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Magnetic stratigraphy and tectonic rotation of the Eocene-Oligocene Keasey Formation, northwest Oregon

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Abstract. The upper Eocene-lower Oligocene Keasey Formation in northwestern Oregon consists of ~700 m of deep marine forearc basin sediments exposed in stream beds and roadcuts. The abundant molluscs of this unit were the basis for the Keasey Stage of the *Weaver et al.* [1944] timescale, but the precise age of this fauna and formation have long been controversial. Analysis of over 130 magnetic samples from the Keasey in five sections yielded a stable remanence held mainly in magnetite which passed a reversal test. On the basis of calibration by benthic foraminifera and molluscs the Keasey Formation is correlative with Chrons C15r-C12r (35.0-33.0 Ma), so the unit spans the latest Eocene and early Oligocene. The magnetic directions suggest a tectonic rotation of 73.7° ± 4.7°, which is consistent with rotation of the nearest volcanic basement rock reported by *Wells and Coe* [1985].

1. Introduction

Since 1957, paleomagnetic studies in the Pacific Northwest coast have demonstrated that much of the region has undergone significant clockwise tectonic rotation [*Cox*, 1957; *Simpson and Cox*, 1977; *Beck*, 1980; *Magill and Cox*, 1980, 1981; *Magill et al.*, 1981, 1982; *Bates et al.*, 1981; *Wells et al.*, 1984; *Grommé et al.*, 1986; *Wells and Coe*, 1985; *Engebretson et al.*, 1985; *Wells and Heller*, 1988; *Wells et al.*, 1989; *Wells*, 1990; *Hagstrum et al.*, 1999]. The degree of rotation tends to increase with the age of the rocks, with proximity to the coast, and also from north to south [*Wells and Heller*, 1988; *Wells et al.*, 1989], apparently due to oblique subduction of the Juan de Fuca plate [*Beck*, 1980; *England and Wells*, 1991]. Various models for this rotation have been proposed, but the data suggest that both localized block rotations caused by north oblique shear on the bottom of the brittle upper crustal layer [*Wells and Coe*, 1985; *England and Wells*, 1991] and the extensional deformation of regions outboard of the Basin and Range Province are responsible [*Magill and Cox*, 1981; *Grommé et al.*, 1986; *Wells*, 1990].

Most of the paleomagnetic data which indicated rotation have come from volcanic rocks in the Cascade Range, Olympic Mountains, and Coast Ranges of Oregon and Washington. There is also an extensive sedimentary record in this region which has the potential to test hypotheses of rotation and considerably improve the data density. Studies of the lower Eocene Tyee-Flournoy Formations of southwestern Oregon [*Simpson and Cox*, 1977] and the middle Eocene Ohanepecosh Formation of western Washington [*Bates et al.*, 1981] showed that sedimentary rocks can reliably record magnetic directions. Recent refinements in the sensitivity of magnetometers and in demagnetization techniques have made the analysis of the magnetism of sedimentary rocks much easier and more reliable than in the past.

The paleomagnetism of Pacific Northwest sedimentary rocks is important for another reason. Unlike the relatively discontinuous, unconformity-bounded units of the passive margins and craton, the thick, relatively continuous sediments of the forearc basin of active margins tend to preserve relatively complete records of geologic time and good records of the evolution of the fossils which lived in this region in the past. Consequently, the standard time scale of the Pacific Northwest [*Weaver et al.*, 1944] was largely based on key stratigraphic units and their contained faunas. Yet the precise age of these rocks and fossils has long been controversial and difficult to date by conventional means. Magnetic stratigraphy offers the potential for high-resolution dating of these units, and correlation of their record to the global time scale and climatic record.

2. Keasey Formation

A particularly important unit is the Keasey Formation of Columbia, Washington, and Tillamook counties in northwestern Oregon (Figure 1). First described as the "Keasey shale" [*Schenck*, 1927], it consists of ~700 m of mostly deep-marine gray tuffaceous siltstone and massive mudstones [*Warren et al.*, 1945; *Warren and Norbisrath*, 1945; *Van Atta*, 1971a, 1971b; *Niem and Van Atta*, 1973; *Niem et al.*, 1994]. The Keasey Formation is divided into three informal members [*Warren and Norbisrath, 1945*; *Hickman, 1976*]. The lower member consists of ~150 m of dark gray, highly micaceous laminated siltstone and mudstone with abundant glauconitic layers. The middle member is ~500 m thick, composed predominately of light gray highly tuffaceous siltstones and mudstones with occasional ash layers. The 50 m of the upper member consists of alternating light to dark gray tuffaceous silt-

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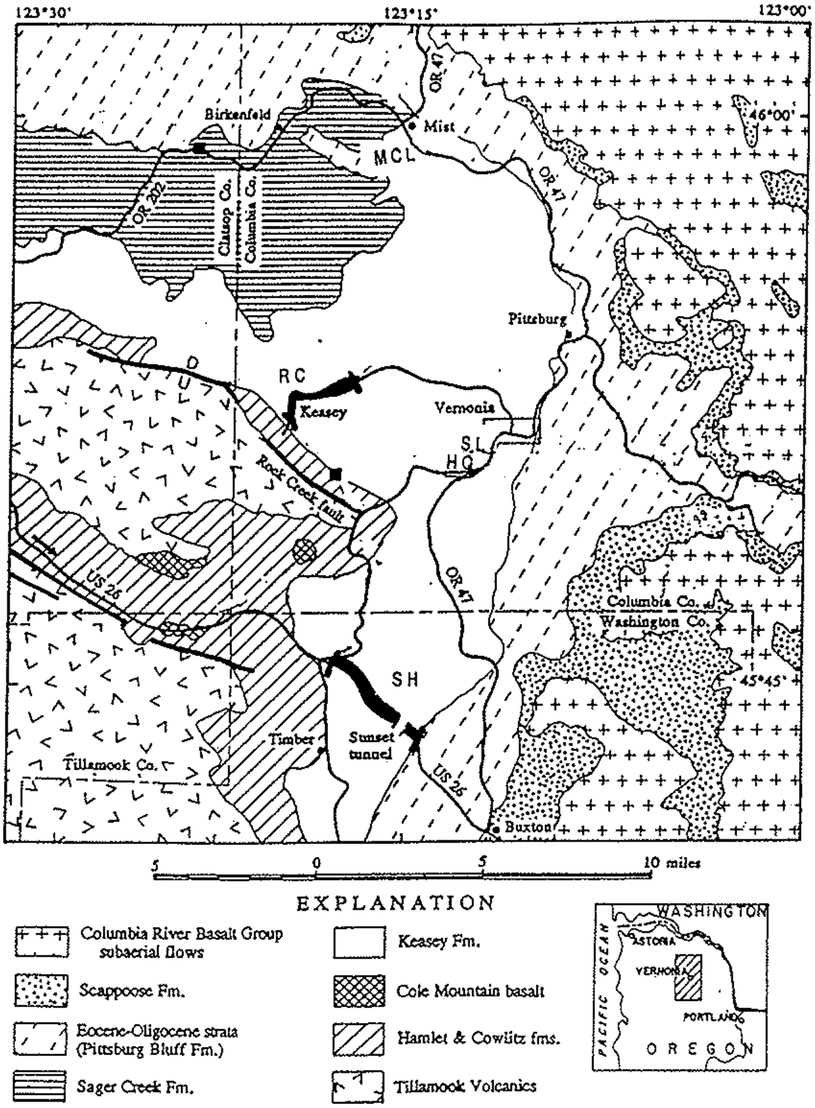

Figure 1. Index map showing outcrop of Keasey Formation in northwestern Oregon and location of sections sampled in this study. HQ, Haydite Quarry; MCL, Mist crinoid locality; RC, Rock Creek; SH, Sunset Highway; SL, Storage Locker. (Modified from *Niem et al.*, 1994).

stones and mudstones, with numerous well-indurated calcareous beds and concretionary siltstone layers. The Keasey Formation is disconformably underlain by the middle Eocene Cowlitz and Hamlet Formations, and disconformably overlain by the lower Oligocene Sager Creek and Pittsburg Bluff Formations [*Niem et al.*, 1994], although these disconformities are subtle and the time gaps between the formations are probably not extensive.

For almost a century the Keasey Formation has been known for its distinctive molluscan faunas [*Dall*, 1909; *Hickman*, 1976], benthic foraminifera [*Schenck*, 1928; *Cushman and Schenck*, 1928; *McDougall*, 1975], crustaceans [*Warren et al.*, 1945; *Steere*, 1957], articulated echinoids, asteroids, and ophiuroids [*Zullo et al.*, 1962], beautifully preserved crinoids [*Moore and Vokes*, 1953], corals [*Durham*, 1942; *Zullo et al.*, 1962], sharks [*Welton*, 1972, 1973], and even terrestrial and marine plants [*Moore and Vokes*, 1953; *Zullo et al.*, 1962]. Of these, the molluscan fauna of the Keasey was the basis for the Keasey Stage of the *Weaver et al.* [1944] timescale.

Despite the use of Keasey as a time term, correlation of the Keasey Formation to the global time scale has been problematic. Because there are few global biostratigraphic index fossils (such as planktonic foraminifera or calcareous nannofossils), correlations were based on benthic foraminifera and molluscs. Both of these groups tend to be highly endemic and regional and thus difficult to compare with fossils from the type sections in Europe. In addition, the distribution of these fossils is often controlled by facies and paleobathymetry rather than evolution through time [*McDougall*, 1980]. An even bigger problem was that for most of this century there was considerable confusion over the basis for the Eocene and Oligocene Epochs and Series in the European type sections, and this issue has only recently been resolved [*Berggren*, 1971; *Berggren et al.*, 1985, 1995]. Consequently, the Keasey Formation has been variously considered late Eocene, early Oligocene, or late Eocene to early Oligocene in age [*Schenck*, 1927; *Moore and Vokes*, 1953; *Warren et al.*, 1945; *Warren and Norbisrath*, 1946; *Durham*, 1954; *McDougall*, 1975;

Hickman, 1976], or "Eo-Oligocene" by *Weaver et al.* [1944]. Precise age dating of the Keasey Formation would not only resolve the controversy over the age of the Keasey Stage but also it would allow the extensive fossil record of this formation to contribute to our understanding of the Eocene-Oligocene transition, a critical period of climatic change [*Prothero*, 1994].

3. Methods

Owing to limited exposures, two main sections were sampled in the Keasey Formation (Figure 1). The type section in Rock Creek [*Schenck*, 1927; *Warren and Norbisrath*, 1946] exposes ~150 m of the lower part of the formation along the creek bed, but the upper part of the type section is discontinuously exposed. The only reasonably continuous section through the entire formation is along Highway 26, the Sunset Highway (also known as the Wolf Creek section). For both of these sections our sampling followed the maps, fossil localities, and sections of *McDougall* [1975, 1979]. In addition, three other important fossil localities with limited exposures were also sampled. A single site was taken in the famous Mist crinoid locality (U.S. Geological Survey [USGS] locality 15318; University of California Museum of Paleontology [UCMP] locality A5018 [*Moore and Vokes*, 1953]) located in SE SE section 23, T6N R52, Birkenfield 7.5-min. quadrangle, Columbia County, Oregon ("MCL" in Figure 1). A single site was taken in the limited exposures of a well-known locality behind a commercial storage locker on Highway 47 in Vernonia (University of Washington locality B6552), located in the center NE section 8, T4N R4W, Vernonia 7.5-min. quadrangle, Columbia County, Oregon ("SL" in Figure 1). Finally, two sites spaced ~15 m apart stratigraphically were taken in the old railroad grade (now hiking trail) just northeast of the Smithwick Haydite Quarry, also known as locality Tok-M112 [*Warren et al.*, 1945] and USGS locality 15508 [*Moore and Vokes*, 1953], which is located in SW NE section 8, T3N R4W, Vernonia 7.5-min. quadrangle, Columbia County, Oregon ("HQ" in Figure 1).

A total of 45 magnetic sites (three samples per site) were taken as oriented block samples in the field, and then subsampled into cores with an air-cooled drill press. Poorly indurated samples were hardened with dilute sodium silicate solution. Samples that could not be drilled were ground into cylinders with a disk sander, and small samples were molded into cylinders using Zircar aluminum ceramic. Measurements were made on the 2G cryogenic magnetometer at the California Institute of Technology paleomagnetics laboratory, using an automatic sample changer. The natural remanent magnetization (NRM) of each sample was measured, then each was demagnetized at alternating fields (AF) of 2.5, 5.0, and 10.0 mT (millitesla) to determine the coercivity behavior and to prevent the remanence of multidomain grains from being locked in during heating. After AF demagnetization, every sample was then thermally demagnetized at 300°, 400°, 500°, and 600°C. Standard orthogonal demagnetization plots ("Zijderveld" plots) were produced for each sample (Figure 2), and lines were fitted to the demagnetization data using the least squares method based on principal component analysis [*Kirschvink*, 1980]. The resultant vectors were then averaged for each site using *Fisher* [1953] statistics, and ranked according to the scheme of *Opdyke et al.* [1977].

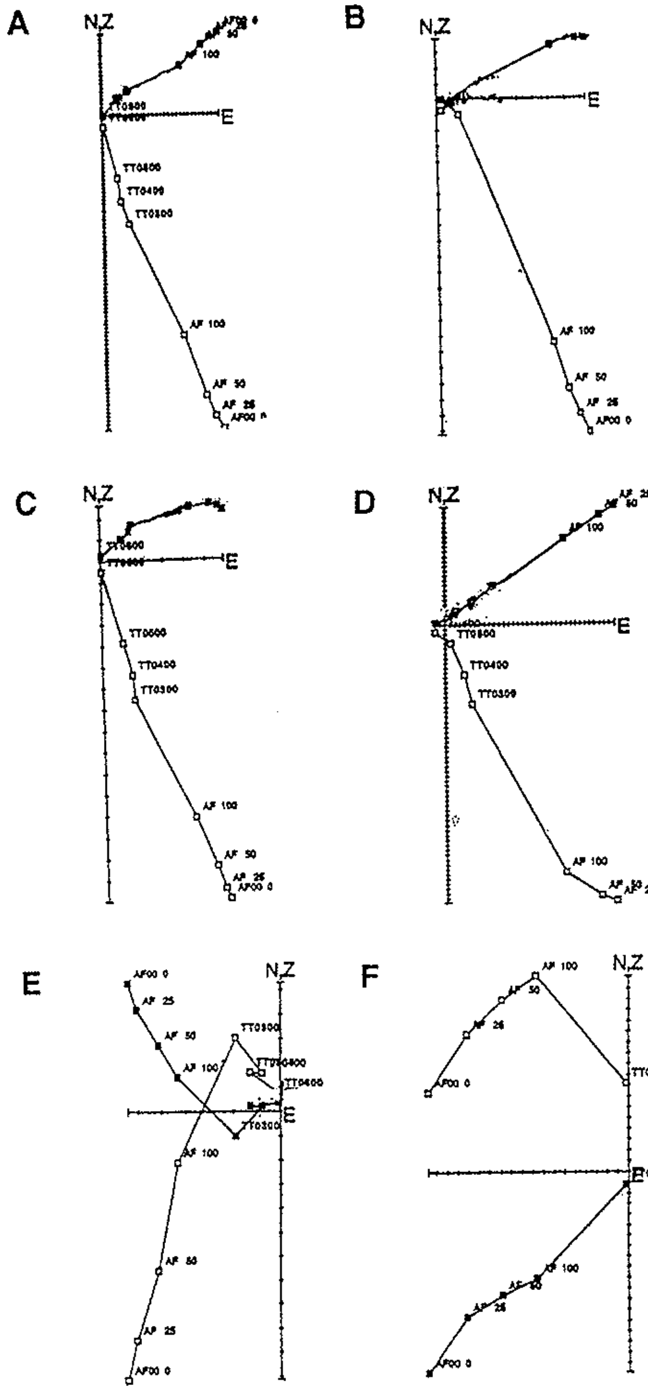

Figure 2. Orthogonal demagnetization plots of representative samples from the Keasey Formation. Solid squares indicate horizontal component; open squares indicate vertical component. AF, alternating field step (in tens of millitesla); TT, thermal step (°C). Each division equals 10^{-6} emu. a-d. Samples showing a normal polarity rotated to the northeast. e-f. Samples showing a reversed polarity rotated to the southwest, with a slight overprint which was removed by 300°C.

Several representative samples were also powdered and placed in epindorph tubes. These samples were subjected to increasing isothermal remanent magnetization (IRM) to determine their IRM acquisition behavior. They were also AF demagnetized twice, once after having acquired an IRM produced in a 100 mT peak field and once after having acquired an anhysteretic remanent magnetization (ARM) in a 100 mT oscillating field. Such data are useful in conducting a modified Lowrie-Fuller test [*Johnson et al.*, 1975; *Pluhar et al.*, 1991].

4. Results

4.1. Rock Magnetic Analysis

Orthogonal demagnetization plots (Figure 2) showed consistent patterns of magnetic behavior. A majority (~70%) of the samples showed a single stable component of magnetization under both AF and thermal demagnetization that was pointed either northeast and down or southwest and up after dip correction. Most samples lost significant magnetic intensity under AF demagnetization, suggesting that the remanence is held by a low-coercivity mineral such as magnetite. This is corroborated by the nearly complete loss of remanence above the Curie point of magnetite (580°C). Some (~20%) reversed samples showed an overprint which was removed by 300°C, suggesting that a chemical remanence held in an iron hydroxide such as goethite might have been present. A few (~5%) samples showed no stable directions that could be interpreted, and another 5% of the sample set had unremovable normal overprints, which were easily recognized by comparing directions before dip correction. These data were rejected from the analysis.

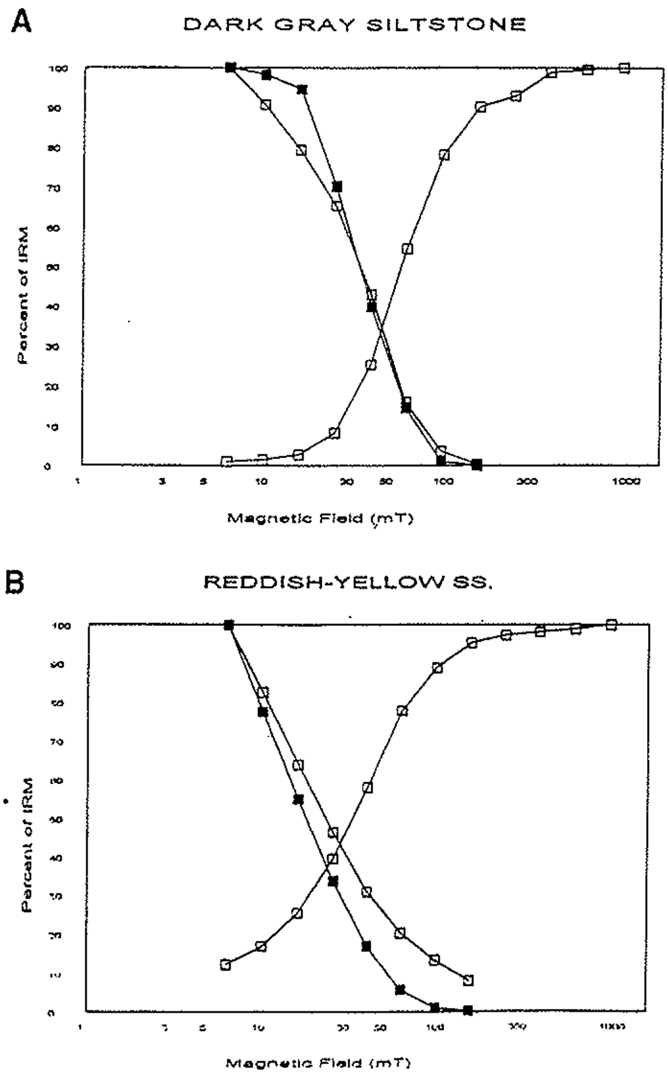

Figure 3. IRM acquisition (ascending curve on right) and Lowrie-Fuller test (two descending curves on left) of representative powdered samples from the Keasey Formation. Open squares are IRM; solid squares are ARM. a. RKCK 13, a dark gray siltstone. b. SUNS 21, a reddish-yellow sandstone.

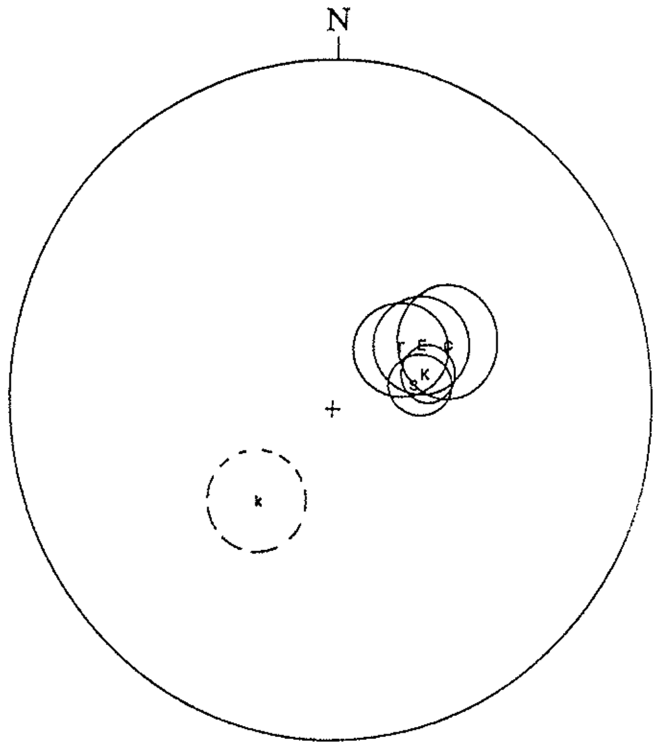

Figure 4. Stereoplots of mean poles and circles of confidence for the data discussed in this study. Solid circles indicate lower hemisphere projections; dashed lines and open circles indicate upper hemisphere projections. K, Keasey normal mean; k, Keasey reversed mean; C, Crescent volcanics, Domain 7 [*Wells and Coe*, 1985]; T, Tillamook volcanics [*Magill et al.*, 1981]; S, Siletz volcanics [*Simpson and Cox*, 1977]; E, Eocene intrusives [*Beck and Plumley*, 1980].

IRM acquisition (Figure 3) of representative lithologies showed that most samples reached saturation at around 300 mT, consistent with the interpretation that magnetite is the primary carrier of remanence. This was true even of sandstones with a reddish-yellow color that might indicate iron hydroxides. In some samples the ARM was more resistant to AF demagnetization than the IRM, suggesting that the remanence is held by single-domain or pseudo single-domain grains, but in others the reverse is true, suggesting the presence of multidomain grains.

Polished thin sections were examined under reflected light, and small (0.01-0.005 mm) magnetite grains were observed, some with oxidation rims of goethite around them. This is consistent with the magnetic behavior just described.

The mean for all normal sites was declination (D) = 72.9, inclination (I) = 64.3, precision parameter (k) = 33.7, and ellipse of confidence (α_{95}) = 5.6, for a number of samples (n) = 21; for all reversed sites, the mean was D = 234.4, I = -55.7, k = 10.8, α_{95} = 11.0 (n = 18). These directions are antipodal (critical error angle, γ_c = 4.07), so this result passes a "Class A" reversal test [*McFadden and McElhinny*, 1990], and the directions probably reflect a primary or characteristic remanence (Figure 4). The dips on these beds were generally quite shallow (10°-

30°) and not variable enough to conduct a fold test nor were there any conglomerates available to conduct a conglomerate test.

4.2. Magnetic Stratigraphy

In the type section at Rock Creek (Figure 5), only the lower 150 m of the Keasey Formation is exposed continuously enough for paleomagnetic sampling. Following *McDougall's* [1975, 1979] sampling scheme, the late Narizian part of the section (lowest 45 m) was reversed in polarity, while the earliest Refugian portion of the section (105 m) was normal in polarity.

The 600 m thick section at Sunset Highway (Figure 6) is the only section which spans most of the Keasey Formation (and the uppermost part of the Hamlet Formation of *Niem et al.*, 1994). At Sunset Highway the lower 100 m of early Refugian strata were normal polarity, consistent with the results from Rock Creek. The middle 100 m of the formation were of reversed polarity, and the upper 50 m of the Keasey was of normal polarity. A single site in the overlying Pittsburg Bluff Formation was of reversed polarity, but the detailed magnetic analysis of this formation is presented elsewhere [*Prothero and Hankins*, 2000]. The Mist crinoid locality site was normal in polarity (D = 42.1, I = 44.5, k = 11.3, α_{95} = 38.6, and n = 3), as was the Storage Locker locality (D = 75.5, I = 67.1, k = 23.4, α_{95} = 54.2, and n = 3). The two sites at the Haydite Quarry were both reversed in polarity (D = 256.9, I = -45.8, k = 5.0, α_{95} = 62.0, and n = 6).

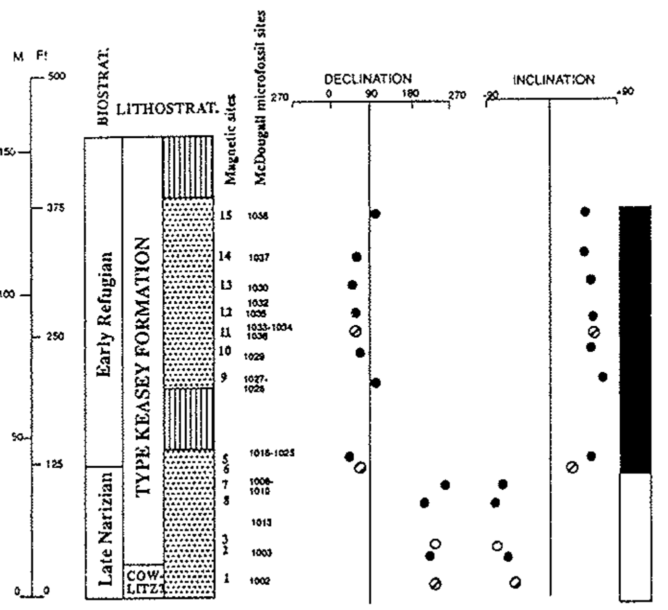

Figure 5. Magnetic stratigraphy of the type section of the Keasey Formation in Rock Creek (stratigraphy after *McDougall*, 1975). Vertically ruled intervals indicate portions of section which were covered and could not be sampled. Solid circles indicate Class I sites [*Opdyke et al.*, 1977], which are statistically distinct from a random distribution at the 95% confidence level; dashed circles are Class II sites [*Opdyke et al.*, 1977], in which one sample was missing or rejected, so statistics could not be calculated; open circles are Class III sites [*Opdyke et al.*, 1977], where one sample was divergent but the other two gave a clear indication of polarity.

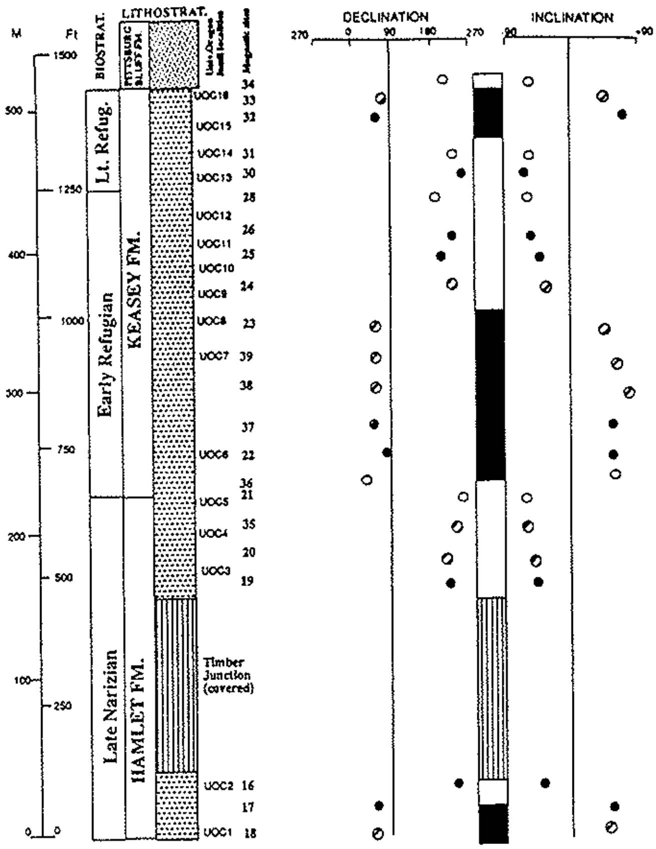

Figure 6. Magnetic stratigraphy of the Sunset Highway section (stratigraphy after *McDougall* [1975, 1979]). Symbols are as in Figure 5.

5. Discussion and Conclusions

5.1. Magnetic Correlations

Although the Keasey tuffs have repeatedly proven too altered for radioisotopic dating [W. Orr and C. Hedeen, personal communication, 1999], and there are no planktonic microfossils, correlation of the Keasey Formation with the magnetic polarity time scale [*Berggren et al.*, 1995] is still possible (Figure 7). The extensive Eocene-Oligocene section in the Lincoln Creek Formation in Canyon River on the south flank of the Olympic Mountains of Washington [*Prothero and Armentrout*, 1985] provides a reference standard for the Keasey section. In the Canyon River section, early Refugian benthic foraminifera and lower Keasey molluscs were associated with NP19-20 calcareous nannofossils and a zone of normal polarity which *Prothero and Armentrout* [1985] correlated with Chron C15n. We suggest that the basal Keasey normal magnetozone is also Chron C15n (34.6-35.0 Ma). The middle Refugian part of the Lincoln Creek Formation was correlative with Chron C13r (33.5-34.6 Ma) and, apparently, so is the middle part of the Keasey. The latest Refugian part of the Lincoln Creek Formation was correlated with Chron C13n since it is overlain by a long early Oligocene (Zemorrian) reversed magnetozone which best correlated with the long reversed Chron C12r. We suggest that the uppermost Keasey Formation is also correlative with Chron C13n (33.0-33.5 Ma). The Mist and Storage Locker sites are also probably correlative with Chron C13n, since they are considered "upper Keasey" [*Moore and Vokes*, 1953]. The Haydite Quarry locality is

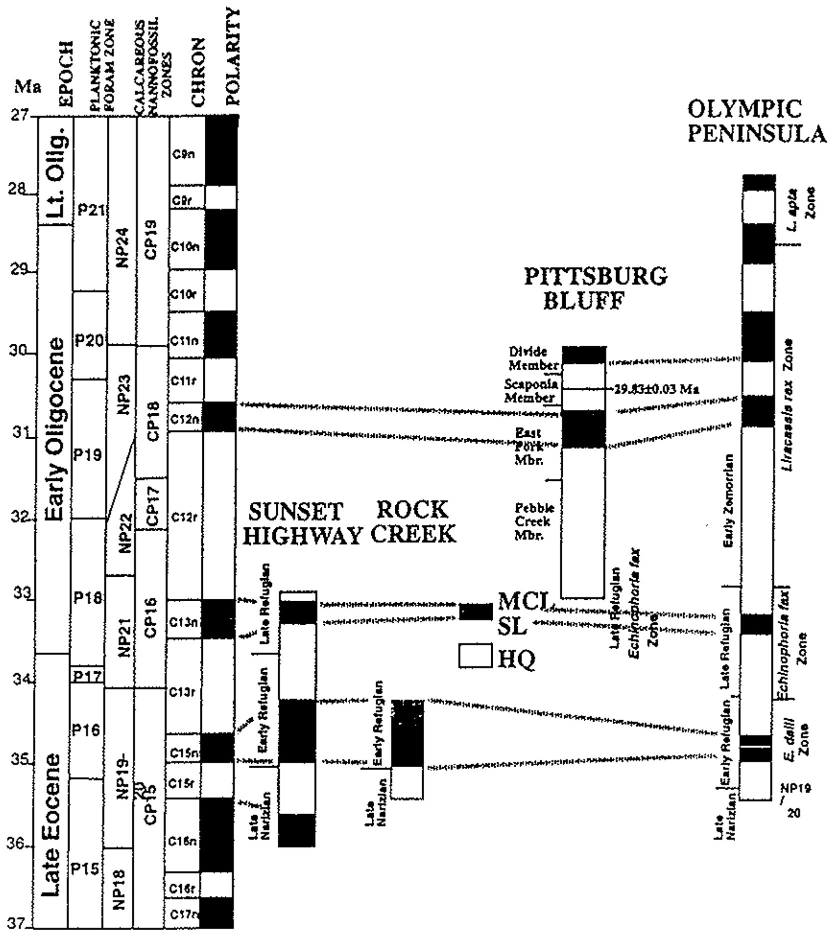

Figure 7. Correlation of the Keasey magnetozones with the Lincoln Creek Formation in Canyon River on the south side of the Olympic Mountains [*Prothero and Armentrout*, 1985], and with the global timescale [*Berggren et al.*, 1995]. HQ, Haydite Quarry; MCL, Mist Crinoid Locality; SL, Storage Locker. Pittsburg Bluff magnetic stratigraphy and $^{40}Ar/^{39}Ar$ date are after *Prothero and Hankins* [2000].

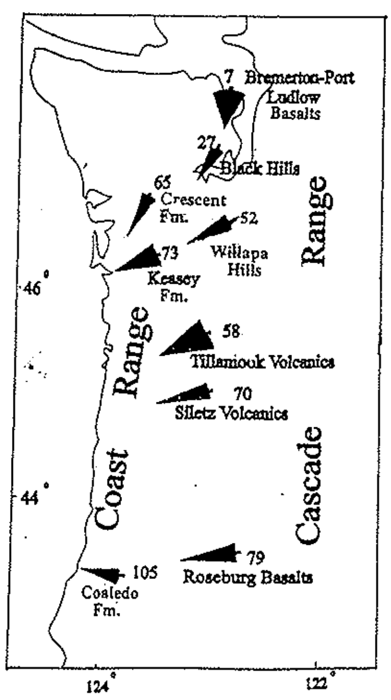

Figure 8. Comparisons of tectonic rotations reported from Eocene-Oligocene rocks in western Oregon and Washington. Line indicates mean rotation; error estimates are shown by wedge on either side of mean. Data are given in Table 1.

probably correlative with C13r, since it was considered "middle Keasey" [*Moore and Vokes*, 1953].

These correlations show that the Keasey Formation spans the interval from 33.0-35.6 Ma, or latest Eocene to earliest Oligocene, thus resolving the long controversy over whether the Keasey is Eocene or Oligocene or both. The Keasey Stage [*Weaver et al.*, 1944] straddles the Eocene/Oligocene boundary. In addition, this correlation is further proof of *McDougall's* [1980] contention that many of the Pacific Coast benthic foraminiferal stages were facies-dependent and time-transgressive. In the type section of the Refugian Stage in Cañada de Santa Anita in the Santa Ynez Range in Santa Barbara County, California, the Narizian/Refugian boundary falls in Chron C16r (and is associated with NP18 calcareous nannofossils), so it is 36.5 Ma in age [*Prothero and Thompson*, 2000]. In both the Keasey and Lincoln Creek Formations (as calibrated by NP19-20 nannofossils), the Nariz-

Table 1. Comparison of Paleomagnetic Rotations in Oregon and Washington

Rock Unit	D	I	N	Age, Ma	Rotation
Keasey Formation, OR	63.7	60.8	39	35	73 ± 6
Crescent volcanics, WA (Domain 7) [*Wells and 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 Formation, OR [*Prothero and Hankins*, 2000]	61.6	53.1	25	31	65 ± 12
Eocene intrusives, OR [*Beck and Plumley*, 1980]	44.5	62	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

ian/Refugian boundary falls late in Chron C15r (35.1 Ma), so it is ~1.4 million years younger than in the type section in Santa Barbara County, California.

Realignment of the Lincoln Creek and Keasey magnetostratigraphies with Chrons C15n-C17n might eliminate some of this time transgression, but it is contradicted by the fact that the lowest Lincoln Creek strata yield NP19-20 (not NP18) calcareous nannofossils and therefore cannot be older than Chron C16n (Figure 7) [*Prothero and Armentrout*, 1985]. In addition, this would also contradict the molluscan zonation which has never been suggested to be time transgressive. Instead, the simplest interpretation is that the planktonic microfossil and molluscan biostratigraphies are reliable, and that the time-transgression occurs only in the benthic foraminifera (as numerous workers have suggested for over 30 years).

5.2. Tectonic Rotation

Averaging the normal vectors with all the inverted reversed vectors gives a formational mean direction of $D = 63.7$, $I = 60.8$, $k = 17.3$, $\alpha_{95} = 5.7$ ($n = 39$). This inclination is ~5° shallower than the present day field in the region ($D = 19°$, $I = 66°$) or the equivalent Eocene paleolatitude [*Diehl et al.*, 1983], but it is statistically indistinguishable from the hypothesis of no latitudinal translation (given the 95% confidence limits). However, the declination is clearly distinct from the present or Eocene declination, suggesting ~73.7° ± 4.7° of clockwise tectonic rotation (correcting for inclination differences [*Demarest*, 1983]).

This result is compared to previous results from the region in Table 1 and Figure 8. At first glance, the Keasey rotation seems to be higher than other comparable rocks of this age. However, it is statistically indistinguishable from the nearest early-middle Eocene volcanic basement rocks, the Crescent volcanics in Domain 7 of *Wells and Coe* [1985], ~20 km north of the Keasey Formation, just across the Columbia River in southwestern Washington. The Keasey Formation seems considerably more rotated than the middle Eocene Tillamook volcanic basement, ~40 km to the south, until one examines the error limits of the data. On a stereonet (Figure 4), all of these results plot with virtually complete overlap of means and circles of confidence, so it is clear that these formations are showing the same degree of tectonic rotation.

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