Geophys. J. Int. (2001) **145**, 223–232

Magnetic stratigraphy and tectonic rotation of the middle Eocene Coaledo Formation, southwestern Oregon

D. R. Prothero[1] and L. L. Donohoo[2]

[1] *Department of Geology, Occidental College, Los Angeles,* CA 90041, *USA. E-mail: prothero@oxy.edu*
[2] *Department of Geological Sciences, Western Washington University, Bellingham,* WA 98225, *USA. E-mail: donohoo@cc.wwu.edu*

Accepted 2000 October 30. Received 2000 October 17; in original form 1999 September 23

SUMMARY

The Coaledo Formation in Coos Bay on the southern coast of Oregon consists of over 2000 m of deltaic sediments that filled a forearc basin during the middle Eocene. This unit yields molluscs of the 'Cowlitz–Coaledo fauna', one of the oldest and best-studied faunas in the Pacific Northwest, but its precise age has been controversial. Over 100 magnetic samples spanning the formation were analysed using both thermal and alternating-field demagnetization. They yielded a stable remanence held mainly in magnetite, which passed a reversal test and showed a tectonic rotation of 105° ± 5°. This is greater than any other tectonic rotation so far reported from the region. It is consistent with the previously observed trends that the tectonic rotations in the Coast Ranges of Oregon and Washington increase with increasing age of the rock unit, and increase towards the southwest. The magnetic polarity pattern in the Coaledo Formation best correlates with Chrons C18r–C20r (40.0–44.0 Ma), which is significantly older than the magnetic pattern in the Cowlitz Formation (36.5–38.3 Ma). This suggests that the 'Cowlitz–Coaledo fauna' is very long-lived (at least 36.5–44.0 Ma), spanning most of the middle Eocene.

Key words: Eocene, mollusc, Oregon, palaeomagnetism, tectonic rotations.

INTRODUCTION

The Eocene forearc basins of the Pacific Northwest yield an abundant record of fossils and sediments that has been studied for over a century. Most of the sediments that fill these Eocene basins have only been roughly dated by molluscs or benthic foraminifera, taxa that are notorious for being facies-controlled and time-transgressive. Planktonic microfossils are rare (McKeel & Lipps 1975; Tipton 1975; Warren & Newell 1980), so in most cases they are unavailable to correlate specific rock units to the global timescale. Datable volcanics are even scarcer, yet the precise ages of these formations and their faunas is important for several reasons. Not only does it help date the tectonic events that formed the basins and contributed their sediments (Heller & Ryberg 1983), but the Eocene–Oligocene formations of Oregon and Washington preserve an excellent record of the faunal and floral changes associated with the end of the Eocene 'greenhouse' climates and the beginning of the Oligocene 'icehouse' climates (Prothero 1994). Combined with the planktonic microfossils and radioisotopic dates that are available, magnetic stratigraphy offers the greatest potential for obtaining precise dates on these units.

Palaeomagnetic data from these units are important for another reason. Since 1957, numerous studies have demonstrated that much of coastal Oregon and Washington has undergone significant clockwise tectonic rotation since the early Eocene, when the exotic volcanic basement terranes docked (Cox 1957; Simpson & Cox 1977; Beck 1980; Magill & Cox 1980, 1981; Magill *et al.* 1981, 1982; Bates *et al.* 1981; Wells *et al.* 1984, 1989; Grommé *et al.* 1986; Wells & Coe 1985; Engebretson *et al.* 1985; Wells & Heller 1988; Wells 1990; Hagstrum *et al.* 1999). The rotation tends to increase with the increasing age of the rocks, with proximity to the coast, and from north to south, so the oldest and southwesternmost units tend to be the most rotated (Beck *et al.* 1986; Wells & Heller 1988; Wells *et al.* 1989). This has been explained as a consequence of oblique subduction of the Juan de Fuca Plate (Beck 1980; England & Wells 1991). Several models for this rotation have been proposed, but the likely cause is a combination of localized block rotations caused by north-oblique shear on the bottom of the brittle upper crustal layer (Wells & Coe 1985; England & Wells 1991) and the extensional deformation of regions west of the Basin and Range province (Magill & Cox 1981; Grommé *et al.* 1986; Wells 1990).

Most of the rotational data came from volcanic rocks, but the extensive sedimentary record of the region offers the potential for additional palaeomagnetic poles that could refine the story derived from the volcanic rocks. A few units, such as the lower Eocene Tyee–Flournoy formations of southwest Oregon (Simpson & Cox 1977) and the upper Eocene–Oligocene Keasey Formation of northwest Oregon (Prothero & Hankins 2000) have been sampled and have demonstrated that sedimentary rocks can yield reliable magnetic directions. However, the data are currently very sparse for southwestern Oregon, a region that might be expected to show the greatest rotation, and might potentially yield data critical to testing various tectonic models used to explain the rotation. The middle Eocene Coaledo Formation of southwestern Oregon is a critical unit for palaeomagnetic analysis because it is further southwest than any other unit on the Oregon coast analysed so far, and is one of the oldest Cenozoic rock units in the region as well.

GEOLOGICAL BACKGROUND

The Coaledo Formation consists of about 2000 m of deltaic sediments that filled an Eocene forearc basin of western Oregon. It prograded outwards from sources in the nearby Ancestral Cascades volcanic arc (Dott 1966; Heller & Ryberg 1983). As its name suggests, the Coaledo Formation was once one of the major sources of coal in the Pacific Northwest, which was mined until about 1923. First named and described over a century ago by Diller (1899, 1901) as a division of the now obsolete 'Arago formation', the Coaledo Formation was extensively discussed by Schenck (1928), Turner (1938), Weaver (1945), Allen & Baldwin (1944), Baldwin (1974, 1975), Baldwin & Beaulieu (1973), Dott (1966), Dott & Bird (1979), Chan & Dott (1983, 1986), Rooth (1974) and Ryberg (1978). The formation is exposed mainly along the shoreline of Coos Bay and Cape Arago (Fig. 1), and along a few rivers in Coos County. It now occupies a north-plunging synclinal basin that surrounds Coos Bay, and extends for about 50 km to the north (Allen & Baldwin 1944; Baldwin 1974; Dott 1966).

Allen & Baldwin (1944) and Baldwin 1974) divided the Coaledo Formation into three informal members. The lower member averages about 600 m in thickness and is made up of tuffaceous, carbonaceous and micaceous sandstone and minor conglomerate and coal. It exhibits a wide variety of sedimentary structures (Dott 1966), including both hummocky and trough cross-stratification, channelling and graded bedding, as well as load casts, contorted strata, slump folds, clastic dykes up to 3 m long, convolute lamination and other soft-sediment deformation features. The lower member has been interpreted as a product of the shoreline to the front of a prograding delta, especially as gravity deformation features are so common. The middle member is about 1000 m in thickness and consists of thin-bedded siltstone with minor thin sandstone beds and rare conglomerate, with fine-scale cross-lamination and ripple bedding as the dominant sedimentary structures. The benthic foraminifera, finer grain size and sedimentary structures suggest that the middle member was laid down in deeper, quieter, more offshore conditions, probably on the pro-delta slope. The

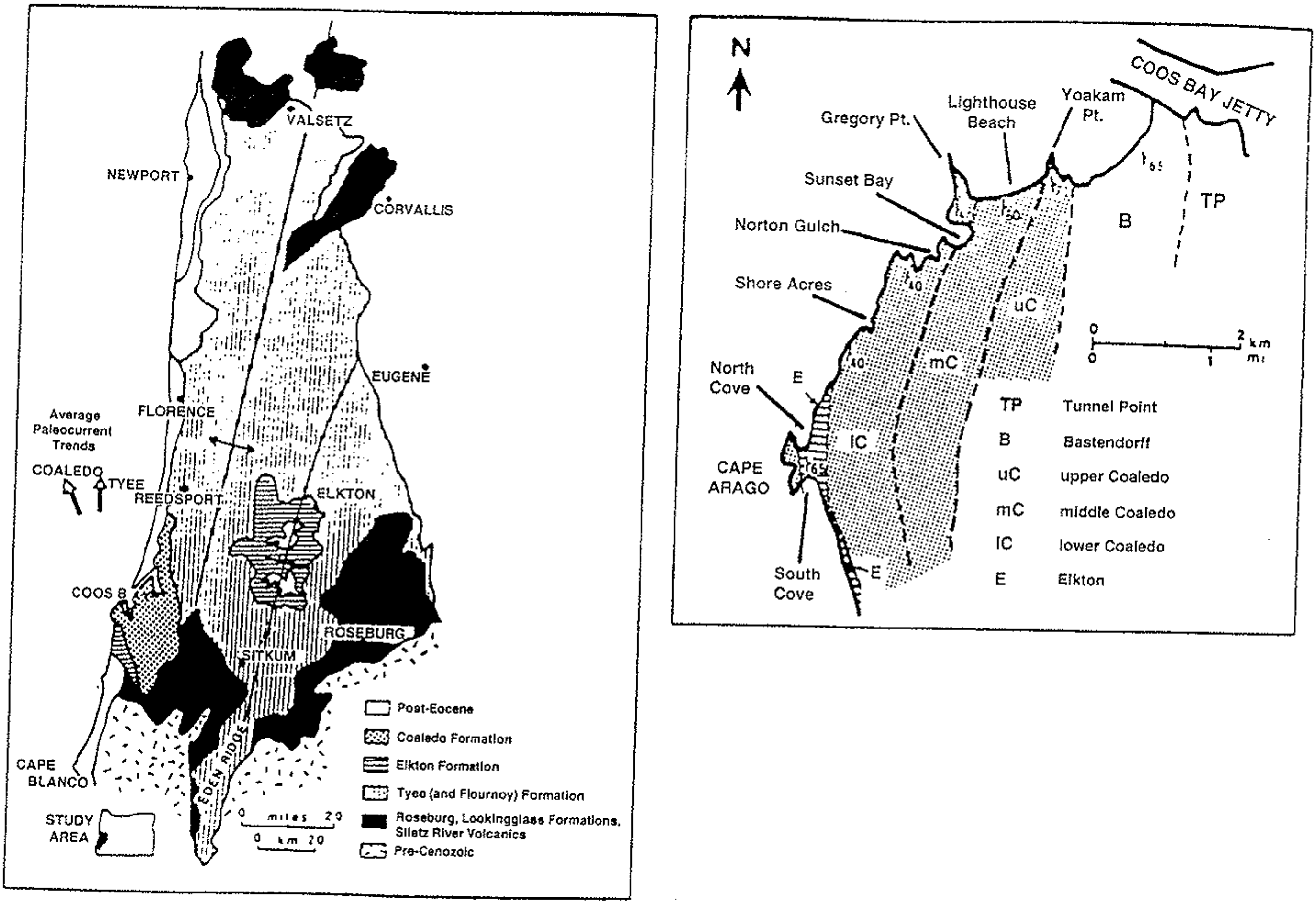

Figure 1. Index map showing general geology of the Eocene strata in the southern Oregon Coast Range (left), and the outcrop of Coaledo Formation in Coos Bay (right). (Modified from Chan & Dott 1986.)

upper member is about 400 m thick at Coos Bay, but about 3 km to the south it thickens to over 900 m. Like the lower member, it is dominated by medium- to coarse-grained micaceous and carbonaceous sandstone, with minor conglomerate and carbonaceous shale. As many as 6 or 7 coal seams are known from the upper member, some up to 3 m in thickness. Sedimentary structures include abundant medium- and large-scale cross-stratification, including festoon and trough cross-stratification. There are far fewer soft-sediment deformation features and gravity flow deposits than in the lower member, but sandstone dykes do occur. Molluscan coquinas and hummocky cross-stratification suggestive of storm deposition are particularly common, suggesting that the upper member was deposited in a shallower, wave- and storm-dominated deltaic topset or upper delta slope setting (Dott 1966).

In its total outcrop area, the Coaledo Formation lies unconformably above the lower to middle Eocene Roseburg, Lookingglass and Flournoy formations, but it is not known to overlie the Tyee Formation. In the Coos Bay area, the Coaledo Formation conformably overlies the middle Eocene Elkton Siltstone. The Coaledo is overlain by the deep-water shale of the upper Eocene Bastendorff Formation, which is in turn overlain by the lower Oligocene shallow-marine Tunnel Point Sandstone.

Biostratigraphic control on the Coaledo Formation is poor. In most places, it is too coarse-grained for planktonic microfossils. One sample yielded assemblages that were thought to be middle–upper Eocene in affinity (McKeel & Lipps 1975), but this assemblage needs to be re-examined in the light of modern foraminiferal taxonomy (W. A. Berggren, personal communication, 1999). Throughout the formation, benthic foraminifera of the upper Ulatisian to middle Narizian Stages are found (Detling 1946; Cushman *et al.* 1947; Stewart 1956; McKeel & Lipps 1975; Rooth 1974). However, the age resolution of Ulatisian and Narizian benthic foraminiferal faunas is coarse (they span nearly the entire middle Eocene), and in some places the zones are time-transgressive (McDougall 1980; Poore 1980; Almgren *et al.* 1988), so this offers little help in correlation to the global timescale. Molluscan faunas were described by Diller (1899, 1901), Turner (1938), and Weaver (1942), who originally thought that the 'Cowlitz–Coaledo fauna' was late Eocene in age (Weaver *et al.* 1944). Subsequent opinion has placed this fauna in the middle Eocene but does not resolve the question of what part of the 12 Myr duration of the middle Eocene they span (Nesbitt 1995). Fossil plants are also known (Diller 1899), especially in the coal seams, but they are not age-diagnostic.

METHODS

Sampling was conducted in August 1998 and 1999, following the maps and stratigraphic sections of Allen & Baldwin (1944) and Weaver (1945) along the coastal exposures around Cape Arago and Coos Bay (Fig. 1). The section ran from Strawberry Point and Sunset Bay (lower member) to Gregory Point and Lighthouse Beach (middle member), and concluded at Yokum Point (upper member). Three oriented block samples were collected at every site (to permit the calculation of site statistics). These were cored using an air-cooled drill press in the laboratory. Samples that could not be cored were ground into cylinders using a disk sander, and small samples were cast into cylinders using Zircar aluminium ceramic. All samples were analysed on a 2G cryogenic magnetometer with an automatic sample changer at the palaeomagnetics laboratory of the California Institute of Technology. After measurement of NRM (natural remanent magnetization), each sample was demagnetized in alternating fields (AF) of 25, 50 and 100 Gauss to determine coercivity behaviour and to prevent baking in of multidomain remanence. All samples were then thermally demagnetized in multiple steps from 300 to 600 °C to remove chemical overprinting from iron oxides such as goethite, and determine how much remanence is left above the Curie temperature of magnetite. The resultant vectors were plotted on orthogonal demagnetization ('Zijderveld') plots, and a characteristic remanence direction was obtained using the least-squares method of Kirschvink (1980).

About 0.1 g of several representative samples was powdered, placed in epindorph tubes, and subjected to increasing IRM (isothermal remanent magnetization). The same samples were AF demagnetized twice, once after having acquired an IRM produced in a 100 mT peak field, and once after having acquired an ARM (anhysteretic remanent magnetization) in a 100 mT oscillating field. Such an analysis allows the determination of IRM acquisition behaviour, and the modified Lowrie–Fuller test indicates whether the remanence is held in single-domain or multidomain grains (Johnson *et al.* 1975; Pluhar *et al.* 1991).

Polished thin sections of representative samples were also examined under reflected light to determine their opaque mineralogy.

RESULTS

Magnetic analysis

Orthogonal demagnetization plots (Fig. 2) showed a consistent pattern of magnetic behaviour for the majority of samples. The dips in this section are very steep (40° – 75°), so it was very easy to recognize modern normal overprints in the uncorrected directions and exclude them from the analysis. After correction for dip, some samples (Figs 2a and b) pointed east-southeast and down at NRM, and maintained that orientation through both AF and thermal demagnetization. Other samples (Fig. 2c) pointed west-northwest and up at NRM (after dip correction), and declined steadily to the origin through AF and thermal demagnetization. A few samples (Fig. 2d) had a small overprint, but this was removed by the 300 °C heating step. In nearly all cases (Fig. 2), there was a large decrease in intensity during AF demagnetization, suggesting that a low-coercivity mineral such as magnetite or titanomagnetite is the primary carrier of the remanence. This is corroborated by the fact that almost no samples showed much remanence at temperatures approaching the Curie point of magnetite.

IRM acquisition of representative samples (Fig. 3) showed saturation around 300 mT, consistent with the premise that magnetite or titanomagnetite is the primary carrier of the remanence. Dott (1966) reported abundant ilmenite and magnetite grains in his separations of heavy minerals from the Coaledo sandstones, and we were able to confirm this in our examination of polished thin sections.

In the modified Lowrie–Fuller test (Fig. 3), the ARM was typically more resistant to AF demagnetization than the IRM, suggesting that single-domain or pseudo-single-domain grains are carriers of the remanence. However, the Lowrie–Fuller test was ambiguous in some cases.

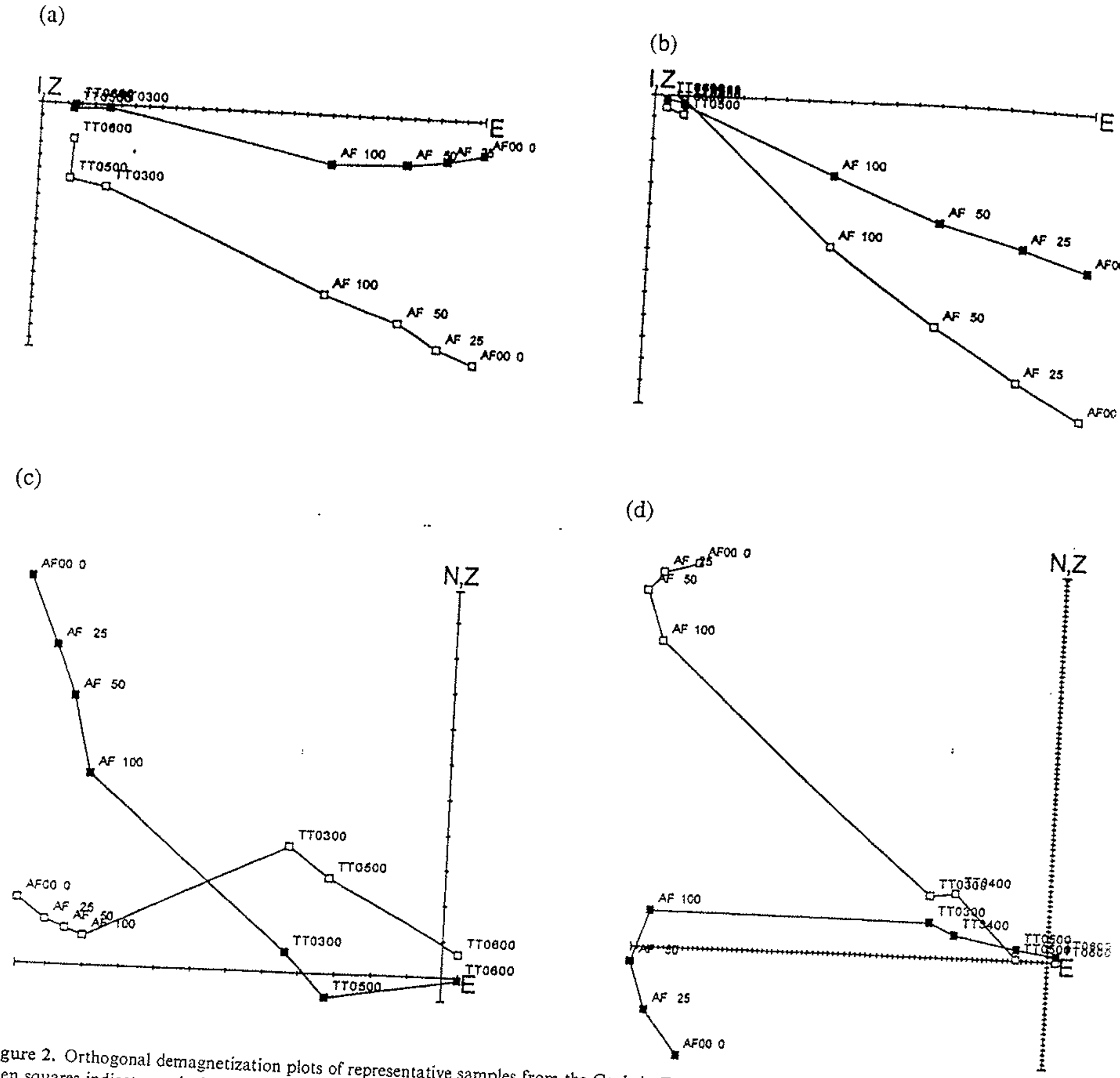

Figure 2. Orthogonal demagnetization plots of representative samples from the Coaledo Formation. Solid squares indicate horizontal component; open squares indicate vertical component. AF: alternating field step (in Gauss); TT: thermal step (°C). Each division is 10^{-6} emu.

After the characteristic remanence directions were determined using the least-squares method of Kirschvink (1980), site statistics were calculated (Fisher 1953), and sites were classified according to the system of Opdyke *et al.* (1977). 30 sites were considered Class I, in that they were statistically distinct from a random distribution at the 95 per cent confidence level (Table 1). Class II sites ($n=3$) had only two samples because one sample crumbled or was lost, so site significance could not be calculated. Class III sites ($n=8$) had one vector that was divergent, but the other two clearly indicated the polarity of the sample.

The dips were not variable enough to conduct a fold test for stability. However, the mean for all normal sites was $D=104.9$, $I=46.6$, $k=24.5$, $\alpha_{95}=7.6$, $n=16$; for the reversed sites it was $D=265.8$, $I=-48.3$, $k=15.6$, $\alpha_{95}=8.8$, $n=19$. On a stereonet, these directions are clearly antipodal (Fig. 4), and they pass a 'Class A' reversal test ($\gamma_c=4.5°$) (McFadden & McElhinny 1990). Thus, the directions are most likely to be due to the primary or characteristic remanence of the sample, and most overprinting has apparently been removed.

DISCUSSION

Magnetic stratigraphy

The magnetic polarity pattern of the Coaledo Formation is shown in Fig. 5. Almost the entire lower member, and the lower third of the middle member, was normal in polarity,

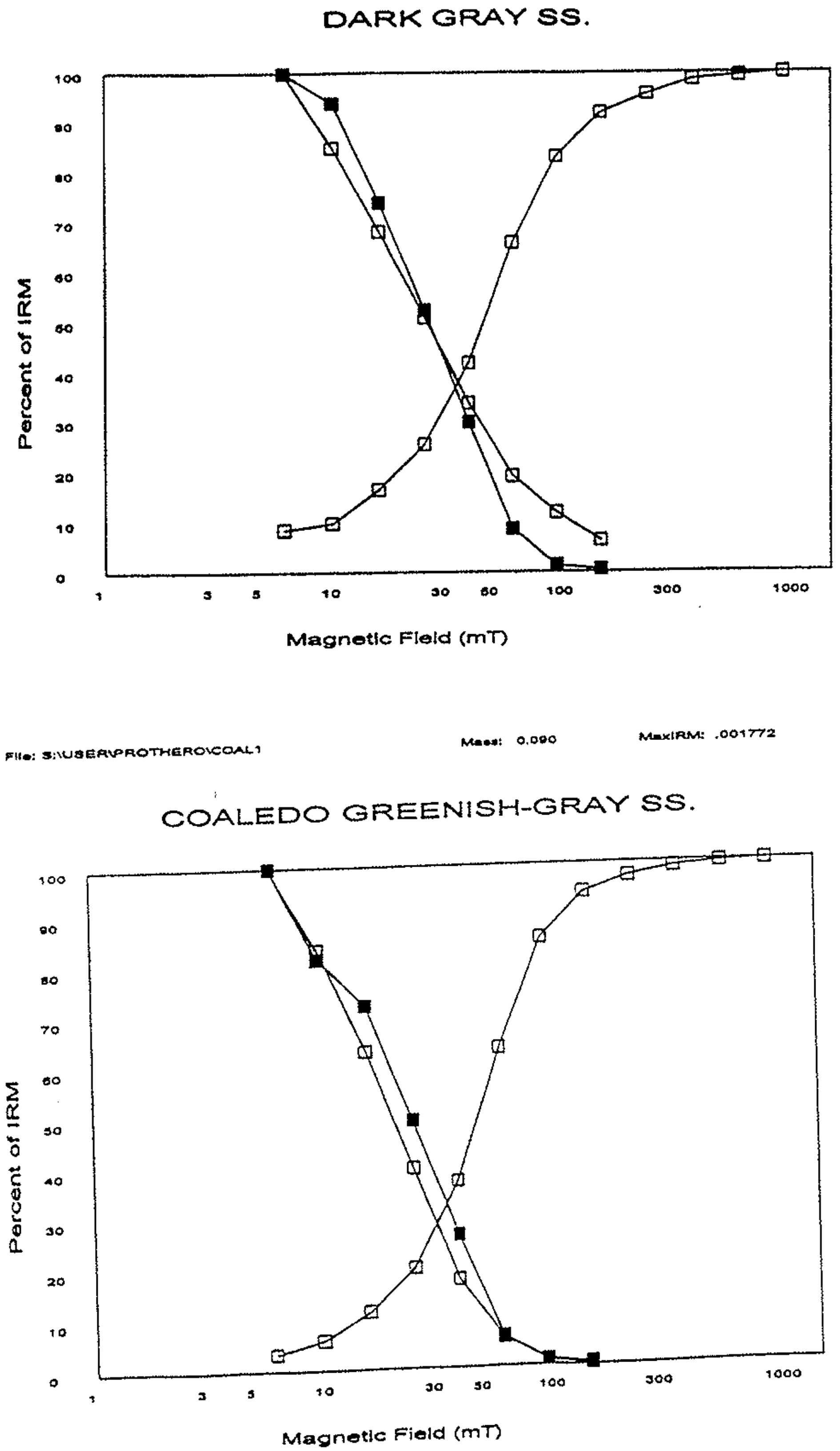

Figure 3. IRM acquisition (ascending curve on right) and Lowrie–Fuller test (two descending curves on left) of representative powdered samples from the Keasey Formation. Open squares: IRM: solid squares: ARM.

except for a short reversed magnetozone in the upper part of the lower member. The remaining part of the middle member was reversed in polarity. The lower part of the upper member was normal, but the rest of the upper member was reversed.

Our interpretation of the correlation of the formation is shown in Fig. 6. The presence of NP18 and CP15a nannofossils (Warren & Newell 1980) in the base of the overlying Bastendorff Shale shows that the Coaledo Formation can be no

Table 1. Palaeomagnetic data from the Coaledo Formation, Coos Bay, Oregon. Site numbers as in Fig. 5. *N*: number of samples per site; *D*, *I*: declination, inclination; *k*, α_{95}, precision parameters.

Site	*N*	*D*	*I*	*k*	α_{95}
1	3	209.9	−59.3	4.1	71.2
2	3	251.6	−35.9	4.1	70.9
3	3	235.8	−56.2	7.7	48.0
4	2	85.6	71.9	52.3	35.3
5	3	105.9	69.9	32.2	22.1
6	3	93.9	30.8	4.1	71.2
7	3	99.4	39.9	12.4	36.6
8	3	121.4	35.2	5.3	60.0
9	3	97.7	57.0	23.1	26.2
10	3	78.7	54.0	9.8	41.8
11	3	106.2	56.4	10.0	41.2
12	3	241.3	−26.2	4.8	63.8
13	3	119.3	48.1	13.8	34.5
14	3	103.2	43.6	13.1	35.6
15	3	122.6	36.7	5.1	61.5
16	3	111.6	45.6	14.5	33.6
17	3	97.3	39.5	16.9	31.0
19	3	242.8	−49.6	130.5	10.8
20	3	241.4	−38.5	12.0	37.3
21	2	258.1	−56.2	7.2	115.2
22	3	265.6	−61.1	7.7	47.7
23	3	257.0	−64.2	2.5	106.1
24	3	88.2	25.6	13.8	34.5
25	3	274.4	−42.6	6.5	52.8
26	3	104.2	47.1	12.4	36.6
27	3	297.3	−56.3	13.6	34.8
28	3	262.6	−30.5	12.0	37.4
29	3	286.6	−35.1	19.1	29.0
30	3	271.6	−59.5	15.8	32.1
31	3	273.7	−19.9	4.9	62.9
32	3	283.6	−28.3	15.6	32.3
33	3	290.9	−55.0	17.5	30.4
35	2	294.6	49.8	2.4	180.0
36	3	119.3	50.1	2.1	130.1
Y1	3	95.9	55.6	75.9	14.3
Y2	3	105.5	44.3	4.8	64.1
Y3	3	69.2	34.0	10.4	40.4
Y4	3	61.7	27.6	4.9	63.1
Y5	3	62.0	41.7	9.9	41.5

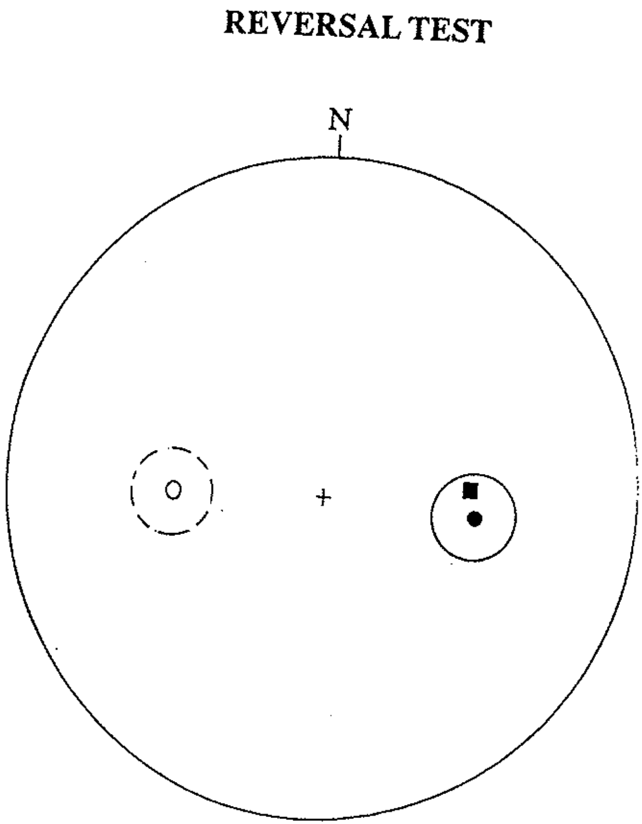

Figure 4. Stereoplots of mean poles and circles of confidence for the data discussed in this study. Solid circles indicate lower-hemisphere projections; dashed lines and open circles indicate upper-hemisphere projections. Solid square indicates mean of reversed samples projected through the origin to the lower hemisphere.

younger than 37 Ma (Chron C17n). Nearly the entire upper half of the Coaledo Formation is reversed in polarity, yet the Chron C17n–C18n interval between 37 and 40 Ma is overwhelmingly of normal polarity. Thus, the likeliest interpretation is that the upper reversed magnetozone in the upper member correlates with Chron C18r (40–41 Ma). The normal magnetozone in the base of the upper member would then be Chron C19n. The middle member correlates with Chron C19r and later Chron C20n, and the lower member probably correlates with early Chron C20n. The lowest part of the formation was inaccessible and not sampled, so conceivably it could range into slightly older chrons.

This correlation implies two major surprising conclusions. The first is that there appears to be a previously unsuspected unconformity between the Coaledo and Bastendorff formations. Our data suggest that this unconformity spans the interval between 36 and 40 Ma. Second, the entire Coaledo Formation appears to be older than the palaeomagnetically sampled portion of the Cowlitz Formation in Washington (Prothero *et al.* 2000), which overlies an $^{40}Ar/^{39}Ar$ date of 38.9 ± 0.01 Ma (Irving *et al.* 1996), making it at least a million years younger than even the oldest Coaledo beds dated so far. If this is so, then the supposedly correlative 'Cowlitz–Coaledo' molluscan fauna (Weaver *et al.* 1944) appears to be very long-ranging, spanning the interval from 44 to 36.5 Ma without any changes that have been documented. Studies of the magnetic stratigraphy of the Cowlitz Formation and its correlatives are now in preparation (Prothero *et al.* 2000), but the preliminary results (Fig. 7) are consistent with this interpretation.

Rotations and translations

After inverting the reversed directions by 180° and combining them with the normal sites, the mean for the entire formation is $D=95.1$, $I=48.0$, $k=17.1$, $\alpha_{95}=6.0$, $n=35$. Comparison with the middle Eocene North American cratonic pole (Diehl *et al.* 1983) and correcting the error estimates for inclination (Demarest 1983) gives a clockwise rotation of the formation of 105° ± 5°. This rotation is greater than any other so far reported for the region (Table 2). Rotations as great as 79° ± 12° were reported from late Palaeocene (approximately 58 Ma) Roseburg pillow basalts (Wells 1990), which lie to the east of the Coaledo Formation, but are amongst the oldest Cenozoic rocks in the area for which we have palaeomagnetic data

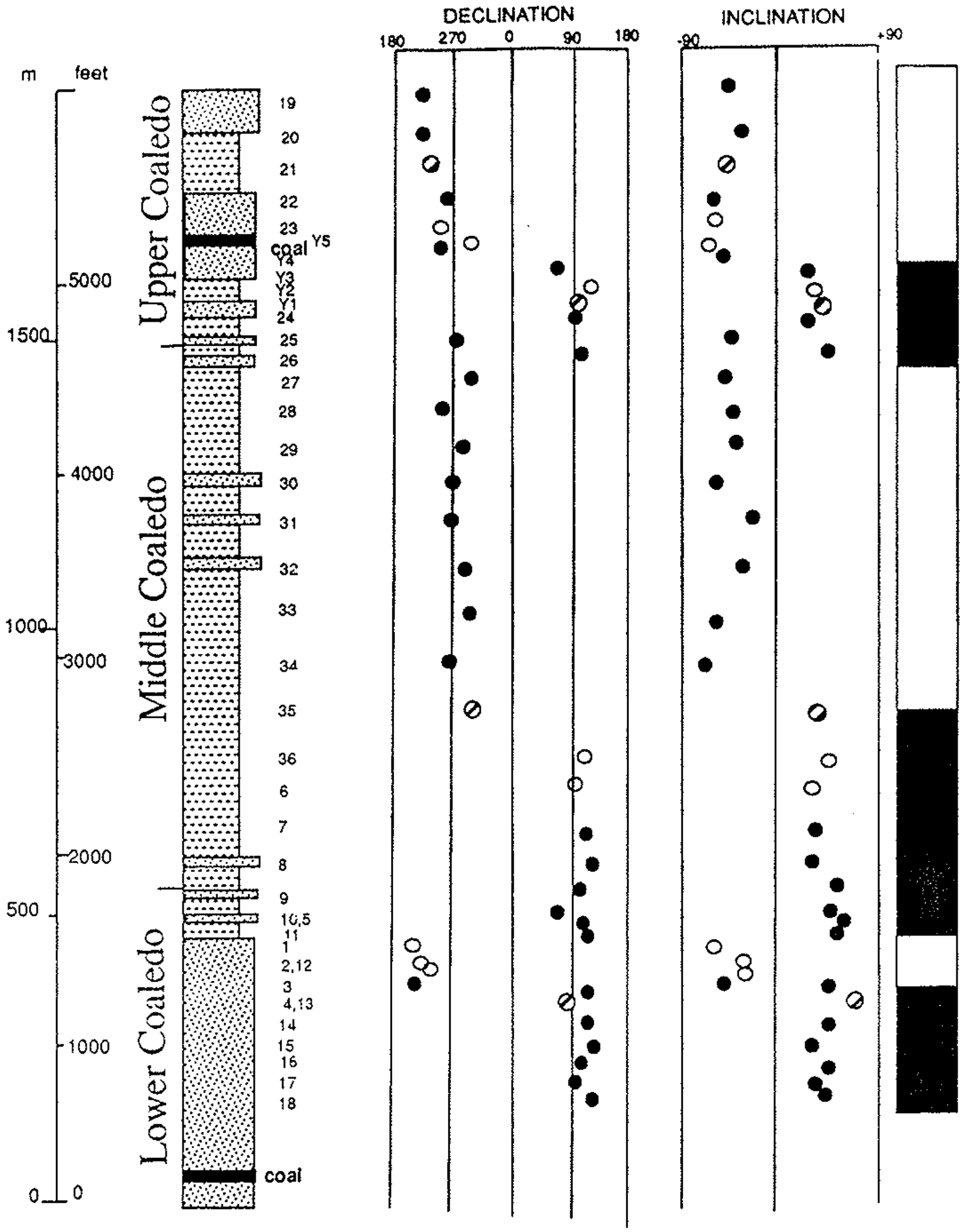

Figure 5. Magnetic stratigraphy of Coaledo Formation on Coos Bay (stratigraphy after Allen & Baldwin 1944). Solid circles indicate Class I sites (Opdyke *et al.* 1977), which are statistically distinct from a random distribution at the 95 per cent confidence level; dashed circles are Class II sites, in which one sample was missing or rejected, so statistics could not be calculated; open circles are Class III sites, where one site was divergent, but the other two gave a clear indication of polarity.

(Fig. 7). The nearest rocks to the Coaledo Formation are the lower Eocene Tyee–Flournoy formations, which directly underlie the Coaledo in the same region, but yield a rotation of 64° ± 16° (Simpson & Cox 1977). Our data suggest that the Coos Bay region lies on a separate tectonic block from the Roseburg basalts and the Tyee–Flournoy samples of Simpson & Cox (1977), and the Coos Bay block has undergone considerably more rotation than the adjacent blocks. The differences in rotations reported for various regions of southwestern Oregon clearly rule out models that postulate a single large rotated terrane (e.g. Simpson & Cox 1977). Instead, our results support a model of multiple independent blocks undergoing differing degrees of dextral rotation, as postulated by Wells (1990).

The mean inclination of 48.0° gives a palaeolatitude of 29° for the Coaledo Formation (compared to its present latitude of 43°), which suggests about 16.6° ± 6° of latitudinal displacement since the middle Eocene. This seems excessively large for a terrane that is thought to be autochthonous and not one of the accreted exotic basement terranes. However, anomalously shallow inclination data are common in this region (Table 2),

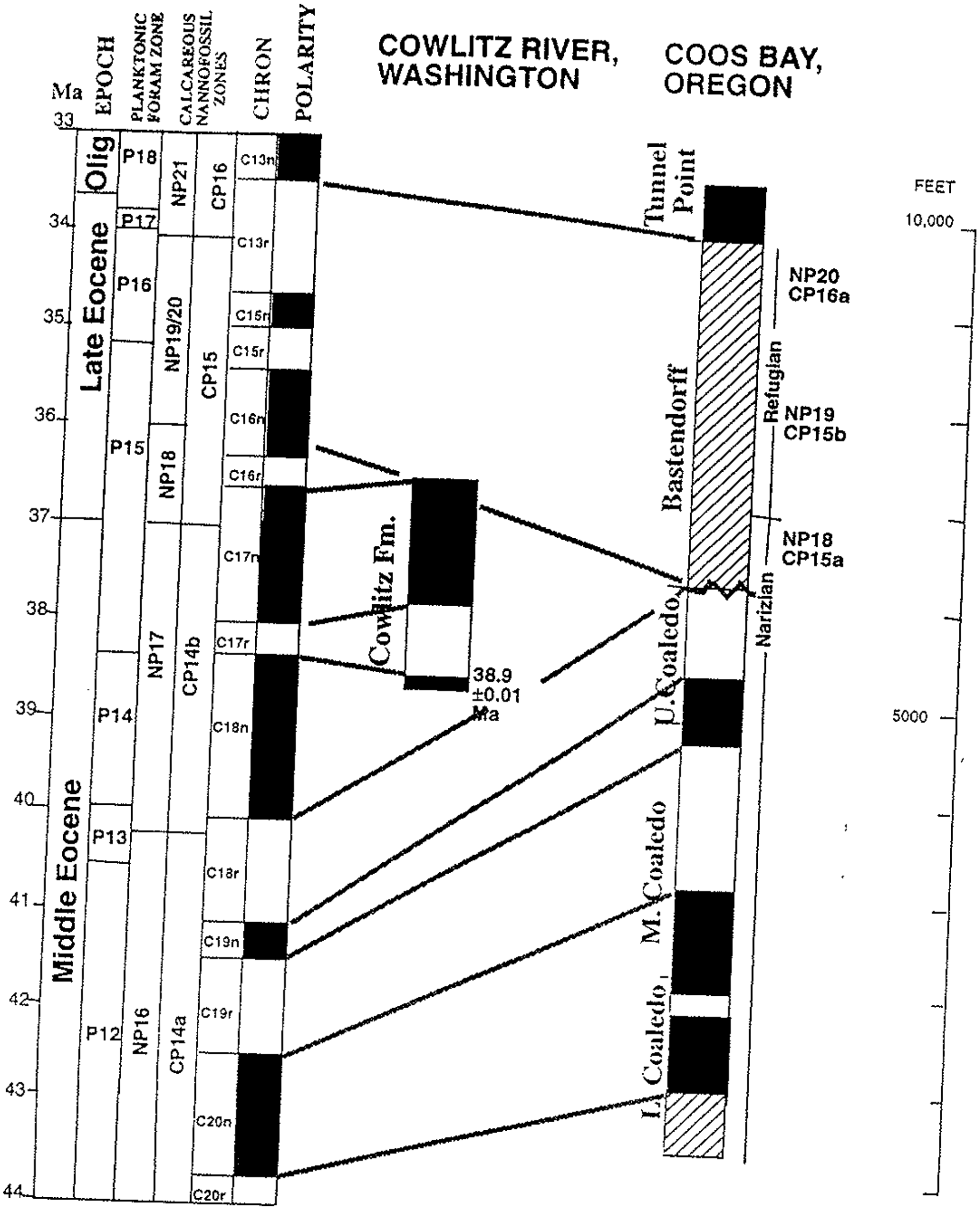

Figure 6. Correlation of the Coaledo magnetozones with the Cowlitz Formation in southwestern Washington (Prothero *et al.* 2000) and with the global timescale (Berggren *et al.* 1995). Nannofossil biostratigraphy of the Bastendorff Formation (now covered, so no magnetic sampling was possible) after Warren & Newell (1980). Benthic foraminiferal zonation after Tipton (1975) and McKeel & Lipps (1975).

and some authors (e.g. Wells & Coe 1985) have not made a case for latitudinal translations out of them. In this case, the possibility of inclination flattening due to sedimentary compaction in these highly fluid deltaic sediments leads us to be cautious about unwarranted inferences of latitudinal translation in these rocks.

CONCLUSIONS

The middle Eocene Coaledo Formation at Coos Bay, Oregon, which was part of the basis for the 'Cowlitz–Coaledo' faunal interval in Oregon and Washington (Weaver *et al.* 1944), is correlated with Chrons C18r–C20n (40–44 Ma). The Coaledo Formation is older than any Cowlitz rocks (36.5–39.0 Ma) that have been dated so far, and the 'Cowlitz–Coaledo' molluscan fauna spans almost 8 Myr without change. The Coaledo Formation has apparently been tectonically rotated 105° ± 5° clockwise since the middle Eocene. This is the greatest tectonic rotation reported from the region but is consistent with the trend towards the southwest of greatest rotations of the rotated blocks. This great degree of rotation suggests that the Coos Bay region is on a separate tectonic block from adjacent areas that yield smaller tectonic rotations, and that each block has undergone dextral rotation to differing degrees.

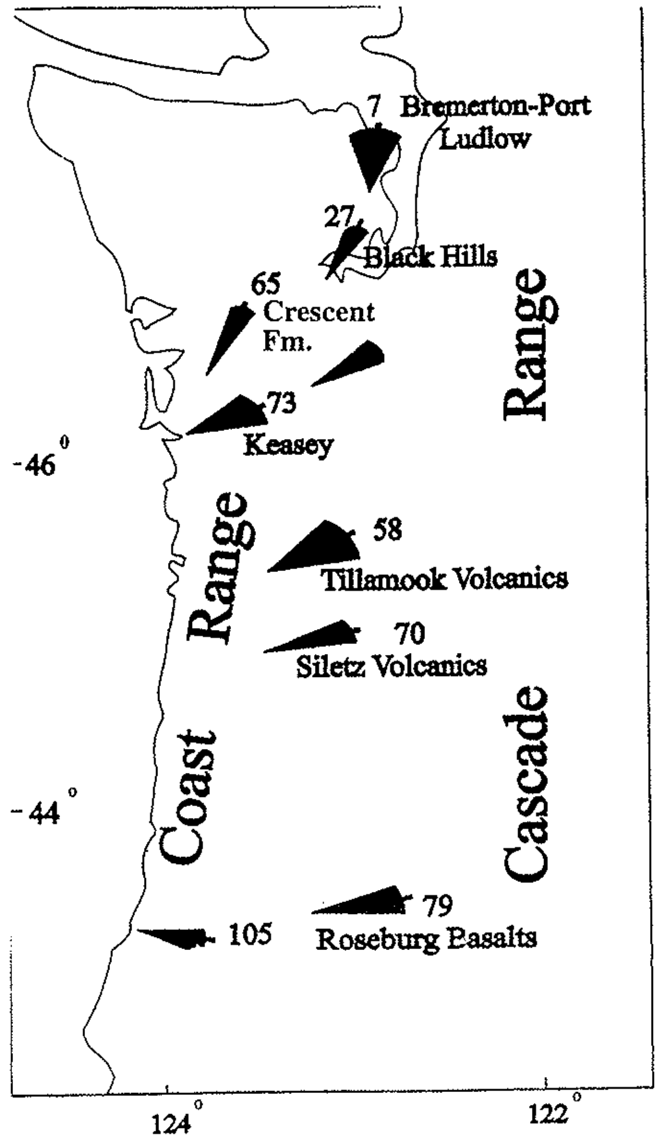

Figure 7. Comparison of rotational data in the Coast Ranges of Oregon and Washington (modified from Wells 1990). Shaded sectors with tick marks indicate tectonic rotation in degrees and 95 per cent confidence limits. Symbols: C = Coaledo Formation (this study); T = Tillamook volcanics (Magill *et al.* 1981); TF = Tyee–Flournoy formations (Simpson & Cox 1977); RB = Roseburg basalts (Wells 1990); SV = Siletz volcanics (Simpson & Cox 1977). Washington data summarized in Wells & Coe (1985) and Wells (1990).

ACKNOWLEDGMENTS

We thank A. Niem, E. Nesbitt and J. Armentrout for help with the stratigraphy, and C. Bitboul, E. Goer, K. Hankins and E. Sanger for help with the fieldwork. We thank J. Kirschvink for access to the Caltech palaeomagnetics laboratory. We thank M. E. Beck, Jr., W. A. Berggren, M. Chan, R. H. Dott, Jr., G. Moore and E. Nesbitt for reviews of earlier versions of this manuscript. This research was supported by NSF grants EAR 97-06046 and EAR 98-05071 to DRP and by a grant from the Donors of the Petroleum Research Fund, administered by the American Chemical Society.

Table 2. Comparison of palaeomagnetic rotations in Oregon and Washington.

ROCK UNIT	*D*	*I*	*N*	Age (Ma)	Rotation
Coaledo Formation, OR (this study)	95.1	48.0	35	40–44	105 ± 5
Keasey Formation, OR (Prothero & Hankins 2000)	63.7	60.8	39	35	73 ± 6
Crescent volcanics, WA (Domain 7) (Wells & Coe 1985)	54.5	47.0	4	40	65 ± 17
Tillamook volcanics, OR (Magill *et al.* 1981)	35.5	64.0	8	45	46 ± 13
Pittsburg Bluff Fm, OR (Prothero & Hankins 2000)	61.6	53.1	25	31	65 ± 12
Eocene intrusives, OR (Beck & Plumley 1980)	44.5	62	10	40	53 ± 13
Tyee–Flournoy Fms, OR (Simpson & Cox 1977)	59	63	40	45	70 ± 8
Siletz volcanics OR (Simpson & Cox 1977)	63	61	33	55	71 ± 6

REFERENCES

Allen, J.E. & Baldwin, E.M., 1944. Geology and coal resources of the Coos Bay Quadrangle, *Oregon Dept Geol. Min. Ind. Bull.*, **27**, 1–53.

Almgren, A.A., Filewicz, M.V. & Heitman, H.L., 1988. Lower Tertiary foraminiferal and calcareous nannofossil zonation of California: an overview, *Pacific Section SEPM*, **58**, 83–105.

Baldwin, E.M., 1974. Eocene stratigraphy of southwestern Oregon, *Oregon Dept Geol. Min. Ind. Bull.*, **83**, 1–38.

Baldwin, E.M., 1975. Revision of the Eocene stratigraphy of southwestern Oregon, in *Paleogene Symposium and Selected Papers. Pacific Section AAPG-SEPM*, pp. 49–64, eds Weaver, D.G., Hornaday, G.R. & Tipton, A., Long Beach, California.

Baldwin, E.M. & Beaulieu, J.D., 1973. Geology and mineral resources of Coos County, Oregon, *Oregon Dept Geol. Min. Ind. Bull.*, **80**, 9–40.

Bates, R.B., Beck, M.E. & Burmester, R.F., 1981. Tectonic rotations in the Cascade Range of southern Washington, *Geology*, **9**, 184–189.

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

Beck, M.E. & Plumley, P.W., 1980. Paleomagnetism of intrusive rocks in the Coast Range of Oregon: microplate rotations in middle Tertiary time, *Geology*, **8**, 573–577.

Beck, M.E., Burmester, R.F., Craig, D.E., Grommé, C.S. & Wells, R.E., 1986. Paleomagnetism of middle Tertiary volcanic rocks from the Western Cascade series, Northern California: timing and scale of rotation in the southern Cascades and Klamath Mountains, California, *J. geophys Res.*, **91**, 8219–8230.

Berggren, W.A., Kent, D.V., Swisher, C.C. & Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy, *SEPM Spec. Publ.*, **54**, 129–212.

Chan, M.A. & Dott, R.H., 1983. Shelf and deep-sea sedimentation in Eocene forearc basin, western Oregon—fan or non-fan?, *Am. Assoc. Petrol. Geol. Bull.*, **67**, 2100–2116.

Chan, M.A. & Dott, R.H., 1986. Depositional facies and progradational sequences of Eocene wave-dominated deltaic complexes, southwestern Oregon, *Am. Assoc. Petrol. Geol. Bull.*, **70**, 415–429.

Cox, A.V., 1957. Remanent magnetization of lower to middle Eocene basalt flows from Oregon, *Nature*, **179**, 685–686.

Cushman, J.A., Stewart, R.E. & Stewart, K.C., 1947. Upper Coaledo (upper Eocene) foraminifera from Yokam Point, Coos County, Oregon, *Oregon Department Geol. Min. Ind. Bull.*, **36**, 57–70.

Demarest, H.H. Jr, 1983. Error analysis for the determination of tectonic rotation from paleomagnetic data, *J. geophys. Res.*, **88**, 4321–4328.

Detling, M.R., 1946. Foraminifera from Coos Bay lower Tertiary, Coos County, *Oregon. J. Paleont.*, **20**, 348–361.

Diehl, J.F., Beck, M.E., Beske-Diehl, S., Jacobson, D. & Hearn, B.C., 1983. Paleomagnetism of the Late Cretaceous-early Tertiary north-central Montana alkalic province, *J. geophys. Res.*, **88**, 10 593–10 609.

Diller, J.S., 1899. The Coos Bay coal field, Oregon, *USGS 19th Ann. Rept.*, **3**, 309–370.

Diller, J.S., 1901. Coos Bay folio, Oregon, *USGS Atlas of the US*, Folio 73.

Dott, R.H., 1966. Eocene deltaic sedimentation at Coos Bay, *Oregon. J. Geol.*, **74**, 373–420.

Dott, R.H. & Bird, K.J., 1979. Sand transport through channels across an Eocene shelf and slope in Southwestern Oregon, U.S.A., *SEPM Spec. Publ.*, **27**, 327–342.

Engebretson, D.C., Cox, A. & Gordon, R.G., 1985. Relative motions between oceanic and continental plates in the Pacific Basin, *Geol. Soc. Am. Spec. Pap.*, **206**, 1–59.

England, P. & Wells, R.E., 1991. Neogene rotations and quasi-continuous deformation of the Pacific Northwest and continental margin, *Geology*, **19**, 978–981.

Fisher, R.A., 1953. Dispersion on a sphere, *Proc. R. Soc. Lond.*, **A217**, 295–305.

Grommé, C.S., Beck, M.E., Wells Jr, R.E. & Engebretson, D.C., 1986. Paleomagnetism of the Tertiary Clarno Formation of central Oregon and its significance for the tectonic history of the Pacific Northwest, *J. geophys. Res.*, **91**, 14 089–14 103.

Hagstrum, J.T., Swanson, D.A. & Evarts, R.C., 1999. Paleomagnetism of an east–west transect across the Cascade arc in southern Washington: implications for regional tectonism, *J. geophys. Res.*, **105**, 12 853–12 863.

Heller, P.L. & Ryberg, P.T., 1983. Sedimentary record of subduction to forearc transition in the rotated Eocene basin of western Oregon, *Geology*, **11**, 380–383.

Irving, A.J., Nesbitt, E.A. & Renne, P.R., 1996. Age constraints on the earliest Cascade arc volcanism and Eocene marine biozones from a feldspar-rich tuff in the Cowlitz Formation, southwestern Washington, *EOS, Trans. Am. geophys. Un.*, **77**, F814.

Johnson, H.P., Lowrie, W.P. & Kent, D.V., 1975. Stability of anhysteretic remanent magnetization in fine and coarse magnetite and maghemite particles, *Geophys. J. R. astr. Soc.*, **41**, 1–10.

Kirschvink, J.L., 1980. The least-squares line and plane and analysis of paleomagnetic data, *Geophys. J. R. astr. Soc.*, **62**, 699–718.

Magill, J.R. & Cox, A.V., 1980. Tectonic rotation of the Oregon western Cascades, *Oregon Dept Geol. Min. Ind. Spec. Pap.*, **10**, 1–67.

Magill, J.R. & Cox, A.V., 1981. Post-Oligocene tectonic rotation of the Oregon western Cascade Range and the Klamath Mountains, *Geology*, **9**, 127–131.

Magill, J.R., Cox, A.V. & Duncan, R., 1981. Tillamook volcanic series: further evidence for tectonic rotation of the Oregon Coast Range, *J. geophys. Res.*, **86**, 2953–2970.

Magill, J.R., Wells, R.E., Simpson, R.W. & Cox, A.V., 1982. Post 12 m.y. rotation of southwest Washington, *J. geophys. Res.*, **87**, 3761–2776.

McDougall, K., 1980. Paleoecological evaluation of late Eocene biostratigraphic zonations of the Pacific Coast of North America, *Paleont. Soc. Monogr.*, **2**, 1–38.

McFadden, P.L. & McElhinny, M.W., 1990. Classification of the reversal test in palaeomagnetism, *Geophys. J. Int.*, **103**, 725–729.

McKeel, D.R. & Lipps, J.H., 1975. Eocene and Oligocene planktonic foraminifera from the central and southern Oregon Coast Range, *J. Foram. Res.*, **5**, 249–269.

Nesbitt, E.A., 1995. Paleoecological analysis of molluscan assemblages from the middle Eocene Cowlitz Formation, southwestern Washington, *J. Paleont.*, **69**, 1060–1073.

Opdyke, N.D., Lindsay, E.H., Johnson, N.M. & Downs, T., 1977. The paleomagnetism and magnetic polarity stratigraphy of the mammal-bearing section of the Anza-Borrego State Park, California, *J. Quat. Res.*, **7**, 316–329.

Pluhar, C.J., Kirschvink, J.L. & Adams, R.W., 1991. Magnetostratigraphy and clockwise rotation of the Plio-Pleistocene Mojave River Formation, central Mojave Desert, California, *San Bernardino Co. Mus. Assoc. Quart.*, **38**, 31–42.

Poore, R.Z., 1980. Age and correlation of the California benthic foraminiferal stages, *USGS Prof. Pap.*, **1162-C**, C1–C18.

Prothero, D.R., 1994. *The Eocene-Oligocene Transition: Paradise Lost*, Columbia University Press, New York.

Prothero, D.R. & Hankins, K., 2000. Magnetic stratigraphy and tectonic rotation of the Eocene-Oligocene Keasey Formation, northwest Oregon, *J. geophys. Res.*, **105**, 16 473–16 480.

Prothero, D.R., Sanger, E. & Nesbitt, E., 2000. Magnetic stratigraphy of the middle Eocene Cowlitz and Hamlet formations and correlatives, western Oregon and Washington, *Pacific Section SEPM Spec. Publ.*, in press.

Rooth, G.H., 1974. Biostratigraphy and paleoecology of the Coaledo and Bastendorff Formations, southwestern Oregon, *PhD thesis*, Oregon State University, Corvallis, OR.

Ryberg, P.T., 1978. Lithofacies and depositional environments of the Coaledo Formation, Coos County, Oregon, *MA thesis*, University of Oregon, Eugene, OR.

Schenck, H.G., 1928. Stratigraphic relations of western Oregon Oligocene formations, *Univ. Calif. Publ. Geol. Sci.*, **18**, 1–50.

Simpson, R.W. & Cox, A.W., 1977. Paleomagnetic evidence for tectonic rotation of the Oregon Coast Range, *Geology*, **5**, 585–589.

Stewart, R.E., 1956. Stratigraphic implications of Cenozoic foraminifera from western Oregon, *Ore Bin*, **18**, 19.

Tipton, A., 1975. Foraminiferal biostratigraphy of the late Eocene to early Oligocene type Bastendorff Formation, near Coos Bay, Oregon, in *Future Energy Horizons of the Pacific Coast, Paleogene Symposium and Selected Papers, Pacific Section*, pp. 563–585, ed. Weaver, D.W., AAPG–SEPM, Los Angeles, CA.

Turner, F.E., 1938. Stratigraphy and mollusca of the Eocene of western Oregon, *Geol. Soc. Am. Spec. Pap.*, **10**, 1–130.

Warren, A.D. & Newell, S.H., 1980. Plankton biostratigraphy of the Refugian and adjoining stages of the Pacific Coast Tertiary, *Cushman Found. Foram. Res. Spec. Publ.*, **19**, 233–251.

Weaver, C.E., 1942. Paleontology of the marine Tertiary formations of Oregon and Washington, *Univ. Washington Publ. Geol.*, **5**, 1–789.

Weaver, C.E., 1945. Stratigraphy and paleontology of the Tertiary formations at Coos Bay, Oregon, *Univ. Washington Publ. Geol.*, **6**, 31–62.

Weaver, C.E. *et al.*, 1944. Correlation of the marine Cenozoic formations of western North America, *Geol. Soc. Am. Bull.*, **55**, 569–598.

Wells, R.E., 1990. Paleomagnetic rotations and Cenozoic tectonics of the Cascades arc, Washington, Oregon, and California, *J. geophys. Res.*, **95**, 19 409–19 417.

Wells, R.E. & Coe, R.S., 1985. Paleomagnetism and geology of Eocene volcanic rocks of southwest Washington: implications for mechanisms of tectonic rotations, *J. geophys. Res.*, **90**, 1925–1947.

Wells, R.E. & Heller, P.L., 1988. The relative contribution of accretion, shear, and extension to Cenozoic tectonic rotation of the Pacific Northwest, *Geol. Soc. Am. Bull.*, **100**, 325–338.

Wells, R.E., Engebretson, D.C., Snavely, P.D. & Coe, R.S., 1984. Cenozoic plate motions and the volcano-tectonic evolution of western Oregon and Washington, *Tectonics*, **3**, 275–294.

Wells, R.E., Simpson, R.W., Bentley, R.D., Beeson, M.H., Mangan, M.T. & Wright, T.L., 1989. Correlation of Miocene flows of the Columbia River basalt group from the central Columbia River Plateau to the coast of Oregon and Washington, *Geol. Soc. Am. Spec. Pap.*, **239**, 113–129.