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Paleomagnetism and Counterclockwise Tectonic Rotation of the Eocene-Oligocene Lyre, Quimper, and Marrowstone Formations, Northeast Olympic Peninsula, Washington State, USA

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With 8 figures and 1 table

Abstract. The Eocene-Oligocene Lyre, Quimper, and Marrowstone formations on the northeast Olympic Peninsula of Washington are an important sedimentary sequence whose age has long been controversial. They were thought to span the Eocene-Oligocene transition. In addition, previous paleomagnetic studies on the underlying volcanic rocks produced a counterclockwise tectonic rotation. We sampled three sections: West Indian Island, West Marrowstone Island, and near Woodman's Wharf on Discovery Bay. After both AF and thermal demagnetization, all three formations produced a single-component remanence held largely in magnetite which passes a reversal test and is rotated counterclockwise by about 35°. This is consistent with the results from the underlying lower Eocene Port Townsend volcanics. It is also consistent with counterclockwise rotations obtained from the lower Eocene Metchosin volcanics and upper Oligocene Sooke Formation on the southern tip of Vancouver Island, showing that the counterclockwise rotation is widespread in the region. Based on magnetobiostratigraphic correlations with other sections in the region, we correlate the Lyre Formation with late middle Eocene Chrons C15r–C16r (35.0–36.5 Ma). The Quimper Sandstone spans the Chron C15n and probably the lowermost part of Chron C13r (34.6–35.0 Ma), so the Eocene-Oligocene boundary probably lies in the middle of the Quimper Sandstone, as previously suspected. The Marrowstone Shale is correlated with late Chron C13r.

Key words. paleomagnetism; Eocene; Oligocene; Washington; tectonics

Introduction

The Quimper Peninsula, on the northeast corner of the Olympic Peninsula (Fig. 1), has rock exposures that have long been considered one of the more important Eocene-Oligocene marine sequences in Washington (Durham 1944; Weaver et al. 1944; Armentrout and Berta 1977). The rocks of the Quimper Peninsula yield one of the more important sequences of Eocene-Oligocene marine fossils in the Pacific Coast, with several faunal assemblages that span the Eocene-Oligocene boundary (Durham 1944). The first recon-

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naissance of the area was published by Arnold (1906), who placed all the rocks in the "Clallam Formation" (a unit found on the northwest coast of the Olympic Peninsula). Weaver (1916) originally followed Arnold's (1906) usage, but in 1937 he formally described the stratigraphic sequence of the Quimper Peninsula, referring the rocks to the "Lincoln Formation" (now the Lincoln Creek Formation, a unit found on the southern flanks of the Olympics), and published the first geologic map of the area. Durham (1942, 1944) modified the earlier stratigraphic nomenclature and named several new formations (Lyre Formation, Townsend Shale, Quimper Sandstone, and Marrowstone Shale), and also defined a biostratigraphic zonation based on megafossils. Durham (1944) regarded the entire Lyre-Quimper-Marrowstone sequence as Oligocene in age. In addition to the fossil invertebrates, Durham (1944) reported the first foraminiferal fauna from the sequence. Durham's (1944) terminology was partly adopted by Weaver et al. (1944), who regarded the Lyre Formation as late Eocene, the Quimper Sandstone as early Oligocene, and the Marrowstone Shale as middle Oligocene. Allison (1959) and Thoms (1959) provided a detailed structural and sedimentological analysis of these beds, with the first detailed geologic maps of the region. Armentrout and Berta (1977) provided a much more detailed stratigraphic analysis of these beds and undertook a study of the foraminiferal faunas of these units. Based on the foraminifera, they regarded the Lyre Formation and Quimper Sandstone as upper Eocene and the Marrowstone Shale as lower Oligocene. Thus, they placed the Eocene-Oligocene boundary between the Quimper Sandstone and Marrowstone Shale, rather than between the Townsend/Lyre formations and the Quimper Sandstone, as suggested by Weaver et al. (1944), or below the entire sequence, as suggested by Durham (1944).

Since these studies, additional work has been done on the molluscan assemblages from both the Woodman's Wharf and West Indian Island sections of the Quimper Formation (unpublished Burke Museum

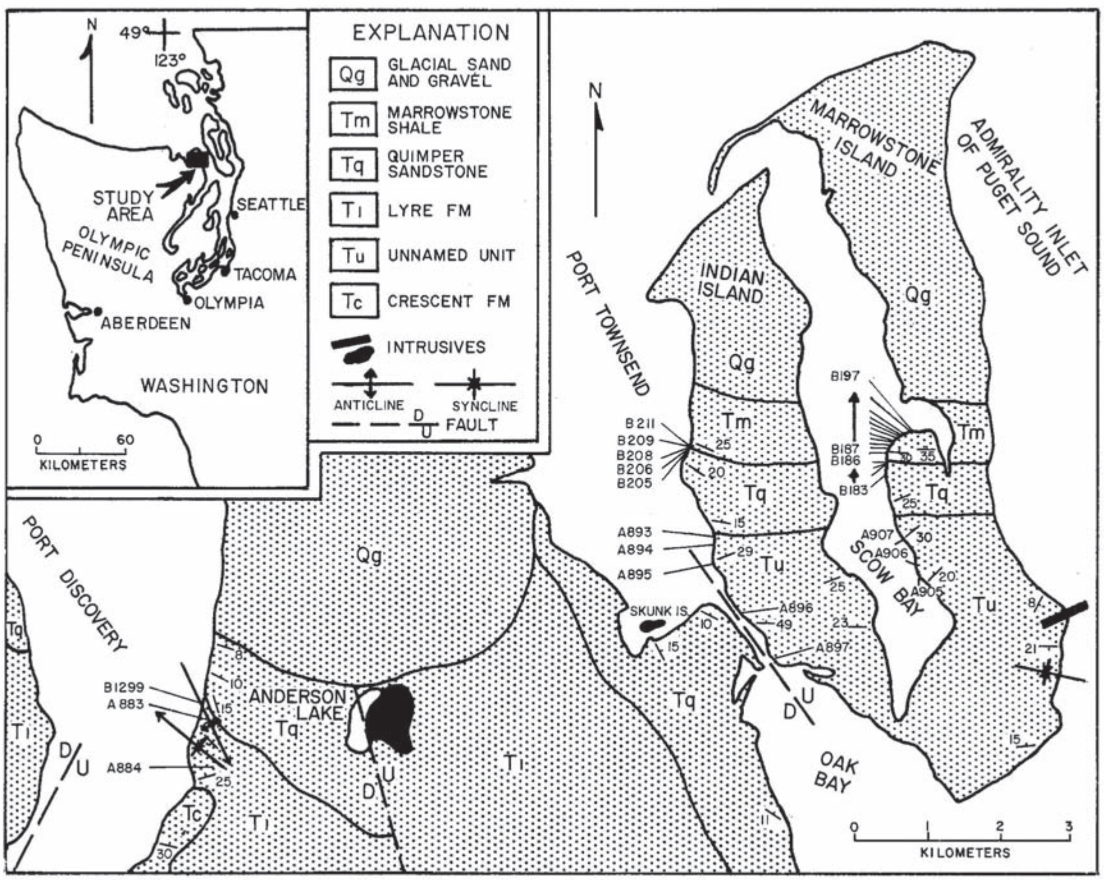

Fig. 1. Location map of the Quimper Peninsula, showing Armentrout and Berta's (3) sections along the west shores of Marrowstone and Indian Islands, and at Discovery Bay (modified from Armentrout and Berta 1977, Fig. 1).

data), and the overlying Marrowstone Shale sections. The Eocene-Oligocene boundary in Washington is placed within the molluscan *Liracassis (= Echinophoria) fax* zone, upper Galvinian Stage (Armentrout 1975; Prothero and Armentrout 1985). Mollusks from the lower strata of the Quimper Formation includes the *Liracassis (= Echinophoria) dalli* the zonal index species for the lower Galvinian Stage (Armentrout 1975; Moore 1984), as well as other taxa restricted to this zone: *Acteon parvum*, *Molopophorus stephensoni, Siphonalia washingtonensis,* and *Tellina townsendesis*. The upper fossiliferous strata on both sections include the zonal index species *Liracassis (= Echinophoria) fax* and the zone-restricted species *Aforia packardi* and *Molopophorus lincolnensis*. The Marrowstone Shale is only fossiliferous in a few strata and these contain *L.fax* and numerous other restricted species from the *L.fax* zone (Durham 1944; Armentrout 1975; unpublished Burke Museum data).

Magnetobiostratigraphic analyses have allowed high-resolution correlation of many Eocene-Oligocene marine sequences from the Pacific Northwest (Prothero 2001) and their precise calibration to the global time scale (Berggren et al. 1995). The "Rosetta Stone" was the 3000-m thick Eocene-Oligocene-Miocene sequence of the Lincoln Creek Formation in the southern Olympics (Prothero and Armentrout 1985; Armentrout 1973). Since then, important Eocene-Oligocene magnetostratigraphic sections have been analyzed in the Pysht and Clallam formations on the north-central coast of the Olympic Peninsula (Prothero and Burns 2001; Prothero et al. 2001b), the Alsea-Yaquina-Nye sequence on Yaquina Bay near Astoria, Oregon (Prothero et al. 2001a), the Eugene-Fisher section near Eugene, Oregon (Retallack et al. 2004), and the Keasey-Pittsburg Bluff section in northwestern Oregon (Prothero and Hankins 2000, 2001), as well as the type Refugian in the Santa Ynez Range of California (Prothero and Thompson 2001), and the San Lorenzo Formation north of Santa Cruz, California (Prothero et al. 2001c). Based on the foraminiferal and molluscan faunas, the Quimper Formation is correlative with all or part of these formations, but more precise correlation would be possible with magnetic stratigraphy.

The only previous paleomagnetic study of rocks of the Quimper Peninsula was by Beck and Engebretson (1982); they focused on the underlying lower Eocene Crescent volcanics of the Port Townsend area, a few km north of the Quimper Peninsula. These rocks showed a consistent counterclockwise rotation of about 30–40° in rocks of reversed polarity (so they were not a normal overprint). Similar results from the nearby Crescent volcanics in the eastern Olympics passed a fold test (Warnock et al. 1993). According to Beck and Engebretson (1982), their samples were treated only with alternating field (AF) demagnetization even though they were highly weathered and had visible iron hydroxides. Such a procedure would not have removed any young chemical remanent overprinting due to iron hydroxides (which must be thermally demagnetized), so the scatter in their data is not surprising. In the past 25 years, paleomagnetists have used both AF and thermal demagnetization with many different steps to recover more reliable paleomagnetic directions, and remove magnetic overprinting.

Paleomagnetic analysis

During the summer of 2001, we took oriented block samples (minimum 3 samples per site, more if the exposures permitted) from beach exposures of the rocks of the Quimper Peninsula. Most of these sections are now closed, because one is on a military base that has restricted its access since 9/11/2001, and the others are on private land that has changed ownership. It is no longer possible to collect more samples. Although many sections were quite thick, the exposures along these beaches were very limited, and the dip was steep, so we took samples wherever possible in three sections. The thickest section followed that of Armentrout and Berta (1977) on the west shore of Marrowstone Island along Scow Bay from their site A905 to the top of the section (Fig. 1). A second section was taken along west shore of Indian Island, following Armentrout and Berta's (1977) section from their site A895 to the top of the section (lower Marrowstone Shale). A third and final section was taken along the east shore of Discovery Bay near the famous fossil locality at Woodman's Wharf (localities A883 and A884 of Armentrout and Berta, 1977). Exact locations of each sampling site were recorded and photographed, and are archived on the first author's website, although since they were collected in 2001, GPS coordinates were not available. Since the outcrops were very limited, it is easy to locate each site in the field, because they correspond very closely to the numbered fossil localities in Figure 1, and their location can be determined on the sections in Figures 4, 5, and 6.

Most of the rocks were well indurated and did not crumble, but dilute sodium silicate was used to harden

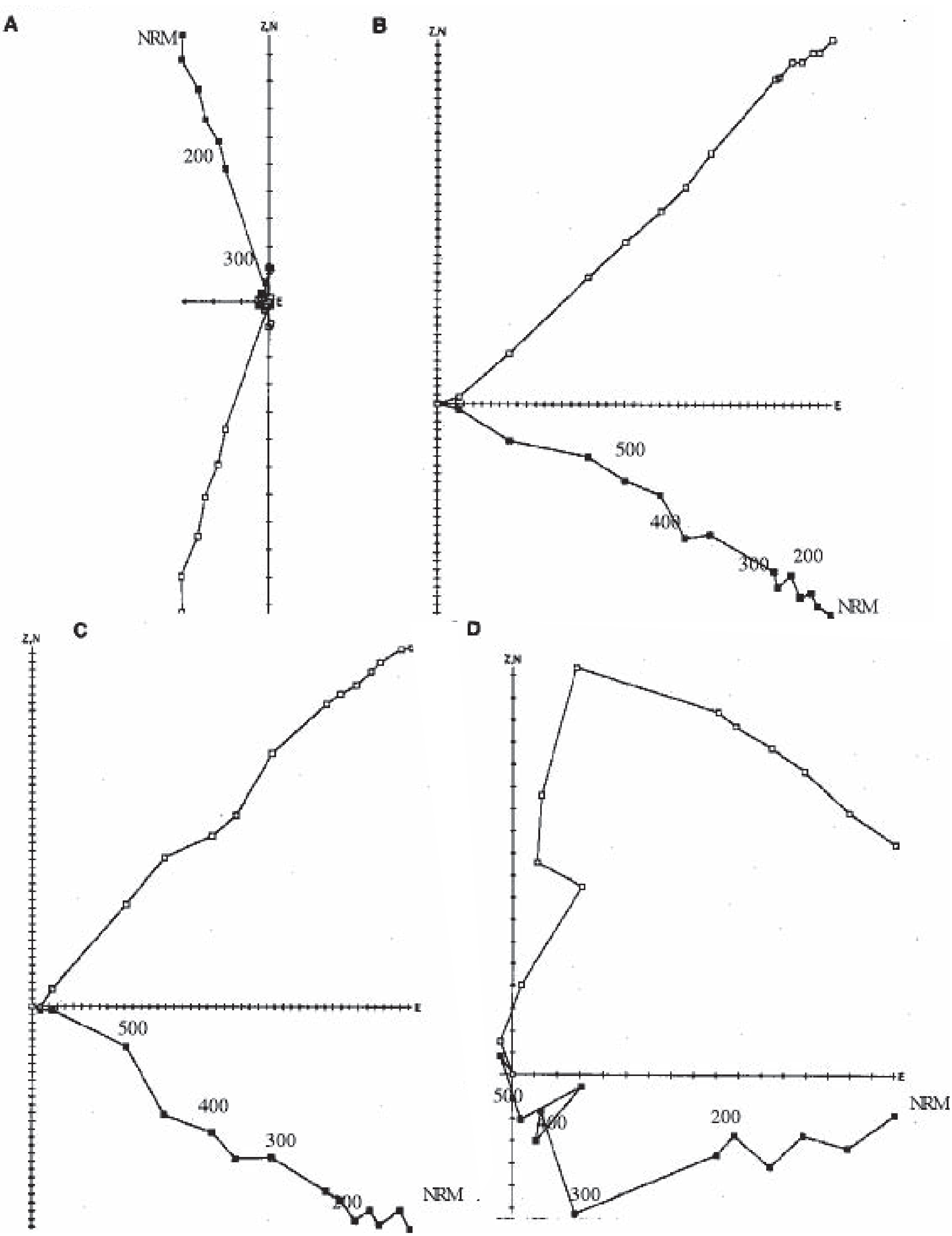

Fig. 2. Orthogonal demagnetization ("Zijderveld") plots of representative samples. Solid squares indicate declination (horizontal component); open squares indicate inclination (vertical component). First step is NRM, followed by AF steps of 2.5, 5, and 10 mT, then thermal steps from 200° to 630 °C in 50 °C increments. Each division equals 10^{-6} emu.

samples that required it. In the laboratory, each block was then subsampled into standard cores using a drill press. Samples that were poorly indurated were molded into disks of Zircar aluminum ceramic for analysis. The samples were then measured on a 2G Enterprises cryogenic magnetometer using an automatic sample changer at the California Institute of Technology. After measurement of NRM (natural remanent magnetization), each sample was AF demagnetized at 2.5, 5.0 and 10 mT (millitesla) to remove any remanence held by multidomain grains, and also to determine the coercivity behavior of each specimen. After AF demagnetization, every sample was then thermally demagnetized at 50 °C increments from 200° to 630 °C. This helps remove high-coercivity chemical overprints due to iron hydroxides such as goethite, and allows us to determine how much remanence was left after the Curie temperature of magnetite (580 °C) was exceeded.

About 0.1 g of powdered samples of a number of both sandstones and siltstones were placed in epindorph tubes and subjected to increasing isothermal remanent magnetization (IRM) to determine their IRM saturation behavior. These same samples were also 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 data are useful in conducting a modified Lowrie-Fuller test (Pluhar et al. 1991). This allows determination of whether the grain size is consistent with single domain or multiple domains.

Results were plotted on orthogonal demagnetization (“Zijderveld”) plots, and average directions of each sample were determined by the least-squares method of Kirschvink (1980). Mean directions for each site were then analyzed using Fisher (1953) statistics, and classified according to the scheme of Opdyke et al. (1977).

Results

Representative orthogonal demagnetization plots and are shown in Figure 2. As can be seen from the plots, the dip-corrected NRM direction of the samples was either northeast and down (a normal direction rotated counterclockwise) or southwest and up (a reversed direction rotated counterclockwise), and nearly all of the samples showed only this single component as their vectors decayed to the origin. A few of samples (e. g., Fig. 2D) showed some overprinting that was typically removed by 300 °C, and then a single component of remanence that decayed to the origin. The fact that nearly every sample showed a significant drop in intensity during AF demagnetization indicates that most of the remanence is held by a low-coercivity mineral such as magnetite; this is consistent with the fact that nearly all the remanence was lost when the Curie temperature of magnetite (580 °C) was exceeded (Fig. 2). Thus, it appears that the samples show a characteristic remanence that is rotated counterclockwise.

Table 1 Paleomagnetic data and Fisher statistics. N = number of interpretable samples; D = declination; I = inclination; K = precision parameter; α_{95} = ellipse of 95% confidence around mean; Class = ranking in the scheme of Opdyke et al. (1977).

SITE	N	D	I	K	α_{95}	Class
West Indian Island						
1	5	128.3	−24.9	12.5	36.4	I
2	3	113.1	−67.1	2.2	119.9	III
3	3	137.1	−32.1	12.6	36.4	I
4	6	313.9	34.0	4.9	63.2	III
5	3	330.1	52.8	4.7	64.6	III
6	3	141.5	−57.7	27.9	23.8	I
7	3	107.7	−46.0	34.5	21.3	I
8	4	112.1	−51.6	5.5	58.4	I
9	5	182.1	−57.7	6.9	51.1	I
10	4	134.9	−66.4	14.0	34.2	I
West Marrowstone Island						
1	4	119.5	−35.7	46.3	18.3	I
2	5	326.1	52.2	28.2	23.7	I
3	4	118.9	−59.6	13.3	35.2	I
4	6	154.5	−42.2	6.1	54.8	I
5	2	109.2	−71.2	12.4	78.5	II
6	4	119.2	−76.2	14.3	33.9	I
7	5	309.1	36.6	42.8	19.1	I
8	2	342.6	39.1	270.1	15.3	II
9	3	153.6	−57.9	2.9	91.6	III
10	2	148.1	−53.3	5.2	180.0	II
11	6	134.9	−37.5	65.8	15.3	I
12	7	144.8	−46.1	96.8	12.6	I
13	5	130.3	−58.9	183.9	9.1	I
Discovery Bay (Woodman’s Wharf)						
1	2	339.5	72.8	38.8	41.3	II
2	4	303.4	49.8	5.5	58.6	I
3	4	106.8	−34.8	29.9	22.9	I
4	2	95.6	−39.8	516.0	11.0	II

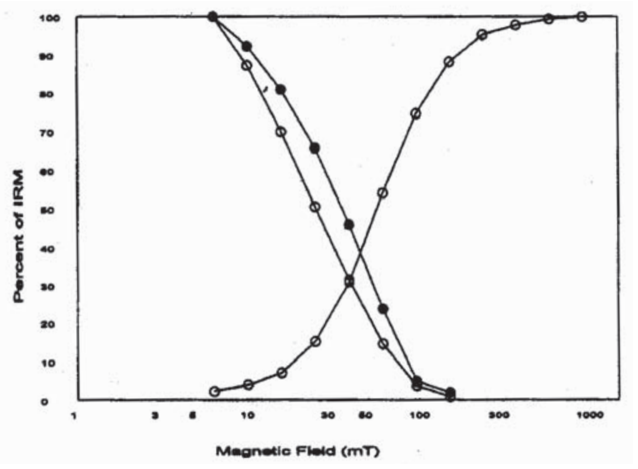

Fig. 3. IRM acquisition (ascending curve on right) and Lowrie-Fuller test (two descending curves on left) of a representative powdered sample. Open circles = IRM; solid circles = ARM. In all samples, the IRM saturates, indicating that magnetite is a primary carrier of the remanence. The ARM is more resistant to AF demagnetization than the IRM, showing that the remanence is held largely in single-domain or pseudo-single-domain grains.

The IRM acquisition experiments (Fig. 3) indicate that the samples contain significant amounts of magnetite, as they saturated at 300 mT. The Lowrie-Fuller tests indicate that the grains in the sample were single-domain or pseudo-single-domain, since the ARM was more resistant to AF demagnetization than the IRM.

The mean for all the normal samples from West Indian Island and Discovery Bay (n = 11) was D = 317.6, I = 51.7, k = 6.4, α_{95} = 19.6; for the reversed samples, the mean (n = 30) was D = 124.5, I = –49.6, k = 7.3, α_{95} = 10.7 (Table 1). Inverting the reversed directions and averaging all the West Indian Island and Discovery Bay samples yields a direction of D = 308.4, I = 51.0, k = 6.7, α_{95} = 9.5 (n = 41). For the Marrowstone Island section, the normal samples yielded a mean of D = 323.5, I = 43.8, k = 23.4, α_{95} = 11.7 (n = 8); for the Marrowstone Island reversed samples, the mean was D = 135.1, I = –53.9, k = 10.2, α_{95} = 9.0 (n = 29). Inverting the reversed directions yields an average for all Marrowstone Island samples (n = 37) of D = 317.4, I = 51.6, k = 11.4, α_{95} = 7.4. These results are statistically indistinguishable from the results at western Indian Island and Discovery Bay (Fig. 4). They are also antipodal within error estimates and pass a "Class A" (McFadden and McElhinny 1990) reversal test (γ_c = 4.1), so the directions are characteristic directions. In addition, the striking consistency in the polarity patterns in each stratigraphic section discussed below are strong evidence that the patterns are real and not due to overprinting or other secondary components.

The magnetic polarity stratigraphy of the West Marrowstone Island section is shown in Figure 5. The entire section of almost 180 m of Lyre Formation (also known as "Scow Bay Formation" in older literature) is reversed in polarity, except for a normal magnetozone in site 2 near the base. The lower 150 m of the Quimper Sandstone is normal in polarity, while the upper third of the Quimper Sandstone and the remaining 250 m of the Marrowstone Shale are reversed in polarity.

The magnetic stratigraphy of the West Indian Island section is shown in Figure 6. As in West Marrowstone Island, the upper 120 m of the Lyre or "Scow Bay" Formation is reversed in polarity. The lower two sites within the Quimper Sandstone were again normal in polarity, and the upper Quimper Sandstone and the entire Marrowstone Shale were reversed in polarity.

The exposures along the shore of Discovery Bay near the important fossil locality at Woodman's Wharf (Fig. 7) were much more limited, so the section is correspondingly shorter and less complete than the previous sections. Two sites in the uppermost Lyre ("Scow Bay") and Townsend formations were reversed polarity, as in our previous sections. Both sites in the lower Quimper Sandstone (including the rich fossil beds of Woodman's Wharf) are normal in polarity, in agreement with all our previous magnetostratigraphic results.

Discussion

Although there are no radiometric dates on the section, both molluscan and foraminiferal biostratigraphic age constraints (Fig. 8) allow us to pin down the age of these formations (Prothero 2001). The lower Quimper Sandstone (including the Woodman's Wharf fauna) contains molluscan species restricted to the *Liracassis dalli* Zone. The upper part of the Quimper and the Marrowstone Shale contain molluscan species restricted to the *L. fax* zone (Durham 1944; Weaver et al. 1944; Armentrout 1975; unpublished Burke Museum data). Benthic foraminifera from the West Indian Island and West Marrowstone Island sections of the Quimper Formation and the overlying Marrowstone Shale are characteristic of the foraminiferal Refugian Stage (Armentrout and Berta 1977). The overlap of these two molluscan zones and the foraminiferal

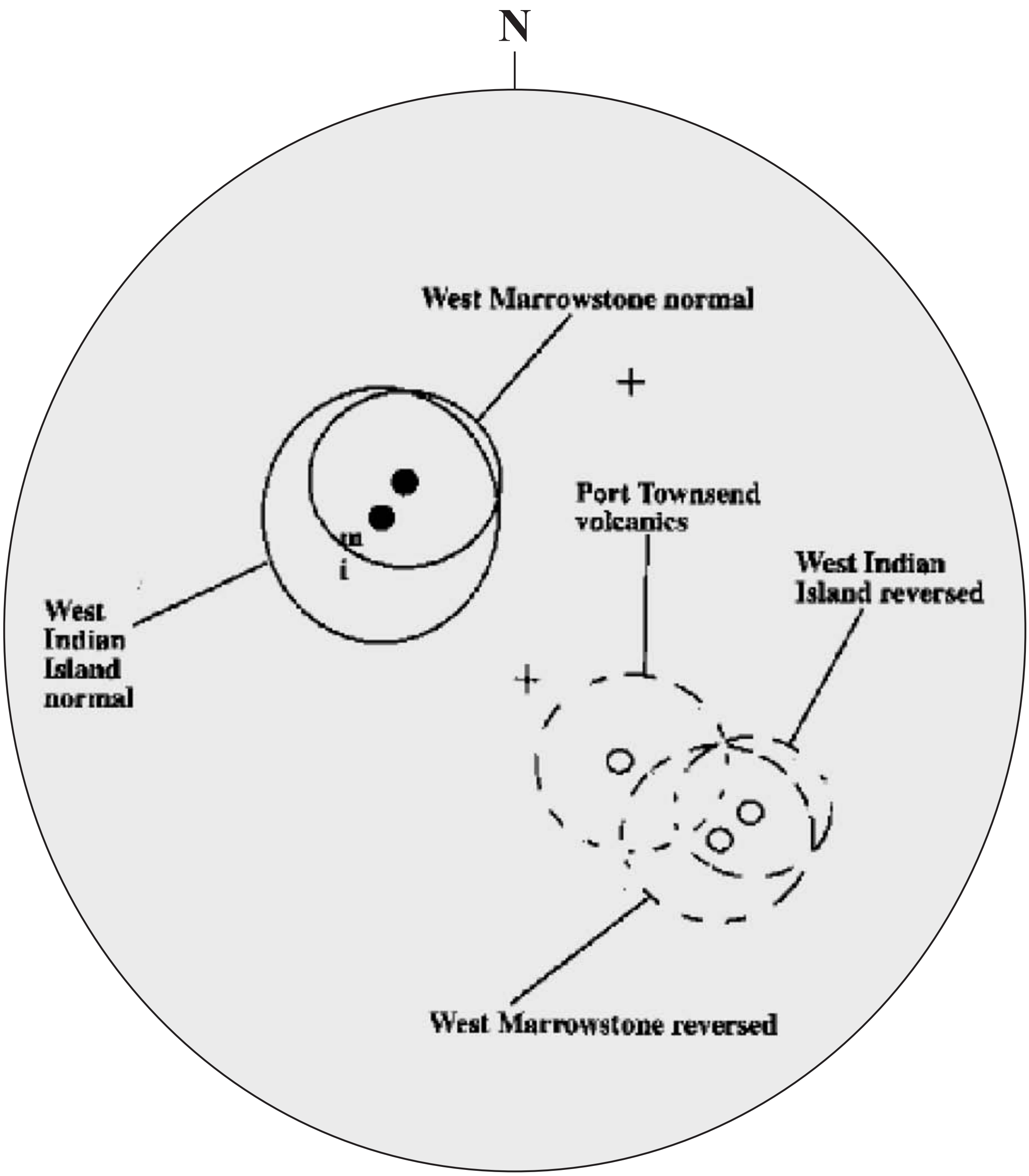

Fig. 4. Stereonet of means of magnetic sites. Solid dots and solid circle indicate mean for normal sites (lower hemisphere projection). Open dots and dashed line indicate mean of reversed samples (upper hemisphere projection). Means of the reversed West Indian Island (i) and West Marrowstone Island (m) are inverted through the center of the stereonet to the lower hemisphere. This shows the directions are antipodal, and that the primary remanence has been obtained and overprinting removed. "+" symbol = position of expected normal direction for this locality. Results from the Port Townsend Crescent volcanics of Beck and Engebretson (1982) are also shown.

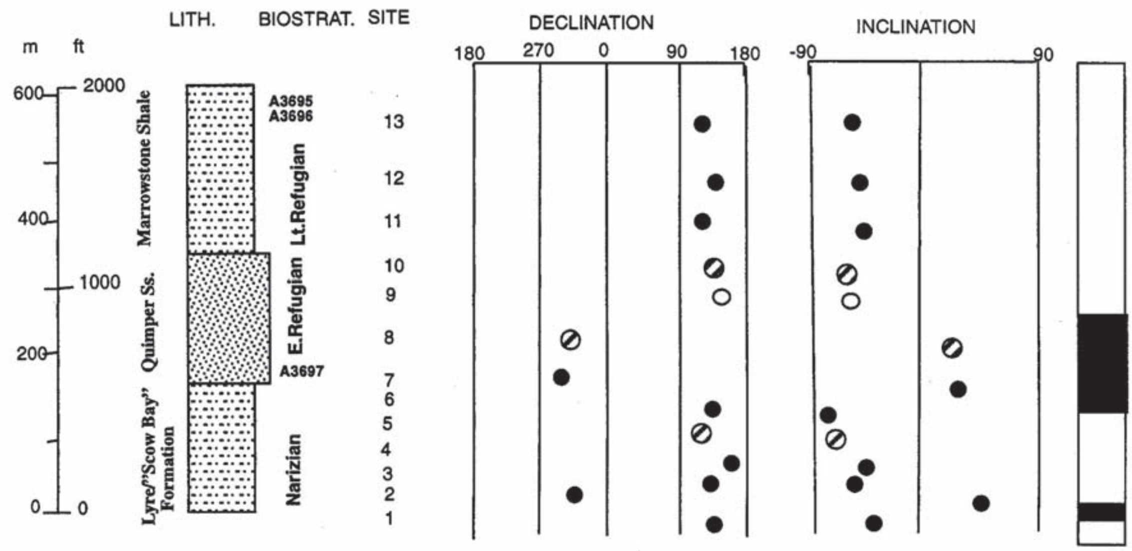

Fig. 5. Magnetic stratigraphy of the West Marrowstone Island section. Stratigraphy after Durham (1944) and Armentrout and Berta (1977). Fossil localities ("Biostrat.") of Durham (1944) shown with the "A" prefix. Solid circles are Class I sites of Opdyke et al. (1977), which are statistically removed from a random distribution at the 95 % confidence level. Hachured circles are Class II sites of Opdyke et al. (1977), which had only 2 surviving samples, so no statistics could be calculated. Open circles are Class III sites of Opdyke et al. (1977), where two directions show a clear polarity preference, but the third direction was divergent.

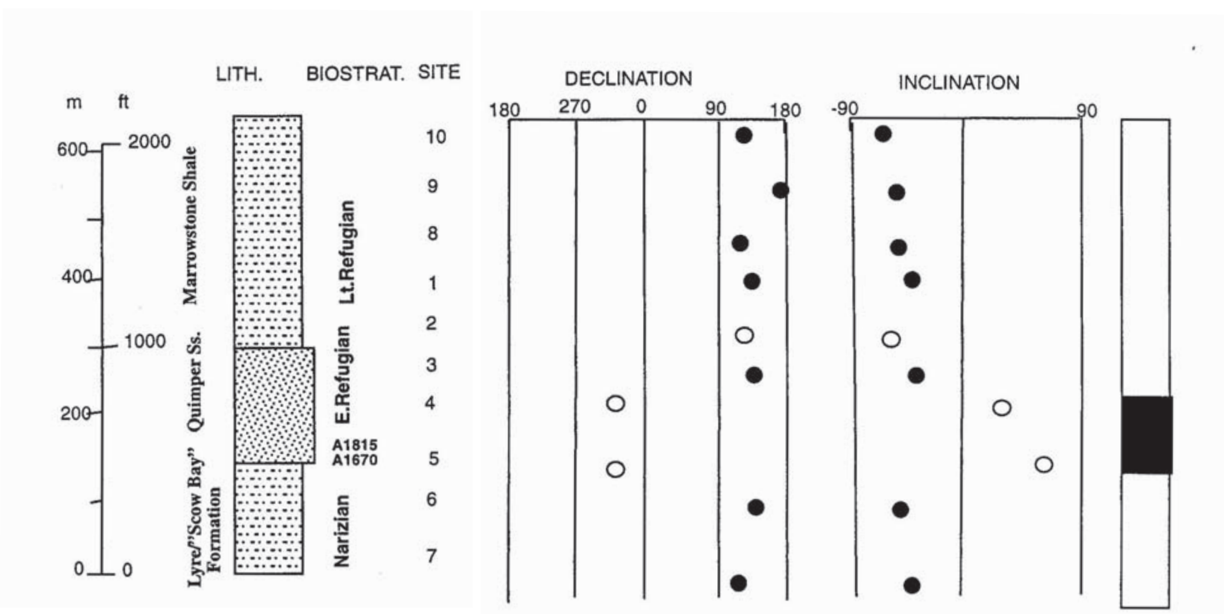

Fig. 6. Magnetic stratigraphy of the West Indian Island section. Conventions as in Fig. 5.

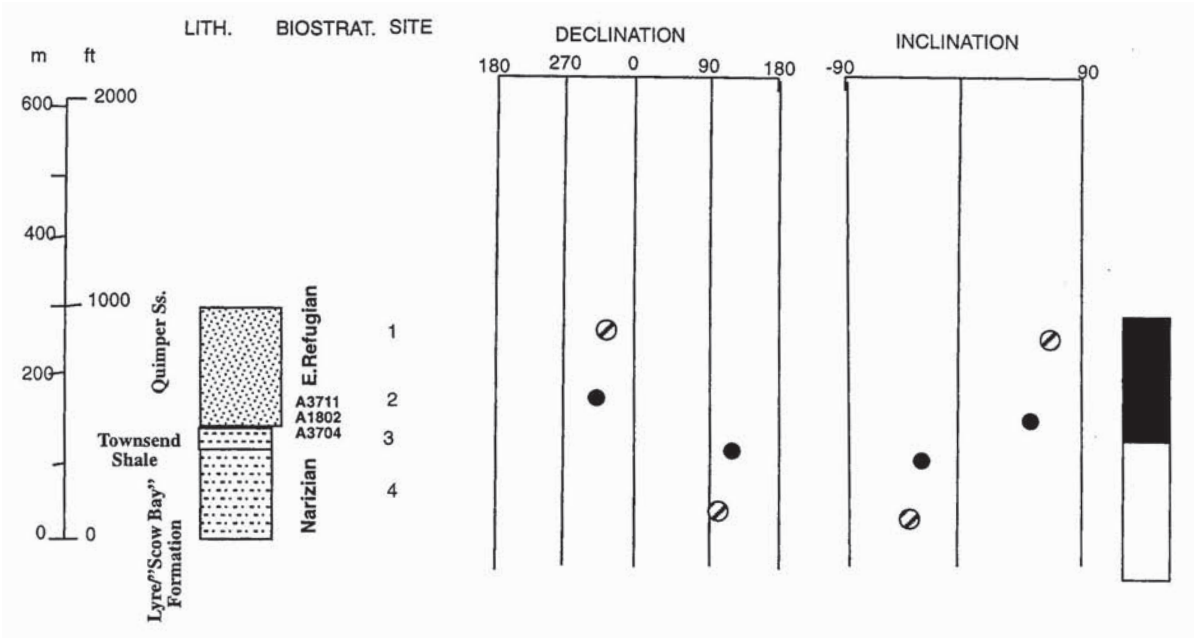

Fig. 7. Magnetic stratigraphy of the Discovery Bay (Woodman's Wharf) section. Conventions as in Fig. 5.

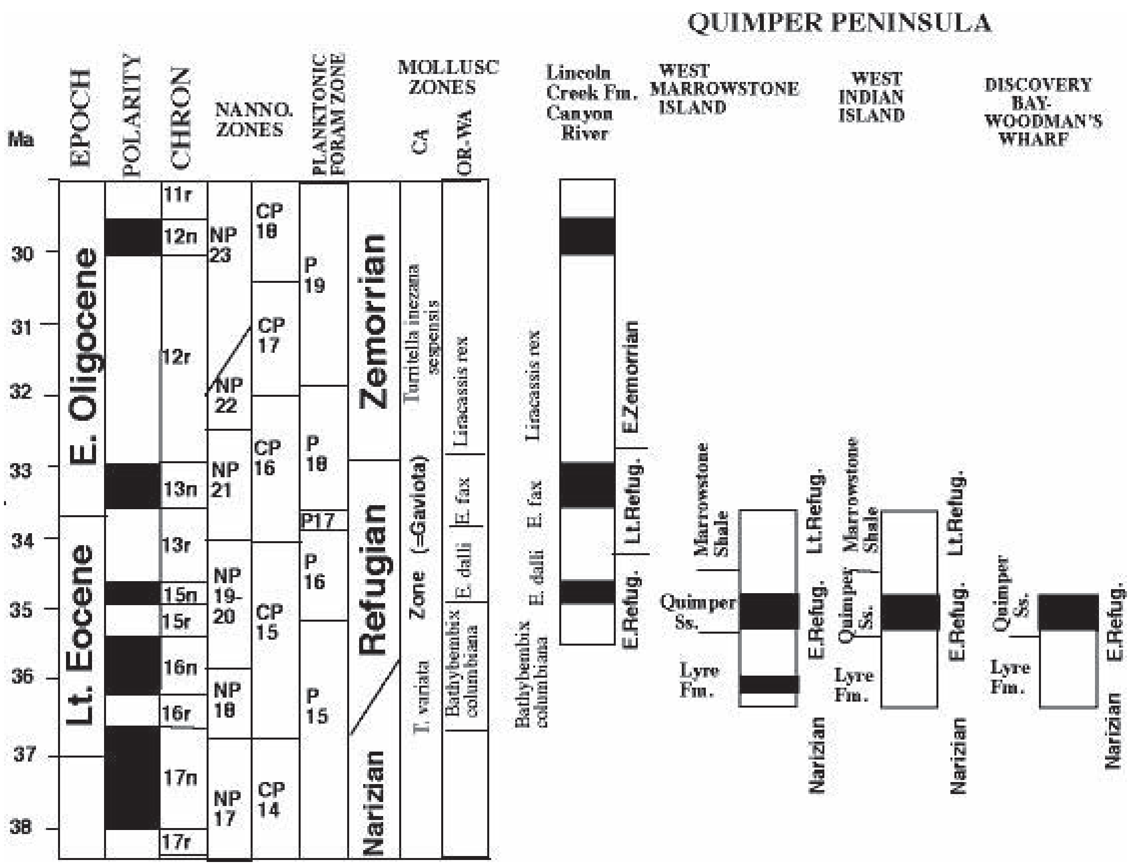

Fig. 8. Correlation of the three Quimper Peninsula sections, based on the dates and age constraints discussed in the text. Magnetic stratigraphy of the Olympics section after Prothero and Armentrout (1985). Time scale after Berggren et al. (1995), Moore (1984), and Prothero (2001).

zones, and the Eocene-Oligocene boundary has been documented from the Canyon River section of the Lincoln Creek Formation, western Washington (Prothero and Armentrout 1985) and the Keasey Formation of northwestern Oregon (Prothero and Hankins 2000). The *L. dalli* zone includes Chron C15n to within Chron C13r, and adjacent *L. fax* zone extends to the end of Chron C13n. The Eocene Oligocene boundary lies within the *L. fax* zone. Thus, the normal magnetozone in the lower part of the Quimper Sandstone correlates with Chron C15n (34.7–34.9 Ma). Likewise the reversed magnetozone in the upper Quimper Sandstone and the entire Marrowstone Shale can be correlated to part of Chron C13r (33.6–34.7 Ma).

Correlation of the upper part of the Lyre Formation (including the Townsend Shale and "Scow Bay" members) is also biostratigraphically constrained. According to Armentrout and Berta (1977), the Lyre Formation underlies the Quimper Sandstone with an unconformable contact, and yields a late Narizian foraminiferal fauna. The Narizian is a very long interval of time (Prothero 2001), covering almost the entire middle Eocene (37–47 Ma), so this in itself is not very diagnostic. However, Durham (1944) indicated that the Lyre Formation contained mollusks of his "*Turcicula columbiana*" Zone, and was correlative with the lower Keasey Formation along Rock Creek, Oregon. Prothero and Hankins (2000) showed that the lower Keasey Formation (including the Rock Creek section) correlated with Chron C15r–C16n. Thus, we correlate the Lyre Formation with late middle Eocene Chrons C15r–C16r (35.0–36.5 Ma), based on its molluscan faunas and Narizian benthic foraminifera.

These magnetic results are rotated about 35° counterclockwise with respect to the Oligocene North American cratonic pole of Diehl et al. (1983) which they give as latitude = 83.2° N, 148.0° E. As can be seen from the stereonet (Fig. 4), our Quimper Peninsula results show the same degree of rotation as that reported by Beck and Engebretson (1982), who found a mean reversed declination of 158.5° and inclination of –71.5° ($\alpha_{95} = 16.1$) for the underlying Eocene Crescent volcanics at Port Townsend (just a few km north of the Quimper Peninsula). A similar degree of counterclockwise rotation is also reported for the Eocene Metchosin volcanics on the southern tip of Vancouver Island (Symons 1973; Irving and Massey 1990) and for the overlying upper Oligocene Sooke Formation in the same region (Prothero et al., 2008), so this result is not an artifact of a particular study or a single laboratory. This counterclockwise rotational trend is in contrast to the clockwise rotation reported throughout the coastal region of Washington and Oregon (Wells and Heller 1988; Wells 1990). Like most of the pre-Miocene rocks of the Cascades and Coast Ranges, the eastern side of Olympic Peninsula and western Puget Sound shows a clockwise rotation (Beck and Engebretson 1982, on the Bremerton basalts; Prothero and Nesbitt 2008, on the Blakeley Formation, both to the southeast of the Quimper Peninsula), as does the Pysht and Clallam Formations of the northern coast of the Olympic Peninsula (Prothero and Burns 2001; Prothero et al. 2001b). The tectonic implications of these results will be explored elsewhere.

Conclusions

The Eocene-Oligocene marine rocks of the Quimper Peninsula yield important marine molluscan and foraminiferal faunas whose precise age was controversial for many years. Our magnetostratigraphic correlations place the Lyre Formation in late middle Eocene Chrons C15r–C16r (35.0–36.5 Ma), based on its mollusks and late Narizian foraminiferal faunas, the lower Quimper Sandstone (and its rich molluscan fauna) in late Eocene Chron C15n (34.7–34.9 Ma) and the upper Quimper Sandstone and overlying Marrowstone Shale in Chron C13r. The Eocene-Oligocene boundary runs through the approximate middle of the Quimper Formation. This also results in a younger top for both the Refugian foraminiferal zone and the *Liracassis fax* molluscan zone than has been determined before.

All of the Paleogene rocks of the northeastern Olympic Peninsula, including the lower Eocene Crescent volcanics at Port Townsend (Beck and Engebretson 1982), and the middle Eocene Lyre Formation and upper Eocene Quimper and Marrowstone formations, show a counterclockwise tectonic rotation of about 30–40°. This is consistent with the counterclockwise rotations on the Eocene Metchosin volcanics and Oligocene Sooke Formation of the southern tip of Vancouver Island (Prothero et al. 2008), but very different from the clockwise rotations of the areas to the south, west, and east of the Quimper Peninsula.

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