PALEOMAGNETISM AND TECTONIC ROTATION OF THE RESTORATION POINT MEMBER OF THE BLAKELEY FORMATION (TYPE BLAKELEY STAGE), BAINBRIDGE ISLAND, WASHINGTON, AND THE PACIFIC COAST OLIGOCENE-MIOCENE BOUNDARY

DONALD R. PROTHERO[1] AND ELIZABETH A. NESBITT[2]

[1] Dept. Geology, Occidental College, Los Angeles, CA 90041 USA;
[2] Burke Museum, University of Washington, Box 353010, Seattle, WA 98195-3010 USA

Abstract—The Restoration Point Member of the Blakeley Formation, on the southeastern tip of Bainbridge Island just west of Seattle, Washington, consists of over 1500 m (4500 feet) of turbidites. Outcrops on the wave-cut platform around Restoration Point were the original basis of the late Oligocene Blakeley Stage, as well as the type section of the "*Echinophoria*" (=*Liracassis*) *rex* zone. Blakeley "age" rocks yield many important marine mammal fossils, especially whales. Paleomagnetic samples spanning the key fossiliferous interval of the upper 650 meters of the formation showed a stable remanence held mainly in magnetite, which exhibits a clockwise tectonic rotation of 80 ± 5°. This is as large as any rotation previously published from the region, but consistent with new data from the upper Oligocene-Miocene Pysht and Clallam formations on the northern flank of the Olympic Mountains. Except for one reversed site, the entire formation was normal in polarity. Based on its Zemorrian and Saucesian benthic foraminifera, we correlate the section with magnetic Chrons C6Cn2n to C6Cn3n (23.7-24.2 Ma), which straddles the Oligocene-Miocene boundary. This is consistent with correlations of similar strata of the Clallam Formation in the northern Olympics, and the Sooke Formation in southwestern Vancouver Island, British Columbia, Canada, suggesting that there was a widespread pulse of deposition in the region in the latest Oligocene. The magnetic polarity pattern of the formation suggests that the entire 650 m of section was rapidly deposited, and does not span the entire late Oligocene as previously suggested.

INTRODUCTION

Exposures of the Blakeley Formation on Bainbridge Island, just across Puget Sound and due west of Seattle (Fig. 1), have long played a prominent role in Pacific Northwest Cenozoic biostratigraphy. Fossils were first reported by Arnold (1906) and Dall (1909), who recognized their Oligocene affinities. Weaver (1912) first named the Blakeley Formation, based on exposures on Restoration Point, and described its molluscan fauna. Weaver referred a number of other rock units in western Washington to his "Blakeley beds," based on faunal rather than lithological similarities.

Arnold and Hannibal (1913) renamed the type Blakeley Formation of Weaver (1912) the "Seattle Formation" (a name that has since been abandoned), and referred Weaver's lower Blakeley beds to the San Lorenzo Formation, which crops out near Santa Cruz, California. In all, they recognized four Oligocene "formations" in the Pacific Northwest (from youngest to oldest): Sooke, San Lorenzo, Seattle, and Twin Rivers (Fig. 2). It is clear that these terms represent their idea of faunal stages, not lithologic units, since they are not in lithostratigraphic sequence in any sedimentary basin, and two of the units come from outside Washington (the San Lorenzo is in California, and the Sooke is in British Columbia).

Weaver (1916a, 1916b, 1916c, 1916d) published a series of papers that documented the Blakeley Formation in greater detail, although it is clear that he (like Arnold and Hannibal, 1913) was still using the term "Blakeley beds" as a faunal, rather than a lithologic, term. As reviewed by Fulmer (1975), a number of subsequent authors described additional fossils from the Blakeley Formation, usually regarding it as upper Oligocene. Weaver (1937) provided a complete summary of the lithostratigraphy of the Blakeley Formation, redefining it in terms of lithology rather than fossils. In the Weaver Committee report (Weaver et al., 1944), the Blakeley formally became part of the standard Pacific Northwest biostratigraphic terminology as the uppermost of their three-fold division of the Oligocene into "Keasey," "Lincoln" and "Blakeley" stages (Fig. 2). By doing this, the Weaver Committee implied that the Blakeley Formation was late Oligocene in age, and younger than some or

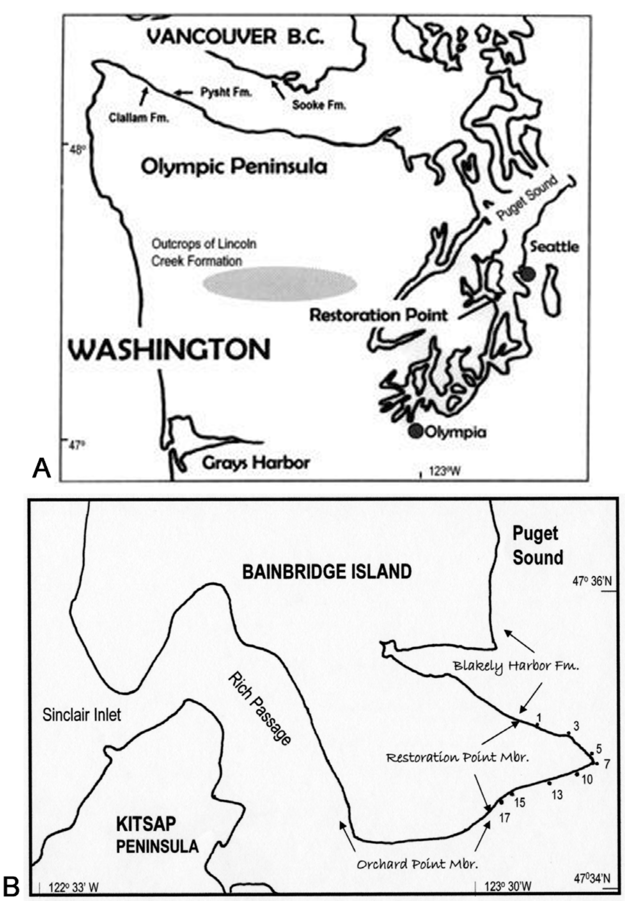

FIGURE 1. Index maps showing location of: **A**, Blakeley Formation on Restoration Point, and other localities mentioned in this paper. **B**, Detail of the paleomagnetic sampling localities and formational contacts.

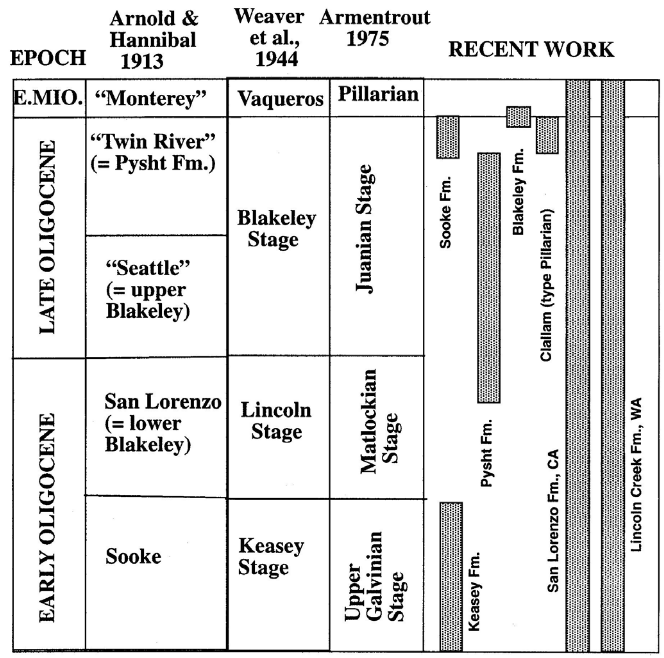

FIGURE 2. Chart showing previous concepts of correlation of the "Blakeley Stage" and Oligocene of the Pacific Northwest, from the early terminology of Arnold and Hannibal (1913) to the Weaver et al. (1944) report, to that of Armentrout (1975). Shaded bars on the right column show our current understanding of the temporal duration of these formations and their included faunas. The Sooke Formation, rather than being earliest Oligocene, as thought by Arnold and Hannibal (1913), is latest Oligocene (Prothero *et al.* in press). The Blakeley Formation, rather than spanning most of the middle and late Oligocene, as thought by all previous authors, spans only a short period of time across the Oligocene-Miocene boundary (this study). The type Pillarian in the Clallam Formation, once thought to be earliest Miocene, is now latest Oligocene (Prothero and Burns 2001). The Pysht Formation does indeed span much of the late Oligocene (Prothero *et al.* 2001a), and the Keasey Formation the late Eocene and early Oligocene (Prothero and Hankins 2000), as thought by previous workers. However, the Lincoln Creek Formation spans almost the entire late Eocene, Oligocene, and early Miocene (Prothero and Armentrout 1975), not just the early Oligocene, and the type San Lorenzo Formation north of Santa Cruz, California, spans a similar portion of the Eocene, Oligocene and Miocene (Prothero *et al.* 2001b), not just the late early Oligocene.

all of the Lincoln Creek Formation. Durham (1944) proposed seven megafaunal zones for the Oligocene of northwestern Washington, and based his "*Echinophoria*" (now *Liracassis*—see Moore, 1984) *rex* zone on fossils from the Blakeley Formation. Further exposures of the Blakeley Formation occur at Alki Point, Seattle, directly west of Restoration Point across Puget Sound, and in a number of road and railway line cuts in Seattle and Bellevue (Fig. 1). These have been correlated by map relationships, lithology, and molluscan fossil assemblages.

Fulmer (1975) provided an update and review of the lithostratigraphy of the Blakeley Formation, and recognized two members. He described the lower Orchard Point Member as composed of coarse clastic sediments interbedded with minor fine-grained sandstone and siltstone, 850 m (2600 feet) in thickness. Fulmer's (1975) upper unit, the Restoration Point Member, is composed mostly of fine-grained sandstone, siltstone, and shale with minor pebbly sandstone, and reaches up to 1500 m (4500 feet) in thickness. Overlying the Restoration Point Member are nonmarine beds that Fulmer (1975) named the Blakely Harbor Formation, a unit that reaches up to 1100 m (3400 feet) in thickness. Fulmer (1975) also documented the benthic foraminiferal faunas of each of the marine units, and regarded the Orchard Point Member as Refugian and the Restoration Point Member as Zemorrian in age. Since Fulmer's (1975) work, little has been done on the Blakeley Formation or the chronostratigraphy of the Blakeley Stage. Armentrout (1973, 1975) documented the biostratigraphy of the "*Echinophoria*" (= *Liracassis*) *rex* and "*Echinophoria*" (= *Liracassis*) *apta* zones in the Lincoln Creek Formation of the southern Olympics and Grays Harbor Basin, more than 80 km southwest of Bainbridge Island. In their correlation chart, Armentrout et al. (1983) concluded that the Orchard Point Member spanned most of the early Oligocene, and the Restoration Point Member spanned most of the late Oligocene (Fig. 2).

Subsequently, a large collection of macrofossils has been assembled in the Burke Museum, University of Washington (UWBM). Contrary to Fulmer's (1975) descriptions, the macrofossil taxon list is the same from both the Orchard Point and Restoration Point members, and from the Alki Point outcrops, and all of the species are from the *Liracassis rex* zone. The Blakeley Formation on Bainbridge Island, the Kitsap Peninsula, and in Seattle strike approximately east-west and have dips from 60°N to more than 90° (Fig. 1). Sedimentological reassessment of the entire Blakeley Formation indicates that this thick sequence of turbidites consists of both proximal and distal parts of a submarine fan that developed both close to the shoreline and to explosive ancestral Cascade volcanoes (Nesbitt and Bourgeois, in prep.). The recently recognized Seattle Fault Zone has been mapped along strike across the entire Blakeley Formation and the leading edge of the hanging wall consists of Blakeley and Blakely Harbor Formation (Blakely et al., 2000, and references therein). A zircon fission-track age from Orchard Point Member of the Blakeley Formation indicates that this section is younger than 31.6 ± 2.1 Ma. A thin tephra layer near the base of the Blakeley Harbor Formation provided a zircon fission-track age of 13.3 ± Ma (Sherrod et al., 2002).

The development of magnetic stratigraphy provides a new opportunity to reassess the age of the Blakeley Formation, and date it more precisely. In the Canyon River section of the Lincoln Creek Formation, Prothero and Armentrout (1985) showed that the *Liracassis rex* zone spanned magnetic Chrons C10n-C12r (23.5-32.5 Ma on the time scale of Berggren et al., 1995), so it is early, not late Oligocene, in age. Thus, magnetic polarity stratigraphy on the type *Liracassis rex* zone in the Restoration Point Member of the Blakeley Formation might help resolve its age.

For vertebrate paleontologists, the age of the Blakeley Stage is very important. Many important marine mammal fossils (especially whales and desmostylians) have been recovered from late Oligocene "Blakeley" units such as the Pysht and Lincoln Creek formations of Washington and the Sooke Formation of British Columbia. Resolving the precise age of these fossils will help in understanding their relationships and evolution.

The paleomagnetism of these rocks is also interesting because many of the Eocene and Oligocene rocks of western Oregon and Washington show significant clockwise tectonic rotations (Simpson and Cox 1977; Beck and Plumley 1980; Magill et al., 1981; Wells and Coe 1985; Wells and Heller 1988; Wells 1990). However, the data from the northern Olympic Peninsula-Puget Sound region are very sparse. Until recently, only Beck and Engebretson's (1982) study of Eocene basalts from the Port Ludlow and Bremerton area have been fully published. Purdy et al. (1986) mentioned paleomagnetic results from the Blakeley Formation in an abstract, but the supporting data have never been published. Thus, the paleomagnetic declination of the Blakeley Formation could be of great interest to the rotational models now under discussion.

METHODS

In the spring of 1999, we took oriented block samples from the low-tide exposures on Restoration Point, following the map and stratigraphic columns of Fulmer (1975). Seventeen sites (3 samples per site) were taken, spanning the upper 650 m (2000 feet) of the unit, which are only continuous and densely fossiliferous exposures available. In the laboratory, each sample was cored using an air-cooled drill press, and

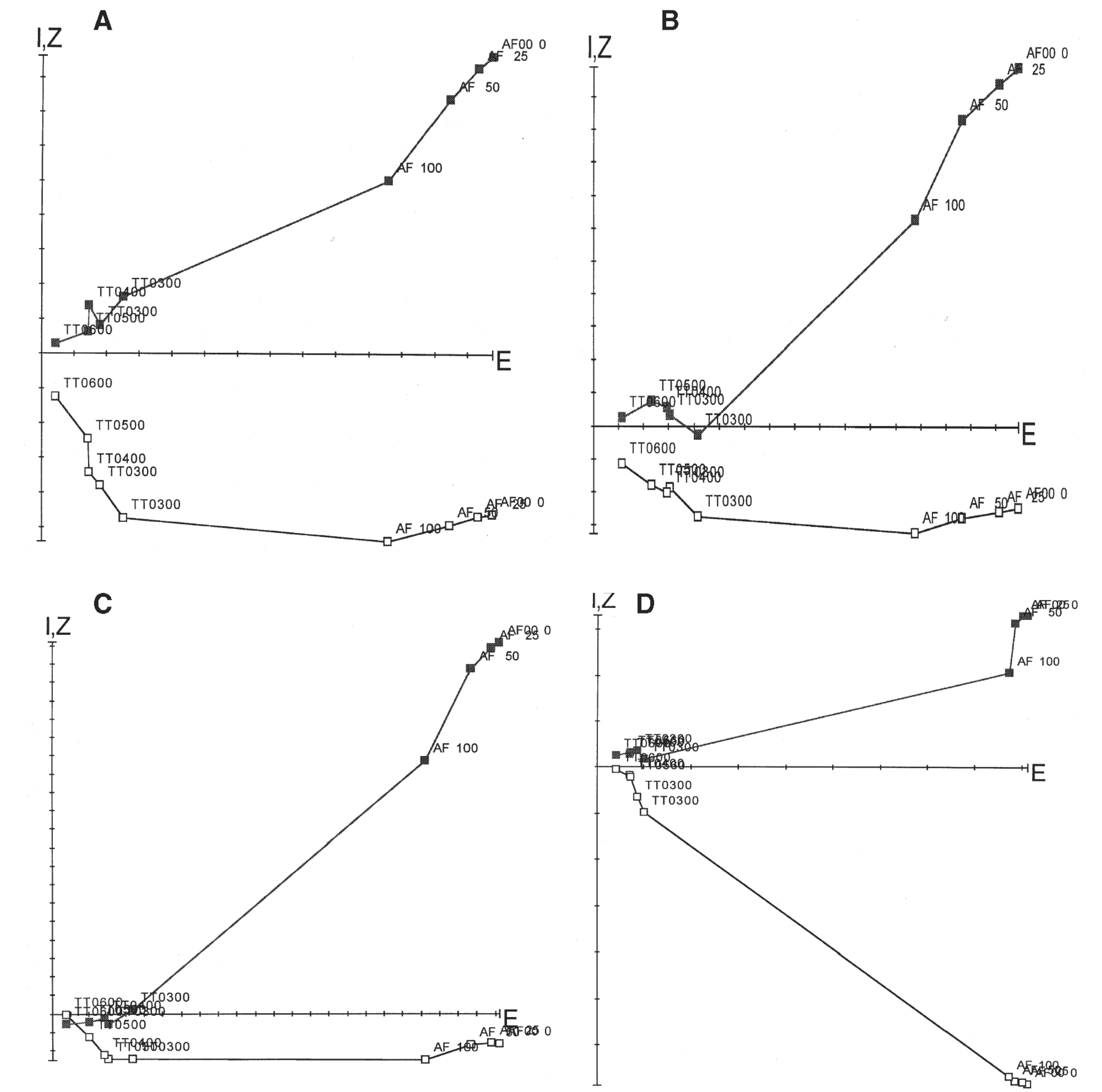

FIGURE 3. Orthogonal demagnetization plots of representative samples from the Blakeley Formation. Solid squares indicate horizontal component; open squares indicate vertical component. AF = alternating field step (in tens of mT); TT = thermal step (°C). Each division = 10^{-5} emu. All four samples have a single component of normal polarity, held mainly in magnetite, and rotated to the northeast.

analyzed on a 2G cryogenic magnetometer with an automatic sample changer at the California Institute of Technology. After measurement of NRM (natural remanent magnetization), each sample was AF (alternating field) demagnetized at 2.5, 5.0, and 10.0 mT. This helps determine the coercivity spectrum of each sample, and demagnetizes multi-domain grains before they are heated, and their remanence locked in. After AF demagnetization, each sample was then thermally demagnetized from 200 to 600°C to remove chemical remanent overprints due to goethite or other iron hydroxides, and to see how the sample behaved as it approached and passed the Curie temperature of magnetite (580°C).

RESULTS

Orthogonal demagnetization ("Zijderveld") plots of representative samples are shown in Figure 3. In most samples (Figs. 3A-C), there was a significant response to AF demagnetization, suggesting that the remanence is held by a low-coercivity mineral such as magnetite. In some samples (Fig. 3D), however, a high-coercivity mineral phase that resists AF demagnetization is also present. The large decrease in intensity after the first thermal step suggests that this phase might be a chemical remanence held in goethite or other iron hydroxides, which dehydrates at

200°C. The presence of magnetite is also suggested by the fact that the sample is almost completely demagnetized once the blocking temperature of that mineral has been reached (above 580°C). Fulmer (1975) did heavy mineral separations and thin section analyses of numerous Blakeley samples, and found both magnetite and ilmenite (derived from the basaltic clastic debris) to be significant components of the heavy minerals.

The stable vector of each sample was calculated using the least squares method of Kirschvink (1980) and averaged using Fisher (1953) statistics (Table 1). Sites were then ranked according to the system of Opdyke et al. (1977). Fifteen of the sites (Fig. 4) were Class I (statistically separated from a random distribution at the 95% confidence level. There was one Class II site (one sample missing so site statistics could not be calculated), and one Class III site (two samples show a clear polarity preference, but one was divergent). All but one site (site 6) carry a single component of normal polarity, as shown by their north and down vector components after dip correction, which were apparent at NRM, and did not change through demagnetization.

The dip-corrected mean direction for the 16 normal sites was D = 70.4, I = 38.5, k = 27.1, α_{95} = 6.1; the mean for the one reversed site was D = 270.2, I = -79.5, k = 34.1, α_{95} = 21.5 (n = 3). These values are antipodal within error estimates, giving a positive reversal test for stability. This suggests that the direction is a primary or characteristic remanence, and most of the overprinting has been removed. In addition, the dips were very steep (mostly in the range of 70-80°), so it was easy to recognize any modern normal overprints in the uncorrected directions, and exclude it from the analysis.

DISCUSSION

The magnetic polarity pattern of the upper Restoration Point Member is shown in Figure 4. As is apparent from this figure, the entire formation shows a northwest and down direction (normal polarity rotated clockwise), except for site 6.

Oligocene molluscan stages in Washington and Oregon have long been based on the apparent evolutionary lineage of the cassid gastropod taxa *Galeodea-Echinophora-Liracassis* (Durham 1944; Armentrout 1975; Moore 1984). However, these fossils can be difficult to interpret and diagnose to species, so a correlation based on this single taxon might be subject to question. In both the Pysht Formation and the Blakeley Formation, *Liracassis rex* and *L. apta* overlap and cannot be reliable stratigraphic markers (unpublished data in the UWBM). The Blakeley fauna contains a number of other molluscan taxa that are typical of the *L. rex* zone in the Lincoln Creek Formation. These include the bivalve *Acila (Truncacila) pugetensis* and the gastropods, *Bruclarkia thor, Neptunia landesi*, *Priscofusus stewarti, Turrinosyrinx borgenae* and *Turritella blakeleyensis*. Besides both *Liracassis rex* and *L. apta*, the following molluscan taxa occur in the Restoration Point strata of the Blakeley Formation as well as in both the *L. rex* and *L. apta* Zones of the Lincoln Creek Formations: the bivalves *Acesta twinensis, Macoma lorenzoensis arnoldi,* and *Yoldia blakeleyensis*, and the gastropods *Amauropsis blakeleyensis, Argobuccinum goodspeedi, Bathybembix washingtoniana, Marginella shepardae, Miopliona weaveri,* and *Neptunia teglandi* (Tegland, 1931; Durham, 1944: Armentrout, 1973; unpublished data in the UWBM).

TABLE 1. Paleomagnetic data from the Blakeley Formation, Restoration Point, Washington. Site numbers as in Figure 4. *N*: number of samples per site; *D, I*, declination, inclination; *k*, α_{95}, precision parameters.

SITE	*N*	*D*	*I*	*k*	α_{95}
1	3	71.9	37.6	12.5	36.5
2	3	73.6	51.8	10.9	39.2
3	3	64.0	44.3	31.2	22.4
4	3	73.6	22.0	31.9	22.2
5	3	57.0	62.5	13.8	34.6
6	3	270.2	-79.6	34.1	21.5
7	3	65.3	36.7	6.4	53.5
8	3	46.9	34.9	6.2	54.7
9	3	85.7	54.6	7.6	48.2
10	3	74.4	30.0	8.4	45.5
11	3	63.8	39.4	84.4	13.5
12	3	70.3	32.7	22.6	26.6
13	3	71.9	22.7	117.7	11.4
14	3	76.4	46.7	5.1	61.5
15	3	76.7	39.6	22.0	26.9
16	3	75.6	28.7	6.9	51.0
17	2	76.4	27.9	8.4	101.3

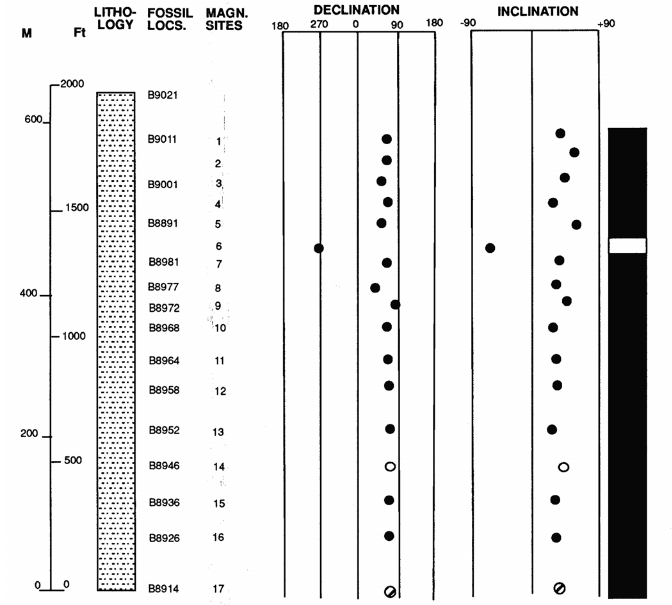

FIGURE 4. Lithostratigraphy, biostratigraphy, and magnetic stratigraphy of the Restoration Point Member of the Blakelely Formation (after Fulmer, 1975). Solid circles indicate Class I sites (Opdyke et al., 1977), which are statistically distinct from a random distribution at the 95% confidence level; open squares 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.

Correlations based on molluscan biostratigraphy places the Blakeley Formation within both the Matlockian and Juanian Stages (Fig. 2) of Armentrout (1975) that spans the entire Oligocene epoch (Prothero and Armentrout, 1985). Thus, the more we have learned about the molluscan biostratigraphy, the less reliable it has become as a temporal guide. Most of the mollusks are long ranging, so they could indicate almost any time within the middle or late Oligocene.

Fulmer (1975) suggested that the benthic foraminiferal fauna of the Blakeley Formation is late Zemorrian in age, and thus the formation is late Oligocene, as had been traditionally thought. Reanalysis of the benthic foraminifera faunal assemblage indicates that the Restoration Point Member of the Blakeley Formation is latest Zemorrian and early Saucesian in age. The following taxa that are abundant throughout the Restoration Point section are Zemorrian index species for the Pacific Northwest or have their lowest occurrence in the Zemorrian: *Cibicides elmaensis, Epionides mansfieldi* var. *oregonensis, Gyroidina healdi* and *Plectofrondicularia californica*. In addition, the following taxa are Saucesian and younger in age: *Bolivina marginata adelaidana, Bulimina alligata, Cyclammina incisa, Islandiella modeloensis, Gyroidina orbularis planata, Plectofrondicularia miocenica directa, Uvigerinells obesa* var. *impolita* and *Valvulinaria aurcana* (Rau, 1966, 1981; McDougall, 1980, 1983; Finger, 1992).

Paleomagnetic stratigraphy of the type sections of the Zemorrian and Saucesian stages demonstrated that the formations are discontinuous, unconformities are difficult to discern in outcrop, and both cover

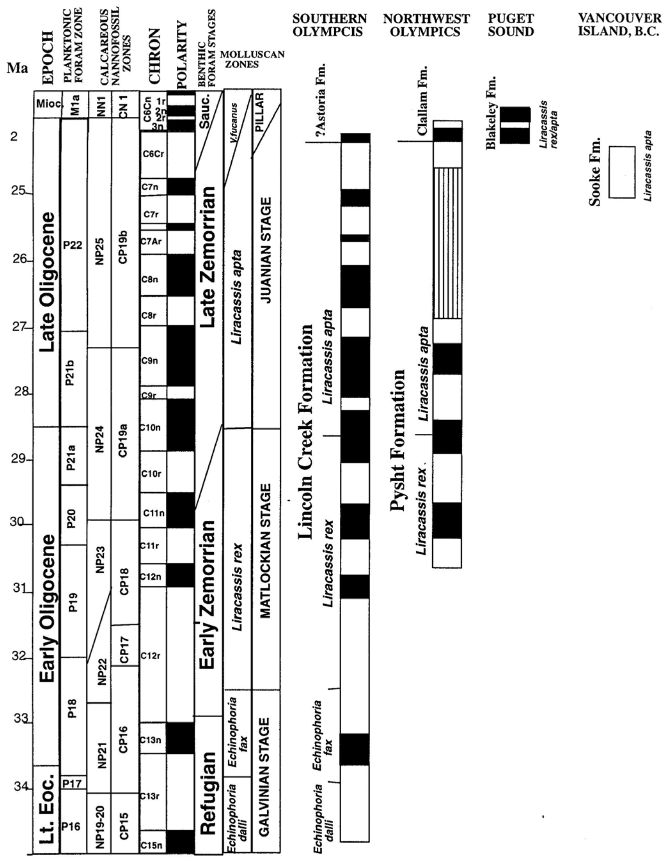

FIGURE 5. Correlation of the Restoration Point Member of the Blakeley Formation to the magnetic polarity time scale (Berggren *et al.* 1995), and to the magnetostratigraphy of the Lincoln Creek Formation at Canyon River (after Prothero and Armentrout 1985), the Clallam Formation (after Prothero and Burns 2001), and the Pysht Formation (after Prothero *et al.* 2001b).

much shorter time spans than previously expected. The type section of the Zemorrian Stage, in Zemorra Creek (Temblor Range, central Coast Ranges of California) is short and incomplete, covering the time periods 23.7-24.7 Ma and 32.0-33.0 Ma (Prothero and Resseguie, 2001). The type Saucesian in the Rincon Shale (Ventura County, California) similarly spans only 1.0 to 1.5 million years at either 22.2-23.2 Ma, or at 20.0-21.5 Ma (Prothero and Rapp, 2001). Thus, the late Zemorrian overlaps with the basal Saucesian (see Prothero, 2001), and both span the Oligocene-Miocene boundary. From this evidence, it is apparent that the age of the Restoration Point Member of the Blakeley Formation can be restricted to within a narrow time period spanning the Oligocene-Miocene boundary, from Chron C6Cn2n to C6Cn3n (23.7-24.2 Ma) (Fig. 5).

Contrary to the longstanding belief that the Blakeley Stage spanned most of the late Oligocene, and was younger than the "Lincoln Stage" of Weaver et al. (1944), it is now clear that the "Blakeley Stage" spans only a small part of the latest Oligocene-earliest Miocene, and is equivalent in age to a short interval within the uppermost Lincoln Creek Formation (Figs. 2, 5). Similarly, the Sooke Formation (Prothero et al., in press) in southern Vancouver Island, B.C., spans a very short interval of latest Oligocene Chron C6Cr (24.2-24.8 Ma). The Clallam Formation, on the northern shore of the Olympic Peninsula, spans Chrons C6Cn3n-C6Cn2, or 23.8-24.2 Ma (Prothero and Burns 2001), which is also latest Oligocene, just slightly younger than our correlation of the Blakeley Formation (Fig. 2). The alleged chronological sequence of molluscan faunas of the Sooke, San Lorenzo, Seattle (= Blakeley Formation), and Twin Rivers (=Pysht and Clallam Formations) suggested by Arnold and Hannibal (1913) has now been radically revised (Fig. 2). The Sooke Formation is latest Oligocene (24.2-24.8 Ma), not early Oligocene (Prothero et al., in press), and the "Seattle" (= Blakeley) Formation is latest Oligocene-early Miocene, while the "Twin Rivers" (Pysht and Clallam formations) span most of the Oligocene (Prothero et al., 2001a; Prothero and Burns, 2001), as does the type San Lorenzo Formation in California (Prothero et al., 2001b).

As Figure 5 shows, the redating of the Blakeley, Clallam, Pysht, and Sooke formations shows that there was a widespread episode of subsidence and deep-water deposition during the latest Oligocene and earliest Miocene all around the northern border of the Olympic Peninsula. Except for the shallow-marine sandstones of the Sooke Formation, all of the rest of these deposits are largely deep-marine turbidites, suggesting that a deep basin had subsided rapidly as the Oligocene ended.

The other unexpected implication of this 650-meter-thick zone of mostly normal polarity is that the entire type section of the Blakeley Stage spans a very short period of time (less than a million years, based on correlations suggested above), so the rates of sedimentation in this section must have been high. This is not surprising, however, since it is composed largely of turbidites, which can accumulate thick sequences of rock in very short periods of time.

The inclination of 38.5° gives a paleolatitude of 22°, which is about 9° south of the present latitude of 47.5°. However, the error estimates are large, so the apparent northward translation may not be as large as this result initially suggests. In addition, Kodama and Davi (1995) have shown that inclination flattening might be a significant problem in rocks like these. This would give apparently shallower paleolatitudes than is really the case.

The declination of 70° suggests a clockwise tectonic rotation of 80 ± 5° by comparison to the Oligocene cratonic pole (Diehl et al., 1983) after correcting the error estimates for inclination (Demarest, 1983). Previous to our recent work, the only pre-Miocene paleomagnetic rotation estimates in the northern Olympics and Puget Sound region came from some altered Eocene basalts in the Bremerton and Port Townsend area (Beck and Engebretson, 1982). These showed widely scattered directions (Fig. 6), with some showing directions with due east and due west declinations. Only AF demagnetization was used, and no thermal demagnetization was employed, which might explain some of the scatter in their data. Beck and Engebretson (1982) reported an average rotation of 4-7° ± 24° for these rocks, but the wide scatter of their data is clearly shown in their Figure 5. However, it turns out that the Bremerton basalts (the outcrops nearest the Blakeley Formation) show between 10 and 22.5 ± 24° of clockwise rotation (Beck and Engebretson, 1982, table 2), while the Port Townsend basalts much farther north show between 4 and 16 ± 62° of *counterclockwise* rotation. Averaging these two results, they obtained almost no net rotation. But these results could also be interpreted as separate rotations on two different blocks, with the result closest to our study (Bremerton basalts) most consistent with our result. On this basis, Beck and Engebretson (1982) suggested that the preliminary paleomagnetic data from around the Olympic Peninsula supported the notion that the region has undergone post-Eocene oroclinal bending.

Purdy et al. (1986) reported a clockwise rotation of 46.0 ± 16.1° for some Blakeley samples, but this was mentioned only in an abstract, without any supporting data to permit further analysis. Given the large error estimates on their data, their rotations could be as much as 62.1°, while ours could be as low as 75° with the lower limits of our error estimates, so the differences may not be as great as they first appear to be.

In addition, numerous studies (Wells and Coe, 1985; Hagstrum et al., 1999; Prothero et al., 2001c) have found that rotations in this region can be highly variable from one tectonic block to another (Table 2). For example, Wells and Coe (1985) reported rotations as great as 65° from Domain 7 of the lower Eocene Crescent volcanics in southwestern Washington, with much smaller (but highly variable) rotations on each of the other domains in a small geographic region. Prothero et al. (2001c) found rotations as low as 55° and as high as 103° on various outcrops of the

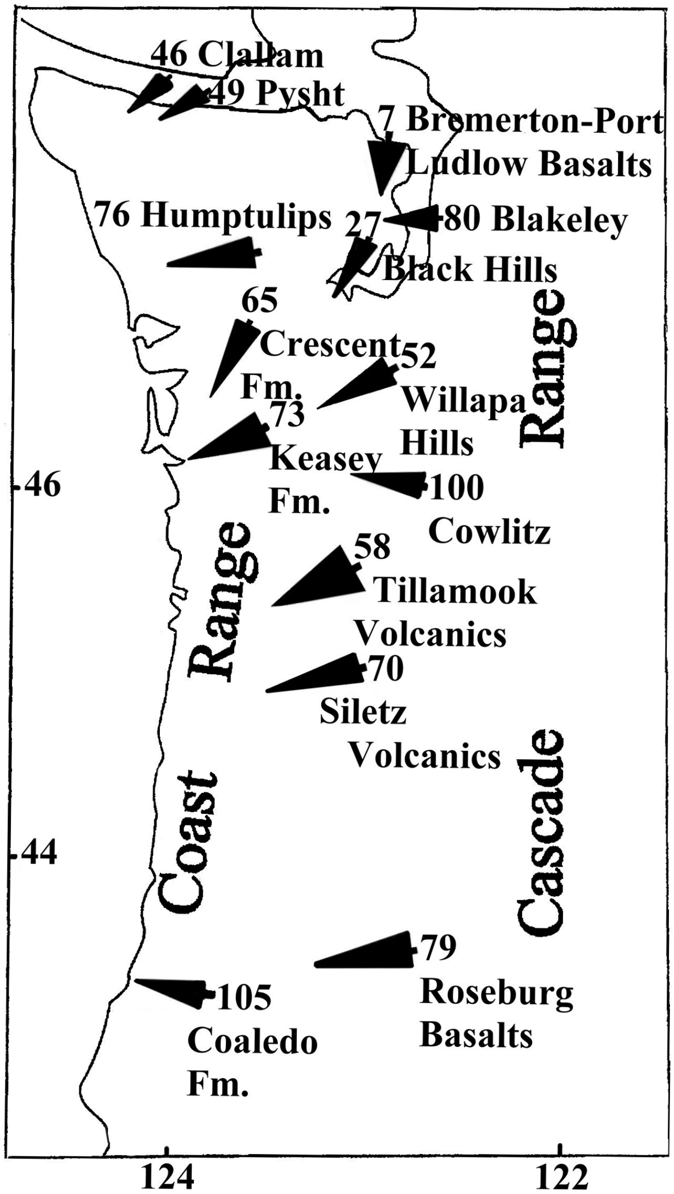

FIGURE 6. Map showing location of previously reported pre-Miocene tectonic rotations in coastal Oregon and Washington, with the results of the present study for comparison. Shaded sectors with tick marks indicate tectonic rotation in degrees and 95 per confidence limits around the mean (tick mark). Detailed data for each study given in Table 2.

middle Eocene Cowlitz Formation, unconformably overlying these Crescent volcanics in the same region of southwestern Washington (Table 2). Thus, the degree of clockwise rotation can vary markedly over short geographic distances in this highly complex region, but all these studies consistently show some significant clockwise rotation.

Our data from the Blakeley Formation, plus the 49 ± 6° clockwise rotation obtained from the upper Oligocene Pysht Formation and the 46 ± 15° from the overlying Clallam Formation on the north flank of the Olympics (Prothero et al., 2001a; Prothero and Burns, 2001), seem to support a model of pre-Miocene clockwise rotation in the Olympics, rather than a model of oroclinal bending suggested by the counterclockwise rotations of the Port Townsend basalts. Further analysis of the paleomagnetism of the Sooke Formation (Prothero et al., in press), plus other Eocene and Oligocene rocks in the area, will test this hypothesis further.

TABLE 2. Comparison of paleomagnetic rotations in Oregon and Washington.

ROCK UNIT	*D*	*I*	*N*	Age (Ma)	Rotation
Blakeley Fm., WA (this study)	70.4	38.5	17	23-24	80 ± 5
Bremerton basalts, WA (Beck and Engebretson 1982)	5.0	65.5	13	49-54?	10-22 ± 24
Port Townsend basalts, WA (Beck and Engebretson 1982)	338.5	71.5	9	49-54?	-16 to -4 ± 62
Bremerton + Port Townsend (Beck and Engebretson 1982)	354	66.5	22	49-54?	2-4 ± 24
Clallam Fm., WA (Prothero and Burns 2001)	35.6	65.1	6	24-25	46 ± 15
Pysht Fm., WA (Prothero *et al.* 2001a)	39.4	52.6	32	25-31	49 ± 6
Humptulips Fm., WA (Prothero *et al.* 2001d)	65.6	44.8	28	48-49	76 ± 8
Crescent volcanics, WA (Wells and Coe 1985)					
Domain 5	25.8	70.0	9	40	36 ± 14
Domain 6	42.0	59.8	12	40	52 ± 10
Domain 7	54.5	47.0	4	40	65 ± 17
Cowlitz Fm., WA (Prothero *et al.* 2001c)					
Olequa Creek	87.8	38.8	25	37-38	100 ± 8
Germany Creek	93.9	60.6	35	40-42	103 ± 7
Coal Creek	62.6	52.9	15	36-40	73 ± 13
Grays River volcanics, WA (= Goble volcanics, Wells and Coe 1985)	14.1	56.0	10	39	23 ± 15
Black Hills volcanics, WA (Globerman *et al.* 1981)	16.3	67.3	35	59	29 ± 15
Keasey Fm., OR (Prothero and Hankins 2000)	63.7	60.8	39	35	73 ± 6
Pittsburg Bluff Fm., OR (Prothero and Hankins 2001)	61.6	53.1	25	31	65 ± 12
Tillamook volcanics, OR (Magill *et al.* 1981)	35.5	64.0	8	45	46 ± 13
Eocene intrusives, OR (Beck and Plumley 1980)	44.5	62.0	10	40	53 ± 13
Tyee-Flournoy Fms., OR (Simpson and Cox 1977)	59	63	40	45	70 ± 8
Siletz volcanics, OR (Simpson and Cox 1977)	63	61	33	55	71 ± 6
Coaledo Fm., OR (Prothero and Donohoo 2001)	95.1	48.0	35	40-44	105 ± 5

CONCLUSIONS

The Restoration Point Member of the Blakeley Formation has long been regarded as late Oligocene, and was the basis for the late Oligocene "Blakeley Stage" of the Weaver Committee (Weaver *et al.,* 1944) and the "*Echinophoria*" (=*Liracassis*) *rex* zone of Durham (1944). Our paleomagnetic and biostratigraphic data, however, show that the type section of the "Blakeley Stage" correlates with Chron C6Cn2n to C6Cn3n (23.7-24.2 Ma), or latest Oligocene-earliest Miocene.

The paleomagnetic data in the Blakeley Formation suggest a clockwise tectonic rotation of 80 ± 5°, which is consistent with recent results from the Oligocene Pysht and Clallam formations on the north flank of the Olympics, and with the clockwise rotation of the Bremerton basalts reported by Beck and Engebretson (1982). Our data suggest that the Olympics have undergone the same pre-Miocene clockwise rotation and dextral shear seen farther south in coastal Oregon and Washington.

ACKNOWLEDGMENTS

We thank B. Crowley, J. Grieff, and S. Riegal for help with the sampling. We thank J. Kirschvink for giving us access to the Caltech paleomagnetics lab. We appreciate the helpful discussions on the fossil faunas with K. Finger, N. Carroll, J. Goedert, C. Hickman, E. Moore, and A. Niem. We thank B. Housen, S. G. Lucas, and an anonymous reviewer for helpful comments on the manuscript. This research was supported by NSF grants EAR97-06046 and EAR98-05071, and by a grant from the Donors of the Petroleum Research Fund, administered by the American Chemical Society, both to Prothero, and from the Barbara Chapple Fund for Nesbitt.

REFERENCES

Armentrout, J.M., 1973, Molluscan paleontology and biostratigraphy of the Lincoln Creek Formation, late Eocene-Oligocene, southwestern Washington [Ph.D. dissertation]: University of Washington, Seattle, WA.

Armentrout, J. M., 1975, Molluscan biostratigraphy of the Lincoln Creek Formation, southwest Washington; *in* Weaver, D.W., ed., Future energy horizons of the Pacific Coast: Paleogene Symposium and Selected Papers, Pacific Section AAPG-SEPM, Bakersfield, CA, p. 14-48.

Armentrout, J.M., Hull, D.A., Beaulieu, J.D., and Rau, W.W., eds., 1983, Correlation of Cenozoic stratigraphic units of western Oregon and Washington: Oregon Department of Geology and Mineral Industries, Oil and Gas Investigations, chart 7.

Arnold, R., 1906, Geologic reconnaissance of the coast of the Olympic Peninsula: Geological Society of America Bulletin, v. 17, p. 461.

Arnold, R., and Hannibal, H., 1913, The marine Tertiary stratigraphy of the north Pacific Coast of America: Proceedings of the American Philosophical Society, v. 52, p. 559-605.

Beck, M.E, Jr., and Engebretson, D.C., 1982, Paleomagnetism of small basalt exposures in the west Puget Sound area, Washington, and speculations on the accretionary origin of the Olympic Mountains: Journal of Geophysical Research, v. 87, p. 3755-3760.

Beck, M.E., Jr., and Plumley, P.W., 1980, Paleomagnetism of intrusive rocks in the Coast Ranges of Oregon: microplate rotations in middle Tertiary time: Geology, v. 8, 573-577.

Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.-P., 1995, A revised Cenozoic geochronology and chronostratigraphy: SEPM Special Publication, v. 54, p. 129-212.

Blakely, R.J., Wells, R.E., Weaver, C.S., and Johnson, S.Y., 2002, Location, structure, and seismicity of the Seattle fault zone, Washington; evidence from aeromagnetic anomalies, geologic mapping, and seismic-reflection data: Geological Society of America Bulletin, v. 114, p. 169-177.

Dall, W.H., 1909, The Miocene of Astoria and Coos Bay, Oregon: U.S. Geological Survey Professional Paper, v. 59, p. 59-136.

Demarest, H.H., Jr., 1983, Error analysis for the determination of tectonic rotation from paleomagnetic data: Journal of Geophysical Research, v. 88, p. 4321-4328.

Diehl, J.F., Beck, M.E., Jr., Beske-Diehl, S., Jacobson, D., and Hearn, B.C., Jr., 1983, Paleomagnetism of the Late Cretaceous-early Tertiary north-central Montana alkalic province: Journal of Geophysical Research, v. 88, p. 10593-10609.

Durham, J. W., 1944, Megafaunal zones of the Oligocene of northwestern Washington: University of California, Publications in Geological Sciences, v. 27, p. 101-211.

Finger, K. L., 1992, Atlas of Miocene foraminifera from the Monterey and Modelo formations, central and southern California: Cushman Foundation Foraminiferal Research Publication, v. 29, p. 1-179.

Fisher, R. A., 1953, Dispersion on a sphere: Proceedings of the Royal Society of London, v. A217, p. 295-305.

Fulmer, C.V., 1975, Stratigraphy and paleontology of the type Blakeley and Blakely Harbor Formations; *in* Weaver, D.W., ed., Future Energy Horizons of the Pacific Coast. Paleogene Symposium and Selected Papers, Pacific Section AAPG-SEPM, Bakersfield, CA, p. 210-271.

Globerman, B.R., Beck, M.E., Jr., and Duncan, R.A., 1981, Paleomagnetism and tectonic significance of Eocene basalts from the Black Hills, Washington Coast Range: Geological Society of America Bulletin, v. 93, p. 1151-1159.

Hagstrum, J.T., Swanson, D.A., and Evarts, R.C., 1999, Paleomagnetism of an east-west transect across the Cascade arc in southern Washington: implications for regional tectonism: Journal of Geophysical Research, v. 105, p. 12853-12863.

Kirschvink, J.L., 1980, The least-squares line and plane and analysis of paleomagnetic data: Geophysical Journal of the Royal Astronomical Society, v. 62, p. 699-718.

Kodama K. P., and Davi, J. M., 1995, A compaction correction for the paleomagnetism of the Cretaceous Pigeon Point Formation of California: Tectonics, v. 14, p.1153-1164.

Magill, J.R., Cox, A.V., and Duncan, R., 1981, Tillamook volcanic series: Further evidence for tectonic rotation of the Oregon Coast Range: Journal of Geophysical Research, v. 86, p. 2953-2970.

McDougall, K., 1980, Paleoecological evaluation of late Eocene biostratigraphical zonations of the Pacific Coast of North America: Paleontological Society Monograph, v. 2, p. 1-75.

McDougall, K., 1983, Upper Eocene to lower Miocene benthic foraminifers from the Santa Cruz Mountains area, California: U.S. Geological Survey Professional Paper, v. 1213, p. 61-77.

Moore, E.J., 1984, Middle Tertiary molluscan zones of the Pacific Northwest: Journal of Paleontology, v. 58, p. 718-737.

Opdyke, N. D., Lindsay, E. H., Johnson, N. M., and Downs, T., 1977, The paleomagnetism and magnetic polarity stratigraphy of the mammal-bearing section of Anza-Borrego State Park, California: Quaternary Research, v. 7, p. 316-329.

Prothero, D. R., 2001, Chronostratigraphic calibration of the Pacific Coast Cenozoic: a summary: Pacific Section SEPM Special Publication, v. 91, p. 377-394.

Prothero, D. R., and Armentrout, J. M., 1985, Magnetostratigraphic correlation of the Lincoln Creek Formation, Washington: implications for the age of the Eocene/ Oligocene boundary; Geology, v. 13, p. 208-211.

Prothero, D.R., and Donohoo, L.L., 2001, Magnetic stratigraphy and tectonic rotation of the middle Eocene Coaledo Formation, southwestern Oregon: Geophysical Journal International, v. 145, p. 1-15.

Prothero, D. R., and Hankins, K.G., 2000, Magnetic stratigraphy and tectonic rotation of the upper Eocene-lower Oligocene Keasey Formation, northwest Oregon: Journal of Geophysical Research, v. 105 (B7), p. 16473-16480.

Prothero, D. R., and Hankins, K.G., 2001, Magnetic stratigraphy and tectonic rotation of the lower Oligocene Pittsburg Bluff Formation, Columbia County, Oregon: Pacific Section SEPM Special Publication, v. 91, p. 201-209.

Prothero, D.R., and Rapp, S.G., 2001, Magnetic stratigraphy and tectonic rotation of the lower Miocene (type Saucesian) Rincon Formation, Ventura and Santa Barbara Counties, California: Pacific Section SEPM Special Publication, v. 91, p. 263-271.

Prothero, D.R., and Resseguie, J.L., 2001, Magnetic stratigraphy of the Oligocene Zemorrian Stage, Temblor Formation, Kern County, California: Pacific Section SEPM Special Publication, v. 91, p. 210-223.

Prothero, D.R., Streig, A., and Burns, C., 2001a, Magnetic stratigraphy and tectonic rotation of the upper Oligocene Pysht Formation, Clallam County, Washington: Pacific Section SEPM Special Publication, v. 91, p. 224-233.

Prothero, D. R., Sutton, J., and Brabb, E.E., 2001b, Magnetostratigraphy of the Eocene-Oligocene San Lorenzo and Vaqueros Formations, Santa

Cruz Mountains, California: implications for California biostratigraphic zonations: Pacific Section SEPM Special Publication, v. 91, p. 154-168.

Prothero, D.R., Sanger, E., Nesbitt, E.A., Niem, A.R., and Kleibacker, D., 2001c, Magnetic stratigraphy and tectonic rotation of the upper middle Eocene Cowlitz and Hamlet Formations, western Oregon and Washington: Pacific Section SEPM Special Publication, v. 91, p. 75-95.

Prothero, D.R., Armentrout. J.M., and Pearson, P., 2001d, Magnetic stratigraphy of the upper middle Eocene (Ulatisian-Narizian) Humptulips Formation, Grays Harbor County, Washington: Pacific Section SEPM Special Publication, v. 91, p. 96-106.

Purdy, J.W., Burmester, R.F., and Engebretson, D.C., 1986, Paleomagnetism and tectonic interpretation of the Crescent and Blakeley formations, Kitsap Peninsula, Washington.: EOS, Transactions of the American Geophysical Union, Abstracts, v. 67, no. 44, p. 1233.

Rau, W. W., 1966, Stratigraphy and foraminifera of the Satsop River area, southern Olympic Peninsula, Washington: Washington Division of Mines and Geology Bulletin, v. 54, p. 1-66.

Rau, W. W., 1981, Pacific Northwest Tertiary benthic foraminiferal biostratigraphic framework—an overview: Geological Society of America Special Paper, v. 184, p. 67-84.

Sherrod, B.L., Vance, J.A., and Leopold, E., 2000, Fission track ages of Tertiary bedrock in the hanging wall of the Seattle fault zone: Geological Society of America Abstracts with Programs, v. 34, p. 108.

Simpson, R.W., and Cox, A.W., 1977, Paleomagnetic evidence for tectonic rotation of the Oregon Coast Range: Geology, v. 5, p. 585-589.

Tegland, N.M., 1931, The gastropod genus *Galeodea* in the Oligocene of Washington: University of California, Publications of the Department of Geological Sciences, v. 19, p. 97-434.

Weaver, C.E., 1912, A preliminary report on the Tertiary paleontology of western Washington: Bulletin of the Washington Geological Survey, v. 15, p. 1-18.

Weaver, C.E., 1916a, The post-Eocene formations of western Washington: Proceedings of the California Academy of Science, Series 4, v. 6, p. 28-41.

Weaver, C.E., 1916b, The Oligocene of Kitsap County, Washington: Proceedings of the California Academy of Science, Series 4, v. 6, p. 51-52.

Weaver, C.E., 1916c, The Tertiary formations of western Washington: Bulletin of the Washington Geological Survey, v. 13, p. 319.

Weaver, C.E., 1916d, Tertiary faunal horizons of western Washington: University of Washington Publications in Geology, v. 1, p. 1-67.

Weaver, C.E., 1937, Tertiary stratigraphy of western Washington and northwestern Oregon: University of Washington Publications in Geology, v. 4, p. 1-266.

Weaver, C.E., and 22 others, 1944, Correlation of the marine Cenozoic formations of western North America: Geological Society of America Bulletin, v. 55, p. 569-598.

Wells, R.E., 1990, Paleomagnetic rotations and Cenozoic tectonics of the Cascades arc, Washington, Oregon, and California: Journal of Geophysical Research, v. 95, p. 19,409-19,417.

Wells, R.E., and Coe, R.S., 1985. Paleomagnetism and geology of Eocene volcanic rocks of southwest Washington: implications for the mechanisms of tectonic rotations: Journal of Geophysical Research, v. 90, p. 1925-1947.

Wells, R. E., and Heller, P. L., 1988, The relative contribution of accretion, shear, and extension to Cenozoic tectonic rotation in the Pacific Northwest: Geological Society of America Bulletin, v. 100, p. 325-338.