar sequence of events seems possible in the Oregon region. A northeasterly trend of the early Eocene Kula-Farallon ridge [*Byrne,* 1979] implies that fracture zones associated with this ridge would strike southeasterly. The southeasterly strike of the western trench shown in Figure 11 may be the result of a Farallon fracture zone converting to a subduction zone. This conversion would be associated with the 55 to 50 m.y. B.P. reorganization of the Kula-Pacific-Farallon ridges noted earlier.

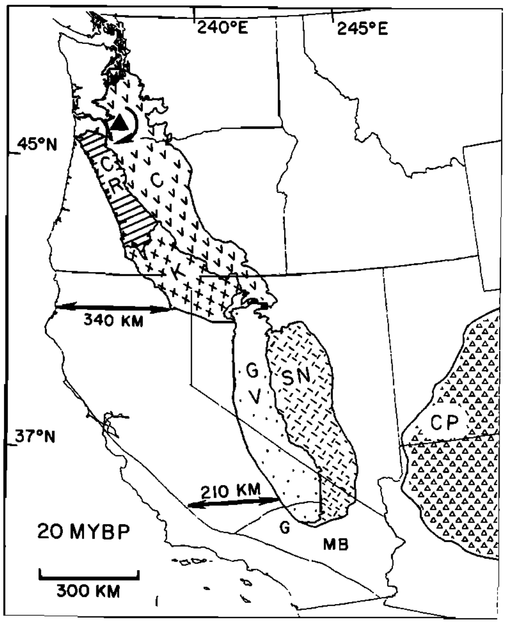

Fig. 13. Position of the primary blocks of the present western U.S. continental margin at the beginning of Phase II rotation, 20 m.y. B.P. See Figure 1 for the present-day position of these blocks. The rotation pivot at the northern end of the Coast Range block is shown by a triangle. The amounts of Basin and Range extension implied by the model are marked by arrows. The Mojave block (MB) and Garlock Fault (G) are shown in their present-day position.

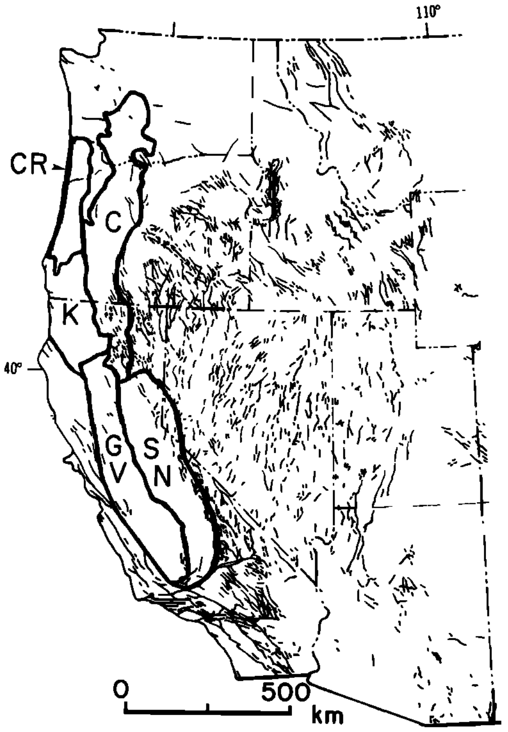

Fig. 14. Steeply dipping faults of western North America active during the past 10–15 m.y. for which some Quaternary movement is suspected. Longer faults are generally strike-slip faults and shorter ones normal faults. Our proposed tectonic blocks are outlined with heavy lines: CR, Coast Range; K, Klamaths; GV, Great Valley; SN, Sierra Nevada. Faults are from *Eaton* [1980].

Phase II: Differential Extension

Our Phase II rotation is similar to model two of *Simpson and Cox* [1977] in which rotation was produced about a northern pivot, but there are distinct differences between the two models. One such difference involves the role of the Klamaths in the rotation. Following an earlier suggestion of *Hamilton* [1969], *Simpson and Cox* [1977] proposed that the Klamaths moved westward along with the southern end of the Oregon Coast Range, rifting away from the Sierra Nevada during the early Tertiary. However, the widespread occurrence of upper Cretaceous marine sediments in the gap between the Klamaths and the Sierra Nevada is difficult to reconcile with post-Cretaceous rifting and, in fact, most geologists working in this area have concluded that the rifting, if real, occurred during the Mesozoic [*Schweikert,* 1976; *Blake and Jones,* 1977; *Irwin,* 1977]. Therefore it seems unlikely that the rifting of the Klamaths away from the Sierra is tectonically associated with the rotation of the Oregon Coast Range.

In our Phase II rotation the southern Coast Range, the Klamaths and the northern end of the Sierra Nevada all move westward together, retaining their east-west spacing relative to each other (Figure 13). In the terminology of *Heptonstall* [1977], these blocks are moved as 'linked plates' free to rotate about hypothetical hinges at their points of contact. As these dominantly coherent units rotated and drifted westward, the Klamath-Sierra Nevada junction behaved as a hinge point accommodating differential motion between the Sierra Nevada and the Klamaths-Coast Range to the north. The amount of westward translation of the Sierra Nevada-Klamath hinge point required to account for the observed angle of rotation R expressed in radians is related to the length L of the rotated block by

$$s = L \times R$$

The paleomagnetic data indicate that the rotated block extends from the Klamaths to the Columbia River, a distance $L = 670$ km. The angle R can be constrained by the paleomagnetic data. A weighted average of all the rotations observed for Cascade and Coast Range rocks less than 40 m.y. old (post Phase I) yields $R = 30° \pm 10°$ (95% confidence). The resulting westward translation of the Sierra Nevada–Klamath hinge point is $s = 340 \pm 110$ km. Although somewhat on the high side, this is within the range of values for the amount of late Cenozoic Basin and Range extension proposed by different researchers [*Hamilton and Meyers,* 1966; *Proffett,* 1971; *Thompson,* 1972; *Elston,* 1976, 1978; *Hamilton,* 1978, 1980; *Stewart,* 1978; *Zoback and Thompson,* 1978].

Concerning the question of timing of the late Tertiary rotation, the paleomagnetic data are neither abundant nor precise enough to determine whether the rotation occurred during the entire interval from 40 m.y. B.P. to the present interval or only during part of it. However regional geology provides additional constraints since the westward motion of the Coast Range, Klamaths and Sierra Nevada was undoubtedly associated with extension in regions immediately to the east. It is not until mid Miocene time that we find clear evidence for broad extension in the region reaching from Arizona to central Oregon. During this period, about 20 m.y. B.P., the Basin and Range Province began its most important phase of development with the broad occurrence of extensional faulting coupled with a pervasive shift to basaltic volcanism [*Snyder et al.,* 1976; *Stewart,* 1978]. Although late Eocene and Oligocene basins of possible extensional origin occur in areas of Washington [*Whetten,* 1976; *Davis,* 1977; *Fox et al.,* 1977], Montana, Wyoming [*Armstrong,* 1978], Nevada [*Axelrod,* 1966*b*] and Arizona, New Mexico [*Eaton,* 1979; *Livaccari,* 1979], these basins are regionally restricted (except in Arizona and New Mexico) and are not associated with widely distributed basaltic volcanism that characterizes the much greater Miocene extension. The most difficult part of the geologic record to interpret is the widespread Oligocene ignimbrites of Nevada and Utah [*Snyder et al.,* 1976], the continuity of which suggests that the Oligocene topography did not include deep extensional basins [*Burke and Mckee,* 1979]. However, *Hamilton and Meyers* [1966], *Elston* [1978] and *Hamilton* [1980] propose that the extrusive ignimbrites were associated with intrusive activity deep in the crust which resulted in significant extension. We conclude, based on the overall geologic record, that Phase II rotation likely began about 20 m.y. B.P., coinciding with mid-Miocene extension in the Basin and Range. However, the possibility of some regional extension during the Oligocene in Arizona and New Mexico and in association with the Nevada-Utah ignimbrites cannot be ruled out, so some amount of Oligocene Phase II rotation is possible.

Our model for late Cenozoic clockwise rotation of the Coast Range, Klamaths and Cascades requires that rifting was greater in southern Oregon than northern Oregon. Three observations suggest that this was the case. First, the distribution of late Cenozoic extensional faults delineating the Basin and Range province (Figure 14) suggests that extensional minima exist in northern Oregon and south of the Sierra Nevada, with a maximum at the latitude of the Oregon-Nevada border.

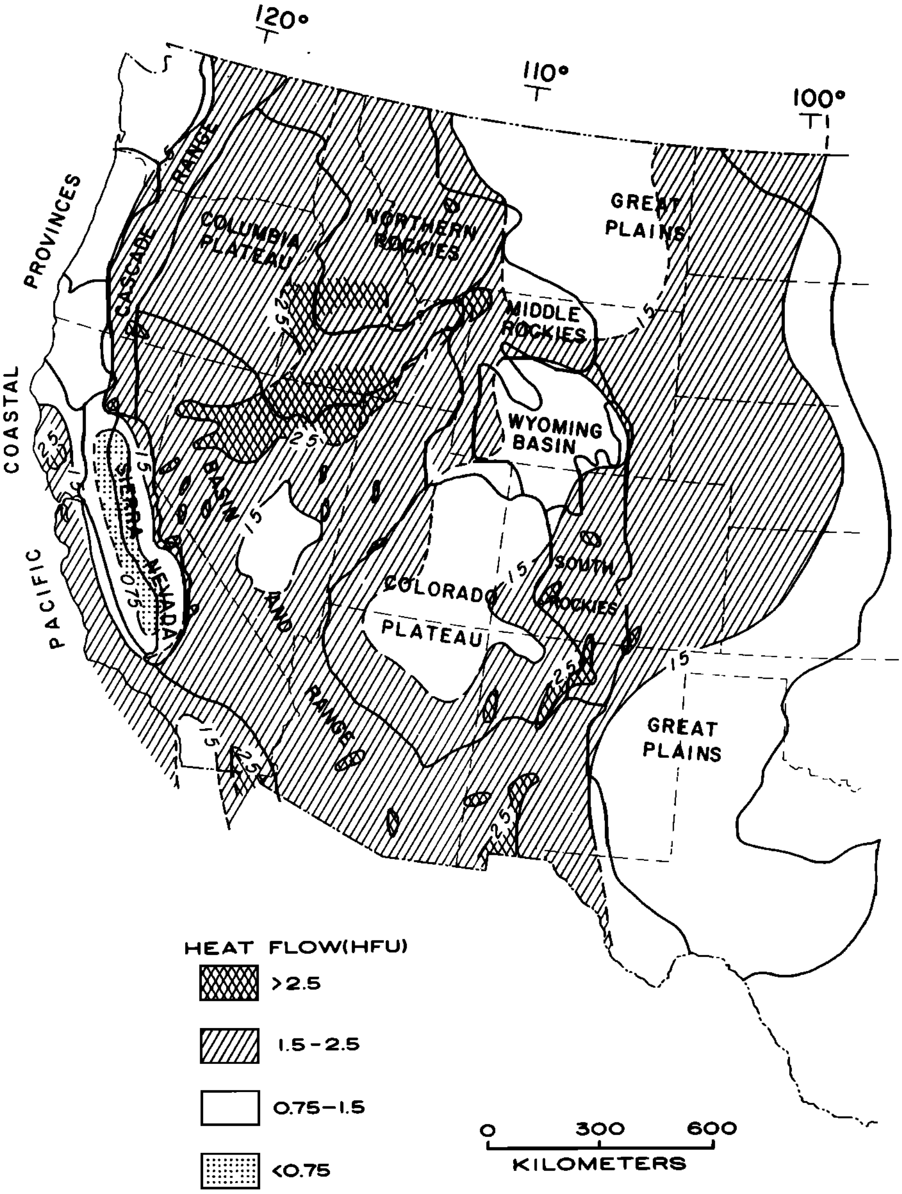

Fig. 15. Heat flow contours superimposed on major physiographic units of the western U.S. Figure from *Lachenbruch and Sass* [1978].

This distribution of extension would produce the clockwise rotation of the Coast Range and related terrane [*Heptonstall*, 1977]. Such a distribution would also produce counterclockwise rotation of the Sierra Nevada in addition to simple westward motion. Second, differential extension would require the formation of strike-slip faults separating the regions of greater and lesser extension. The northwest trending right-lateral faults in Oregon proposed by *Lawrence* [1976] appear to be such faults. Third, the Columbia River Basalts [*Watkins*, 1965; *Watkins and Baski*, 1974] show only 2° of clockwise rotation in northwestern Oregon and southeastern Washington (Figure 2, Table 3) and about 12° of clockwise rotation in south-central Oregon (Figure 2, Table 3). These results would suggest that the southern region has experienced more rotation and extension than the northern region. In fact, the northern region would appear relatively stable and may mark the northeastern limit of significant extension and related rotation. However the confidence limits of these paleomagnetic data are too large to permit this interpretation to be made with confidence.

Interestingly, paleomagnetic studies of Mesozoic rocks in the Sierra Nevada and the Great Valley are consistent with a small counterclockwise rotation of the Sierra Nevada–Great Valley. The results of these studies are summarized in Table 3. The four studies yield an algebraic mean rotation of 4.4° ± 5.7° (95% confidence limits) in a counterclockwise sense. This is our best estimate of the Sierra Nevada–Great Valley rotation. However two facts should be kept in mind regarding the accuracy of this mean result. First, two of the magnetic studies are based on rocks which underwent post-folding remagnetization events and hence have unconstrained tectonic tilt corrections. Second, all the individual rotational uncertainties are between 14° and 23° (Table 3) and hence introduce considerable uncertainty to the derived mean rotation.

The direction of motion of the Klamath–Sierra Nevada junction appears to have had both a southwesterly and a northwesterly component. The southwesterly component is due to the extension of the Basin and Range province, which appears to be a continental analogue of broadly distributed back-arc spreading. This appears to be necessary to explain the high heat flow, thin crust, anomalous upper mantle and regional uplift of the Basin and Range [*Scholz et al.,* 1971; *Thompson,* 1972]. The northwesterly component of motion is associated with broad regional right lateral shear [*Atwater,* 1970; *Christiansen and Mckee,* 1978; *Livaccari,* 1979; *Zoback and Thompson,* 1978]. The late Cenozoic right lateral motion (48 km minimum) along the Walker Lane [*Albers,* 1967; *Slemmons et al.,* 1979] requires north-northwest motion of the Sierra Nevada relative to the stable part of the North American plate. Regional shear reflected in the northwesterly motion of the Sierra Nevada and adjacent terrane to the east would appear to be the likely cause of Miocene to present north-south compression in the Columbia Plateau [see *Davis,* 1977] as the plateau is pushed from the south against a more stationary Mesozoic terrane to the north. A similar buttress effect likely constrains the Coast Range and Cascades to the north as evidenced by north-south compressional earthquakes [see *Davis,* 1977] in Washington and northern Oregon. The Phase II rotation of the Coast Range, Klamaths and Cascades would thus appear to be the result of southwesterly Basin and Range extension with superimposed northwesterly motion of the Sierra Nevada, both acting to push the Coast Range, Klamaths and Cascades in a northwesterly clockwise sense about a northern pivot.

Our Phase II rotation involves the rotation of the Coast Range, Cascades, Klamaths and Sierra Nevada as predominantly coherent units in response to Basin and Range extension. The behavior of these blocks as coherent units is suggested by the distribution of strike-slip and extensional faults in the western U.S. Figure 14 shows the Quaternary faults bounding the blocks but generally not internal to the blocks. This distribution is equally pronounced if we consider all faults without regard to age [see *Eaton,* 1980]. Regions of high heat flow are confined to the Basin and Range province and the Cascades and are not present in the main mountain belts (Figure 15). These observations suggest a significant contrast in the scales and intensity of late Cenozoic deformation between the Basin and Range and main mountain belts and provides the basis for our treating the Cascades, Coast Range, Klamaths and Sierra Nevada as coherent blocks in our reconstructions.

The existence of a tectonic boundary near the Columbia River was previously inferred from the smaller amount of rotation observed in Coastal Washington than in coastal Oregon. However, the difference may reflect only Phase I tectonics. The observed rotations of all the Oregon and Washington units are consistent with the 30° ± 10° of rotation proposed for our Phase II rotation, suggesting that the entire coastal margin of the western U.S. may have participated in Phase II. In support of this, *Bentley* [1979, 1980] has recently recognized NW trending strike-slip faults in the Washington Columbia Plateau similar to those of *Lawrence* [1976] in Oregon. These faults suggest some differential extension in the plateau and rotation of the Washington Coast Range and Cascades to the west. The proposed tectonic boundary at the Columbia River would then appear to be an Eocene and/or Oligocene tectonic boundary probably related to the complexities of accreting the seamount province to North America. Eocene-Oligocene tectonic activity north of the Columbia River related to such complexities is evident by faulting [*Stacey and Steele,* 1970; *Rau,* 1973; *Cady,* 1975; *MacLeod et al.,* 1977; *Muller,* 1977; *Fairchild,* 1979] and metamorphism [*Tabor,* 1972] in the Olympic Peninsula–Vancouver Island region.

Palinspastic Maps

In order to test whether the above two phase rotation is consistent with regional geologic information, the palinspastic maps shown in Figures 11, 12, and 13 were generated by the following procedure, working back in time.

1. The outlines of the Coast Range, Klamath Mountains, and Sierra Nevada were digitized along the boundaries between early Tertiary and younger rocks.
2. The Klamath Mountains and the Coast Range of Oregon were rotated counterclockwise about a finite rotation pole at 46.0°N, 237.5°E at a constant rate of 1.5°/m.y. from the present back to 20 m.y., the total rotation angle being 30.4°, in accord with the paleomagnetic data. (The actual rate of rotation was likely spasmodic, associated with periods of pronounced extension and alternate periods of relative stability.)
3. The Sierra Nevada and Great Valley were rotated 13.0° clockwise about a finite rotation pole at 26.9°N, 242.7°E. This preserved the relative position of the northern Sierra Nevada relative to the Klamaths and produces counterclockwise rotation of the Sierra Nevada. The resultant extension in the southern Basin and Range is 210 km compared to 340 to the north (Figure 13).
4. All blocks were retained in this position from 20 back to 42 m.y.
5. From 42 back to 50 m.y. the Oregon Coast Range was rotated counterclockwise at a rate of 6°/m.y. about a pole to the south located at 43.0°N, 238.7°E, the total rotation angle being 46.0° in accord with the paleomagnetic data (Figure 11).

Our 20 m.y. B.P. reconstruction agrees well with accepted geodynamic constraints for the western U.S. The rotation pole to the north (Figure 13) preserves general continuity of the Cascade volcanic arc and implies mild compression in the Cascades of southern Washington, likely producing the Miocene uplift of this region [*Hammond,* 1979]. The position of this pole also implies a southwest-northeast opening of the Basin and Range in good agreement with the trend of the Nevada rift (Figure 1) and the orientation of early extensional basins [*Eaton,* 1979; *Zoback and Thompson,* 1978]. Moreover, the suggested reconstruction of the Sierra Nevada–Great Valley is consistent with accepted geologic constraints. The finite rotation used to determine the early Tertiary position of the Sierra Nevada may, in fact, be decomposed into the three following rotations, each corresponding to a different geologic constraint or observation. The rotations are listed in the sequence in which they were made in order to produce the palinspastic restoration shown in Figure 13.

1. Counterclockwise rotation of 4.0° about a pole at 46.0°N, 237.5°E partially closing the Basin and Range province in partial compensation for Miocene extension. Blocks west of the Basin and Range province, including the Sierra Nevada and Mojave blocks are moved eastward in this restoration. This same pole position with a larger rotation was used to produce the 20 m.y. B.P. restoration of the Oregon Coast Range.
2. Assuming that motion along the Walker Lane reflects strike-slip motion between the North American (NA) and Pacific (PAC) plates, this motion can be described by the PAC-

NA pole at 51.0°N, 294.0°E of *Minster et al.* [1974]. Clockwise rotation of 1.2° about this pole produces right lateral motion of 90 km along the Walker Lane, in broad agreement with geologic observations [*Albers*, 1967; *Slemmons et al.*, 1979]. A counterclockwise rotation of 1.2° was therefore used in the reconstruction.

3. Left lateral motion along the Garlock Fault can be described by a pole at 33.0°N, 243.0°E. Counterclockwise rotation of 17.0° about this pole produces 85 km of left lateral motion on the Garlock, which is consistent with geologic observations [*Davis and Burchfiel*, 1973]. A clockwise rotation of 17.0° about this pole was used to move the Sierra Nevada east relative to the Mojave block to its position prior to differential Basin and Range extension. These three rotations carried out in the sequence listed above are exactly equivalent to the rotation about the single pole used to produce the reconstruction of the Sierra Nevada block (Figure 13). Because the rotation in step 2 is small, the sequence in which steps 1 and 2 are made is not important. These two combined rotations were used to rotate the Sierra Nevada block, the Mojave block and the pole for the intervening Garlock Fault. Holding the Mojave block fixed, the Sierra Nevada block was then rotated relative to the Mojave block about the rotated Garlock Fault pole. A remarkably similar three pole system was derived independently by *Eaton* [1979] on the basis of the distribution and direction of extension in the Basin and Range. The fact that several primary geotectonic features of the Basin and Range and western U.S. can be explained by a reconstruction based mainly on paleomagnetic constraints lends considerable credibility to the reconstruction.

Our 20 m.y. B.P. reconstruction proposes a 13° rotation of the Sierra Nevada about a pole at 26.9°N, 242.7°E which should be observable as a 15° counterclockwise rotation of pre-late Tertiary magnetic field directions. As noted above, the paleomagnetic data from the Sierra Nevada–Great Valley would support a smaller 4.4° rotation but the error limits are large and do not rule out a larger 15° rotation. *Magill and Cox* [1980] present alternative Phase II models and conclude that a 15° rotation of the Sierra Nevada yields a reconstruction which is most consistent with the paleomagnetic data from the Sierra Nevada and Coast Range and the regional geology of the Cascades and Basin and Range province.

Tectonic Significance of the Clarno Formation

The proposed two phase rotation may help explain the small clockwise rotation (20° ± 19°, Table 3) of the middle Eocene Clarno Formation of central Oregon. The small rotation indicates that the Clarno likely did not participate in the Phase I rotation but was probably part of stable North America at that time. However the paleomagnetic data are consistent with the Clarno having participated in the Phase II rotation, in which case the rotation of the Clarno would be of post mid-Miocene age.

Comparison With Other Models

In *Hammond*'s [1979] elaboration of model 2 of *Simpson and Cox* [1977] all of the observed Coast Range rotation was around a northern pivot near the Olympic Peninsula of Washington, swinging the Oregon and Washington coast ranges and Klamaths out seaward from an Eocene position near the Olympic-Wallowa lineament. This model appears unrealistic for three reasons. First, as noted earlier, there is no evidence for large scale Eocene extension in eastern Washington and Montana as required by the model. Second, the rotations of the Willipa Hills and Black Hills of the Washington Coast Range appear to be more complex and of significantly smaller magnitude than the rotations of contemporaneous rocks of the Oregon Coast Range, indicating the presence of a tectonic boundary near the Columbia River where none exists in Hammond's model. Third, the model is difficult to reconcile with the presence of the middle Eocene Clarno Formation within the zone which, according to Hammond's model, was traversed by the rotating coastal block. The difficulty is compounded by the small rotation of the Clarno which suggests that the Clarno was not attached to the trailing edge of the coastal block.

Heptonstall [1977] proposed a model to explain the Oregon Coast Range rotation based on a plate linkage mechanism in which Basin and Range extension was directly associated with rotation of the Oregon Coast Range. While our model incorporates these two parts of his model, ours differs from his in the following ways: (1) all of his rotation took place during the period 32 and 4 m.y. B.P.; (2) his model places a major boundary with large post-Eocene deformation and strike-slip displacement between the Klamaths and the Sierra Nevada, which we regard as incompatible with the geology of this region; (3) in his model, Washington undergoes a counterclockwise rotation which is inconsistent with the paleomagnetic results from Washington; (4) Heptonstall's model requires hundreds of kilometers of compression along the Oregon-Washington border, which is incompatible with the geology.

CONCLUSIONS

The paleomagnetic results from lower to upper Eocene rocks from the Oregon Coast Range and from the Goble volcanics of southern Washington, including the 46° of clockwise rotation of the Tillamook Volcanic Series reported here, establish that approximately 46° of rotation took place during the Eocene. This rotation appears to have been the result of trapping of a wedge of oceanic plate between two active Eocene trenches. Considered in the context of the regional geology and geophysics, these paleomagnetic results establish that the extent of the tectonic block which experienced this Eocene rotation was from the Klamath Mountains on the south to the Columbia River in the north, where it probably terminated. The existence of rotated Coast Range rocks of Oligocene and early Miocene age indicates that a second phase of rotation occurred. This second phase, approximately 30° in magnitude, was likely associated with the opening of the Basin and Range province which began in mid-Miocene time. Miocene rotation of the Coast Range was accompanied by a similar rotation of the Cascades and Klamaths and possibly by a small counterclockwise rotation of the Sierra Nevada.

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