MAGNETIC STRATIGRAPHY OF THE LOWER AND MIDDLE MIOCENE ASTORIA FORMATION, LINCOLN COUNTY, OREGON

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ABSTRACT

The Astoria Formation, one of the world's richest sections of Miocene fossiliferous marine rocks, crops out along seacliffs north and south of Yaquina Head at Newport, Oregon. It contains molluscs, crabs, marine mammals, and many other taxa, and in 1976 Warren Addicott made it the basis of his Newportian Molluscan Stage. The upper part of the formation north of Yaquina Head is 190 m thick, and the lower part south of the head is 130 m thick. A total of 59 paleomagnetic sites were spaced through the two parts of the section, which we think do not overlap, and a gap of several meters may lie between them. Most samples yielded a stable single-component remanence held in magnetite, occasionally overprinted with goethite. Six normal and five reversed magnetozones characterize the total Astoria Formation, and the top of the formation is normal in polarity. The formation is overlain by the Cape Foulweather (Gingko) Basalt, which has been dated at 15.4 ± 0.3 Ma. Two possible correlations are suggested. The radiometric date on this basalt suggests a correlation with Chron C5Cn1 to C6An1 (16.0-20.7 Ma). The early to middle Miocene age of the molluscan fossils suggests a correlation with Chron C5Bn2 to C6n (15.1-19.2 Ma).

INTRODUCTION

The first Cenozoic fossils described from the West Coast of North America were molluscs collected by J.K. Townsend between 1834 and 1837 from the Astoria Formation, near Astoria, Oregon. Conrad (1848) described these fossils and correctly realized that they were of Miocene age (even though the concept of Miocene was still poorly defined in the type areas of Europe at that time). Subsequently, many other collectors accumulated large samples of Astoria molluscs, and quite a few species were described (see review in Moore, 1963). According to Moore (1963), the Astoria Formation yields 73 genera and 97 species of molluscs, as well as marine mammals (especially cetaceans, pinnipeds, and desmostylians—see Ray, 1976), bryozoans, corals, echinoderms, brachiopods, crabs, fish, plants (including fossil logs), and benthic foraminifera of Saucesian (early to middle Miocene) age.

Although the original concept of the formation and its original collections came primarily from the type area near the town of Astoria, those exposures are now largely covered and inaccessible. Much better exposures now occur along the coasts of Tillamook and Lincoln Counties, Oregon, where they have been extensively studied and described by many geologists (Howe, 1926; Moore, 1963; Snavely et al., 1964, 1973, 1976), and more recently mapped in detail by A.R. and W.A. Niem.

In most places, the Astoria Formation consists of volcaniclastic sandstone and siltstone, deriving its clasts from the Cascade volcanics, or from eroded Columbia River Basalt. Numerous tuff layers have recently been mapped within the Astoria Formation around Yaquina Head. In many places, there are large concretions reaching 0.5 m in diameter, or concretionary layers; some of these contain large marine-mammal fossils. Glauconitic horizons are also common in the Astoria Formation, and large fossilized logs (of such taxa as *Metasequoia*) also occur in the formation. In other places, there are distinctive shell beds with complete articulated specimens (such as the arc shell, *Anadara devincta*), suggesting rapid burial of living molluscs. One of these shell beds, the *Anadara* layer (Moore, 1963, p. 17), can be traced for miles and serves as a local marker horizon in the stratigraphy.

In the Newport area, the Astoria Formation disconformably overlies the lower Miocene Nye Mudstone. The Astoria Formation is unconformably overlain by Pleistocene terrace deposits. In the Coos Bay area, however, the Astoria Formation unconformably overlies the lower Oligocene Tunnel Point Sandstone, and is unconformably overlain by the upper Miocene Empire Formation. In southwestern Washington, rocks referred to the Astoria Formation by Rau (1967) unconformably overlie the Lincoln Creek Formation and are unconformably overlain by the upper Miocene Montesano Formation.

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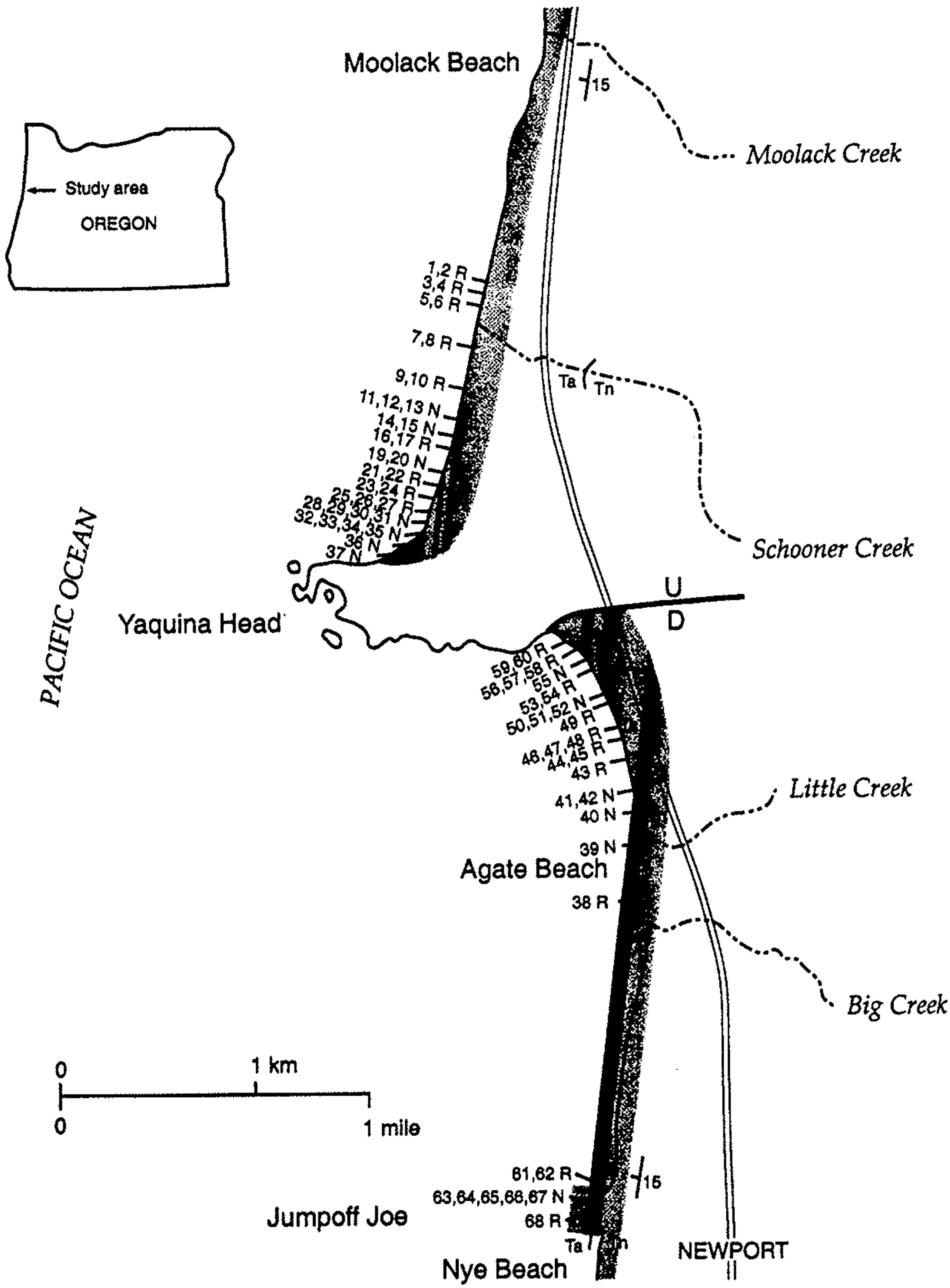

Figure 1. Index map showing the location of the sample sites near Newport, Oregon (N = normally magnetized; R = reversed). Normal and reversed magnetozones are shown (respectively) by dark and light gray stripes.

Addicott (1976a) erected the Newportian Molluscan Stage based on the Astoria fauna near Newport, Oregon, which he at that time assigned to the middle Miocene. Later, Moore and Addicott (1987) assigned the Newportian Stage to the late early and middle Miocene.

Benthic foraminifera from the Astoria Formation in the Astoria and Newport areas were analyzed by Mallory (in Moore, 1963, p. 26), who reported mostly Saucesian taxa. The Saucesian benthic foraminiferal stage in California also spans much of the early and probably some of the middle Miocene, so this does not increase the precision. Snavely et al. (1973) reported a range of dates from 13.7 to 16.3 Ma from the Cape Foulweather Basalt, which closely overlies the Astoria Formation at Newport. The Depoe Bay Basalt lies 50 m below the Cape Foulweather Basalt about 10 km to the north, but it does not reach the Astoria Formation in our study area. Wells et al. (1989) correlated the Cape Foulweather Basalt with the better dated Gingko Basalt of the Columbia River Plateau and obtained an age of 15.4 ± 0.3 Ma. Magnetic stratigraphy combined with several of these other chronostratigraphic data offers the potential of high-resolution dating of the Astoria Formation to the nearest 200,000 years.

METHODS

Sampling of the Astoria Formation (Fig. 1) followed sections published by Moore (1963), and unpublished sections by A.R. and W.A. Niem. Most samples were taken either from seacliff exposures or from resistant ridges and ledges on the modern wave-cut marine terrace accessible at very low tide. Sites were located every 10-30 m in the section, depending upon exposure, although several large gaps in the sampled section were unavoidable. Samples were collected with simple hand tools as oriented blocks of rock in the field, then subsampled into cylinders with a drill press in the laboratory. Some samples that were too small to be cored were cast into cylinders using Zircar aluminum ceramic.

The lower part of the Astoria Formation and the upper part of the Nye Mudstone were sampled along Agate Beach, from the mouth of Little Creek to the south flank of Yaquina Head (section D of Moore, 1963, plate 33). This section spans approximately 130 m (430 feet) in 23 sites. It runs from NW NW section 32 to NW NW section 29, T10S R11W, Newport North 7.5' Quadrangle, Lincoln County, Oregon. The Nye-Astoria contact was also sampled at a local promontory known as Jumpoff Joe, just north of Nye Beach, SW NW section 5, T11S R11W, in the Newport North 7.5' Quadrangle. At that location, eight sites were taken, spanning about 60 m (200 feet) of section.

The upper part of the formation was sampled along Moolack Beach from north of Schooner Creek (beginning just below the distinctive *Anadara* layer) to the north flank of Yaquina Head, where the section is capped by invasive dikes and flows of the Cape Foulweather Basalt. This section spans about 190 m (620 feet) with 35 sites, and runs from NW SW section 20 to center section 30, T10S R11W, Newport North 7.5' Quadrangle.

In the paleomagnetics laboratory of the California Institute of Technology, samples were measured in a 2G Enterprises cryogenic magnetometer with an automatic sample changer. After measurement at NRM (natural remanent magnetization), each sample was AF (alternating field) demagnetized at 25, 50, and 100 Gauss to determine the coercivity spectrum, and to demagnetize any multidomain grains before they were heated and their remanence was locked in. Each sample was then thermally demagnetized in multiple steps from 300 to 600°C to remove any chemical remanence caused by an iron hydroxide such as goethite, and to determine how much remanence was left above the Curie temperature (580°C) of magnetite.

About 0.1 g of powdered rock from several samples was 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 (Pluhar et al., 1991).

RESULTS

Orthogonal demagnetization ("Zijderveld") plots of four representative samples are shown in Figure 2. In these samples, there is relatively little response to AF demagnetization, suggesting that the remanence is held largely in a high-coercivity mineral such as hematite or in an iron hydroxide such as goethite. The abrupt decrease in intensity at 300°C (above the dehydration temperature of goethite) suggests that much of this high-coercivity remanence is indeed held in iron hydroxides. In a few samples (for example, Fig. 2D), thermal demagnetization at 300°C removed a normal overprint to reveal a stable reversed direction. In nearly every sample the remanence was almost completely gone by 500°C, which is more consistent with a mineral such as magnetite, which has a Curie temperature of 580°C. Thus, it seems likely that the remanence is held mainly in magnetite or possibly minor hematite, with chemical overprinting by goethite or other iron hydroxides.

Representative IRM acquisition analyses are shown in Figure 3. Most samples showed near saturation at 300 mT (millitesla), suggesting that the

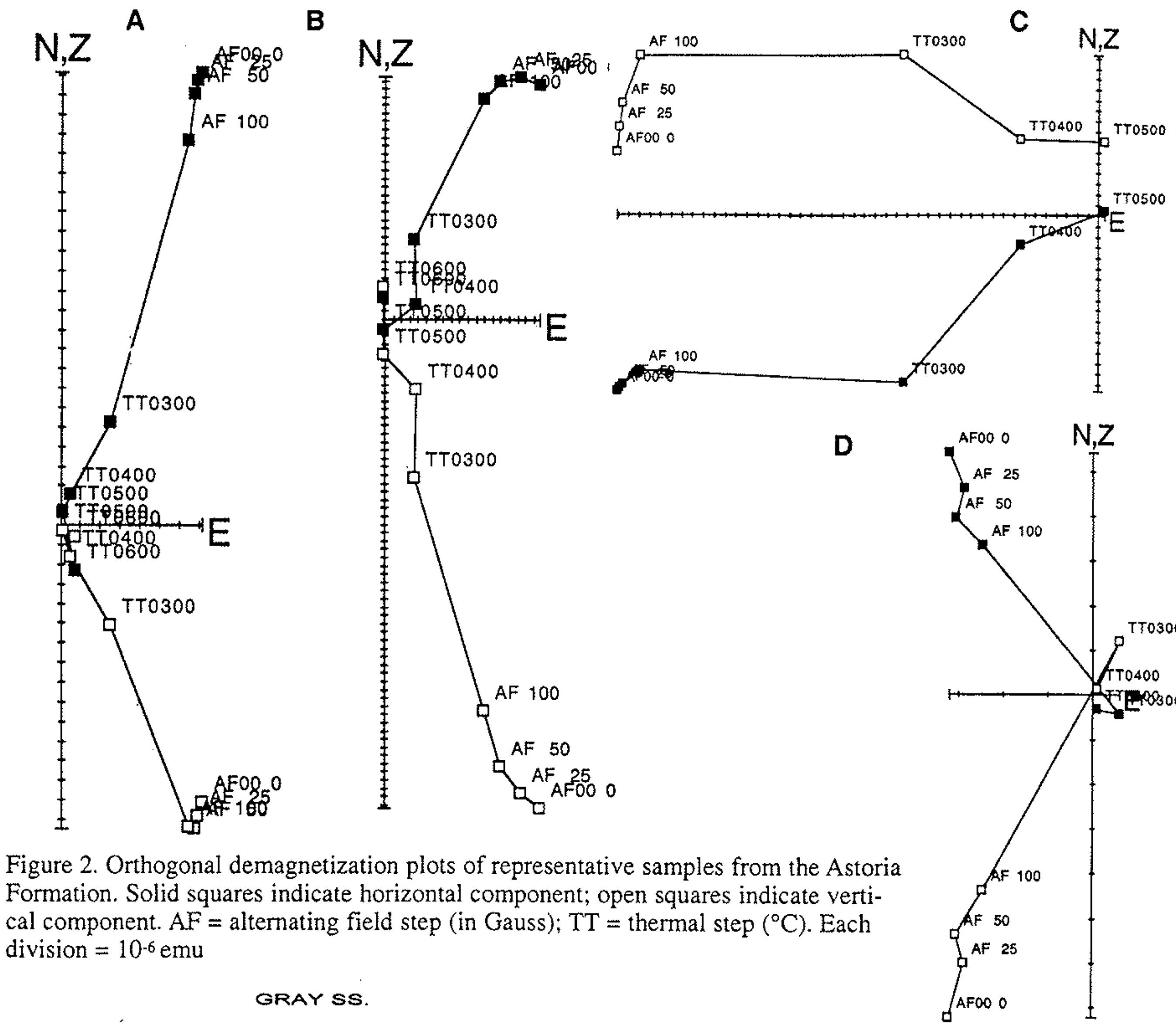

Figure 2. Orthogonal demagnetization plots of representative samples from the Astoria Formation. Solid squares indicate horizontal component; open squares indicate vertical component. AF = alternating field step (in Gauss); TT = thermal step (°C). Each division = 10^{-6} emu

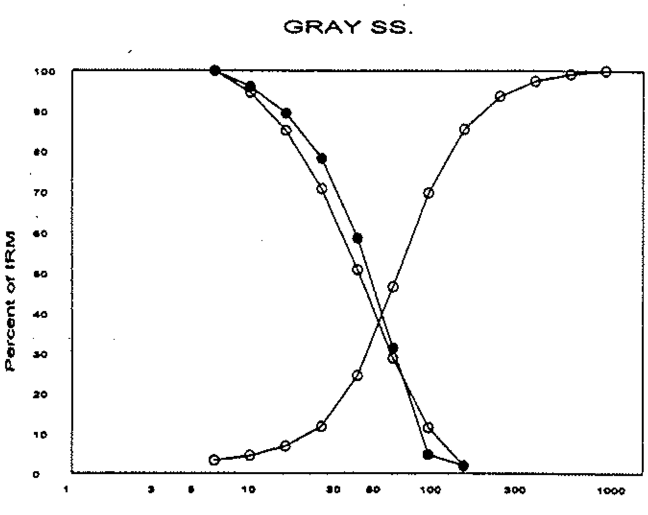

Figure 3. IRM acquisition (ascending curve on right) and Lowrie-Fuller test (two descending curves on left) of representative powdered samples from the Astoria Formation. Open squares = IRM; solid squares = ARM.

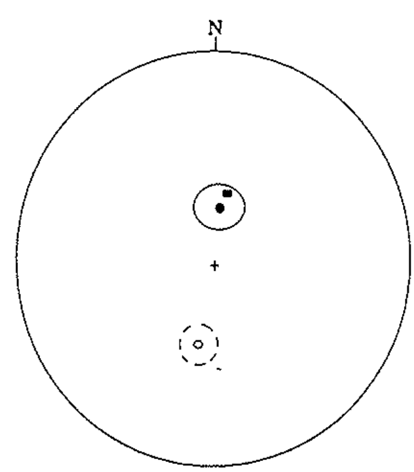

Figure 4. Equal area stereoplot of mean poles and circles of confidence for the data discussed in this study. The solid circle indicates lower hemisphere projections; dashed lines and open circles indicate upper hemisphere projections.

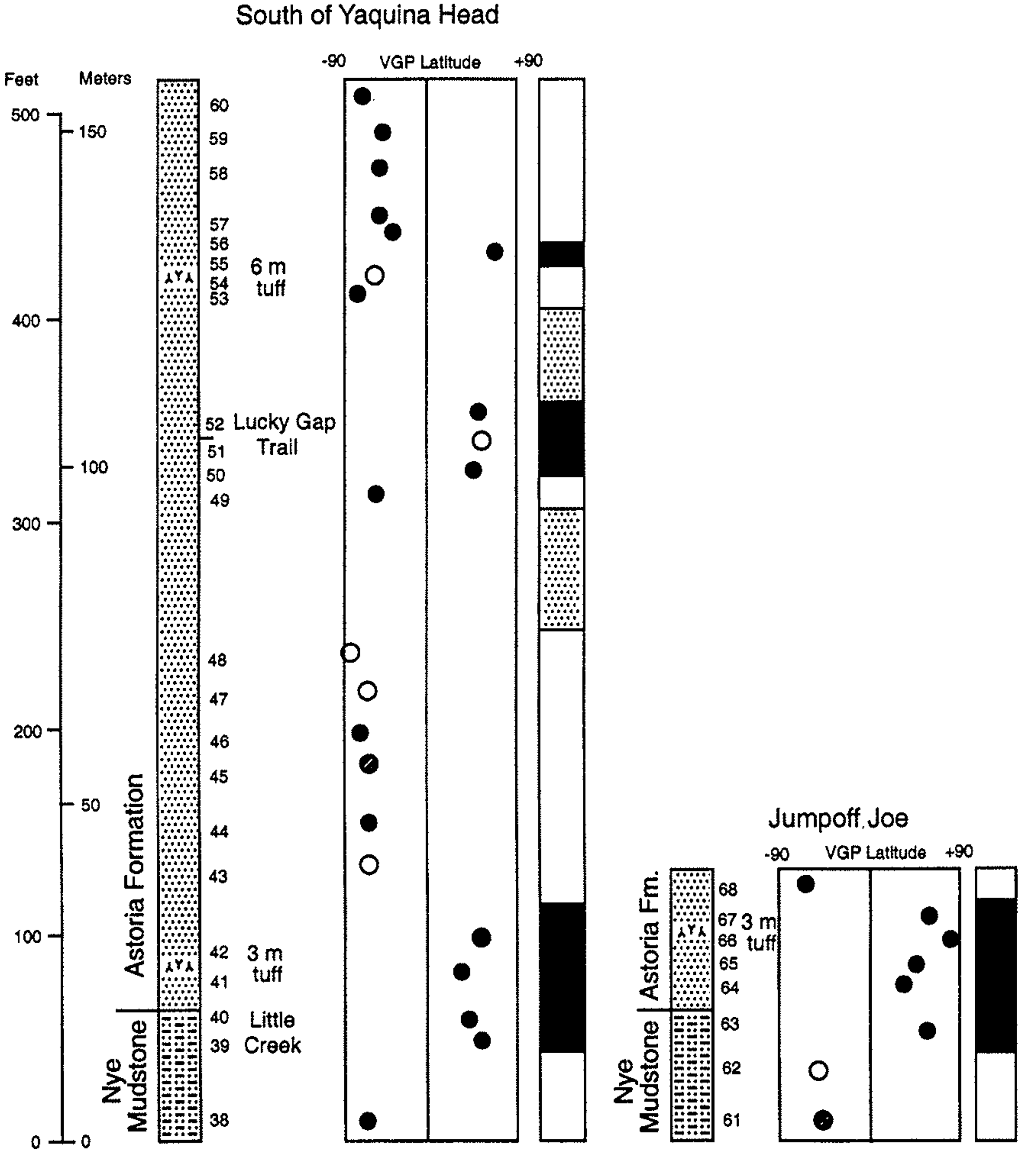

Figure 5. Lithostratigraphy and magnetic stratigraphy of the Nye and Astoria Formations at Agate Beach, south of Yaquina Head, and at Jumpoff Joe. Stratigraphy of the Agate Beach section after Moore (1963, plate 33). Numbers indicate magnetic sites. Solid circles indicate Class I sites (Opdyke et al., 1977), which are statistically distinct from a random distribution at the 95% confidence level; circles with diagonal patterns are Class II sites, in which one sample was missing, 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. VGP = virtual geomagnetic pole latitude.

remanence is held largely in magnetite, although the continuing increase in IRM suggests some hematite was present as well. In most samples, the ARM was more resistant to AF demagnetization than the IRM, suggesting that the remanence is held in single-domain or pseudo-single-domain grains.

Once the overprinting had been removed and a stable component was isolated, each direction was summarized using the least squared method of Kirschvink (1980), and averaged using Fisher (1953) statistics. Each site was then ranked according to the scheme of Opdyke et al. (1977). Of the 67 sites, 45 were statistically separated from a random distribution at the 95% confidence level (Class I sites of Opdyke et al., 1977). Nine sites had only two usable samples, so no site statistics could be calculated (Class II sites of Opdyke et al., 1977). The remaining 13 sites showed a clear polarity preference, but the third sample was divergent (Class III sites of Opdyke et al., 1977).

Although there is a homoclinal dip of about 15° in the sequence, the dips were not variable enough to conduct a fold test. However, the mean of all normal sites was $D = 7.3$, $I = 51.0$, $k = 9.3$, $\alpha_{95} = 9.1$, $n = 30$; the mean for all reversed sites was $D = 188.9$, $I = -45.3$, $k = 14.7$, $\alpha_{95} = 6.5$, $n = 37$. These directions are antipodal (Fig. 4) within error estimates, and pass a Class A reversal test of McFadden and McElhinny (1980) ($\gamma_c = 4.7°$). Thus, the overprints seem to have been removed, and a primary or characteristic remanence has been isolated.

The mean direction for the formation (adding in the inverted reversed directions) is $D = 3.3$, $I = 48.1$, $k = 16.5$, $\alpha_{95} = 8.3$, $n = 20$. Within error limits, this direction is indistinguishable from the present day and the Miocene pole position (Diehl et al., 1983), although its range from 8° counterclockwise to 13° clockwise comes close to overlapping with the clockwise rotation that has been reported for the overlying Cape Foulweather (Gingko) Basalt (Wells et al., 1989). The mean inclination of $48.1 \pm 8.3°$ gives a paleolatitude of 23-37°, which is statistically distinct from the present latitude of 47°. At face value, this suggests that 10-26° of northward translation has taken place. However, the possibility of inclination flattening in these compacted fine-grained sedimentary rocks cannot be ruled out (Kodama and Davi, 1995).

The magnetic stratigraphy of the Astoria Formation is shown in Figures 5 and 6. At both Jumpoff Joe and the Agate Beach section south of Yaquina Head (Fig. 5), the Nye-Astoria contact lies within a 30-m-thick normal magnetozone, with rocks of reversed polarity above and below it. Most of the lower Astoria Formation sampled south of Yaquina Head is of reversed polarity, except for a short normal magnetozone at about 90-105 m in the section. The upper Astoria Formation along Moolack Beach and from Schooner Creek to the north flank of Yaquina Head (Fig. 6) was of reversed polarity at the base, with two short normal magnetozones. The rest of the section, from about 85 m to the top of the north of Yaquina Head section, is entirely of normal polarity.

Each of these partial sections can be linked by distinctive marker horizons. The Jumpoff Joe section and the section south of Yaquina Head can be aligned along the Nye-Astoria contact (Fig. 6), and they show a consistent magnetic pattern in the interval of section overlap. Based on projections of the dip through Yaquina Head, the top of the section south of Yaquina Head nearly overlaps with the base of the section to the north, giving an almost complete composite section through the Astoria Formation in this area. The top of the Astoria Formation contains several thin beds of basaltic sand. If these were derived from the Depoe Bay Basalt, then the upper part of the Astoria at Yaquina Head probably correlates with the Whale Cove Sandstone, which is sandwiched between the Depoe Bay and Cape Foulweather Basalts at the City of Depoe Bay.

DISCUSSION

This composite magnetic pattern is summarized (Fig. 7) as a normal magnetozone at the Nye-Astoria contact, a long reversed magnetozone (with short normal intervals within it) through the lower Astoria, and a long normal magnetozone in the upper Astoria (Fig. 6).

The radioisotopic date from the closely overlying Cape Foulweather Basalt spans an age between 15.1-15.7 Ma (Wells et al., 1989). This suggests a correlatioin of the upper normal magnetozone north of Yaquina Head with Chron C5Bn2 or possibly C5Cn1. In turn, the normal magnetozone at the Nye-Astoria contact would then correlate with either Chron C6n (19.2 Ma) or C6An1 (20.7 Ma). This places the Nye-Astoria contact below the early to middle Miocene boundary, which is consistent with the molluscan and benthic foraminiferal biostratigraphy that suggests the Nye is early Miocene, and the Astoria is early and middle Miocene.

Although this interpretation is not constrained by ironclad calibration points, it is a parsimonious interpretation of our data. If the composite Nye-Astoria section were shifted into older magnetozones (for example, chorn C6An1), it would make much or all of the Astoria early Miocene, which is inconsistent with the molluscan biostratigraphy. If it were shifted into younger magnetozones in the middle Miocene (for example, chrons C5Cn3 to C5ADn), it would make the Nye Mudstone middle Miocene, which is also inconsistent with the molluscan biostratigraphy,

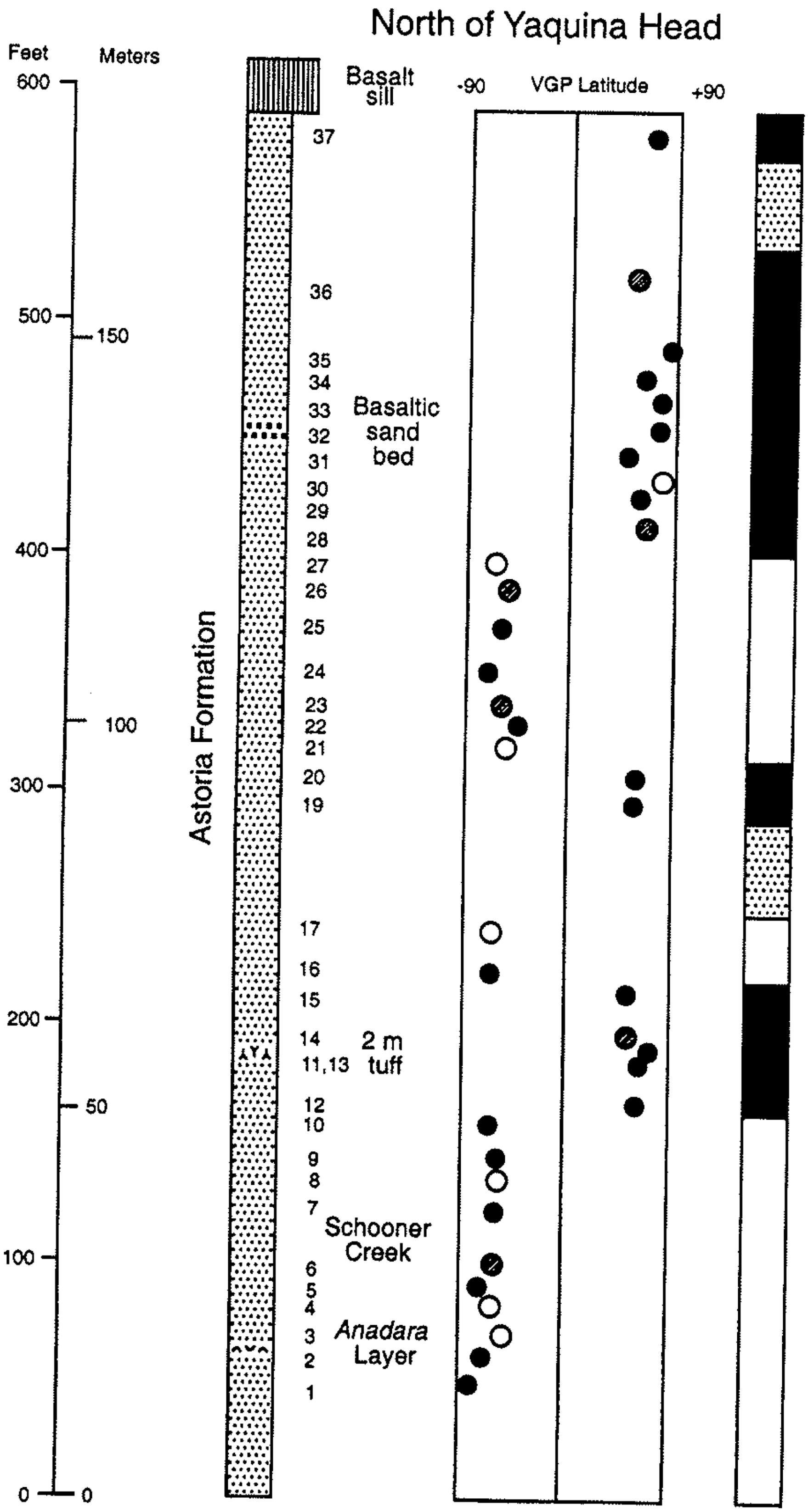

Figure 6. Stratigraphy and magnetic stratigraphy of the Moolack Beach and Schooner Creek section north of Yaquina Head. All conventions as in Figure 5.

and also conflicts with the radiometric constraints on the Cape Foulweather Basalt. Thus, we feel these interpretations are the simplest and the most consistent with the available data.

Rau (1967, p. 18) described a limited outcrop of marine siltstone exposed along the south flank of the Olympic Mountains. Because these strata are lithologically similar to the Astoria Formation and contain similar molluscs and foraminifera, he referred these strata to the Astoria(?) Formation [query in the original]. In the Canyon River section, the Astoria(?) Formation contains Saucesian benthic foraminifera, whereas in the Wishkah River area, the benthic foraminifera are Relizian in age. Fowler (1965) reported that the limited planktonic foraminifera from this section are representative of the early Miocene Aquitanian Stage. However, Barron (1981) reported a diatom assemblage from 10 m below the top of the Astoria(?) Formation on the Middle Fork of the Wishkah River. It contains taxa that are indicative of Diatom Zones XIX or XXI-XXII of Barron (1976), which span the interval from about 13 to 14.5 Ma on the global time scale. This suggests that the upper Astoria(?) Formation in Washington might be slightly younger than it is in the Newport Embayment in Oregon, although the Aquitanian and Saucesian foraminifera in the lower part of the formation probably overlap the Oregon strata in age.

Finally, Addicott (1976a, b) and Moore and Addicott (1987) pointed out that the molluscs from the type exposures of the Astoria Formation near Astoria, Oregon, indicate an early Miocene (Pillarian) age for the lower part of these rocks, and an early to middle Miocene (Newportian) age for the upper part, so they probably have a longer total range than the Astoria exposures in the Newport Embayment.

CORRELATION OF KEY VERTEBRATE LOCALITIES WITHIN THE ASTORIA FORMATION

The Astoria outcrops along the coast north of Newport have long produced many marine vertebrate fossils. The richest area has long been the famous "Iron Mountain bed", which yielded many important marine mammals for Douglas Emlong and later collectors. According to Charles Repenning, Larry Barnes, and others who have collected it since, it is an area of light-brown to dark-gray sandstone nodules west of Iron Mountain exposed in the sea cliffs north of Schooner Creek and just south of Moolack Beach (Fig. 1), just north of our northernmost paleomagnetic site (sites 1-2). It produces marine mammals such the enaliarctine pinnipeds *Desmatophoca oregonensis* (Condon, 1906), *Pteronarctos piersoni* (Barnes, 1990), and *Pacificotaria hadromma* (Barnes, 1992), the primitive walrus *Proneotherium repenningi* (Barnes, 1995), the desmostylian *Desmostylus* (Mitchell and Repenning, 1963), the whale *Cophocetus oregonensis* (Packard and Kellogg, 1934), and even land mammals, including the dome-skulled chalicothere *Tylocephalonyx* and the rhinoceros *Aphelops* (Munthe and Coombs, 1979; Coombs, 1979). Based on the fact that the Iron Mountain bed lies to the north and along strike with our reversed magnetozone running from sites 1-8 (Fig. 1), we correlate these fossils with Chron C5Cr (16.6-17.3 Ma). The other major vertebrate locality in our sampled area is Jumpoff Joe, which produced the enaliarctine pinniped *Pteronarctos goedertae* (Barnes, 1989). Based on our correlations, it came from the normal magnetozone that we correlate with Chron C6n, so it is about 19.1-20.2 Ma in age. In addition, the Astoria Formation yields the teeth of at least five genera of sharks (Welton, 1972), as well a number of fossil birds (Moore, 1963) and a sea turtle (Packard, 1940).

CONCLUSION

The Astoria Formation in the Newport Embayment, northwestern coast of Oregon, yields a stable magnetic remanence held mainly in magnetite with minor overprinting by iron hydroxides. It passes a reversal test, and shows either no significant tectonic rotation, or a slight clockwise rotation, consistent with Miocene rocks reported elsewhere in the region. Based on the radiometric age of the overlying Cape Foulweather Basalt, and the biostratigraphic constraints of molluscs and benthic foraminifera, we correlate the magnetostratigraphy of the Astoria Formation with either magnetic Chrons C6n-C5Bn2 (19.2-15.1 Ma) or C6An2-C5Cn1 (20.7-16.0 Ma). This makes the Astoria Formation late early to early middle Miocene in age. This is younger than the lower part of the type Astoria exposures near Astoria, and slightly older than the referred Astoria(?) strata reported on the south flank of the Olympic Mountains in Washington, although the lower part of those beds may overlap in age with those in Oregon.

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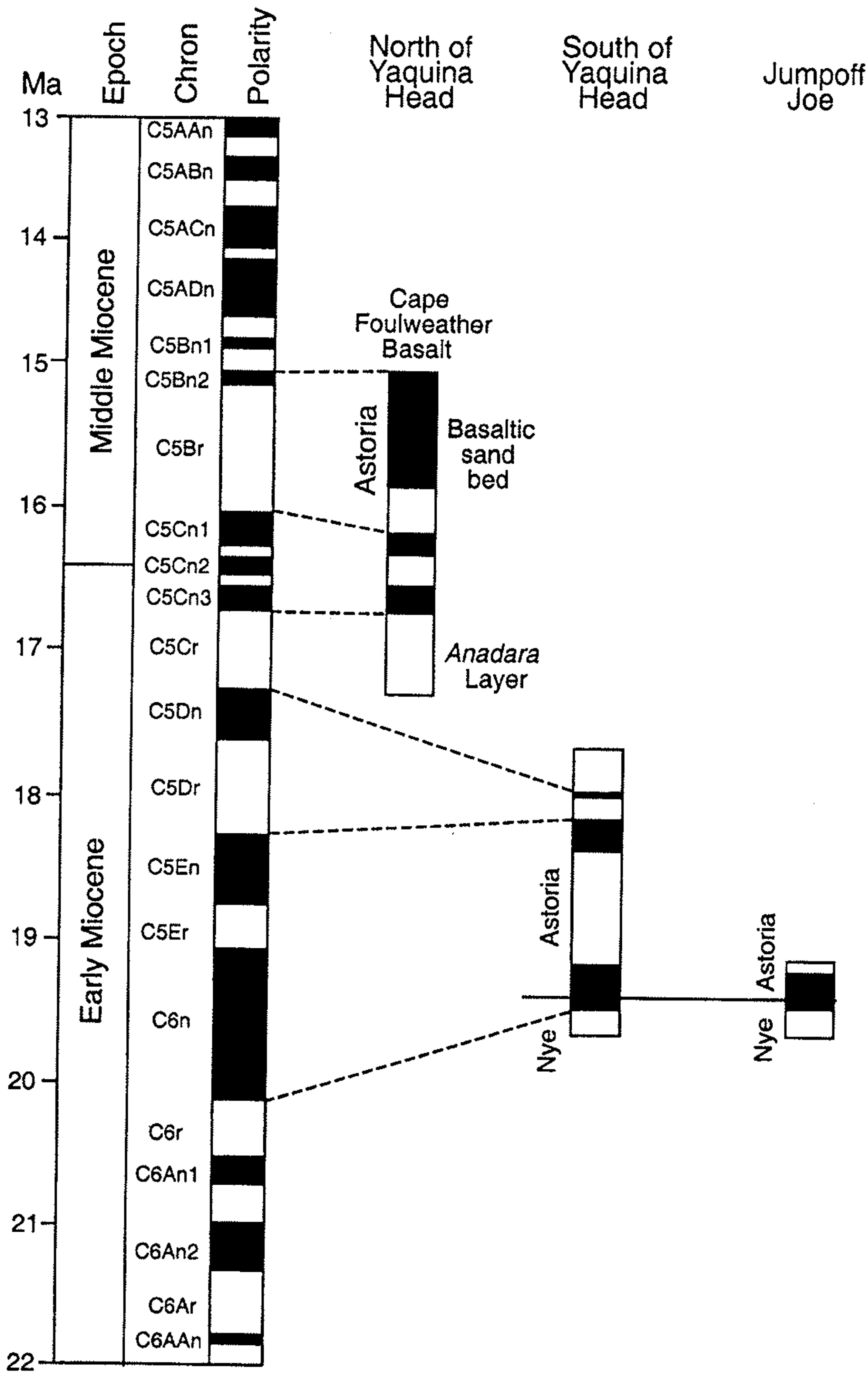

Figure 7. Preferred correlation of the Astoria Formation with the magnetic polarity time scale (Berggren et al., 1995).

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TABLE 1—Summary of site statistics

SITE NUMBER	N	D	I	k	α_{95}
1	3	185.9	-62.3	26.4	24.5
2	3	170.5	-43.4	13.5	34.9
3	3	226.1	-37.5	3.4	80.5
4	3	197.7	-28.1	3.0	90.7
5	3	206.3	-50.7	28.5	23.5
6	2	191.5	-27.5	3.5	180.0
7	3	166.8	-30.0	10.2	40.7
8	3	157.2	-38.4	4.1	71.4
9	3	169.0	-32.9	13.0	35.6
10	3	169.3	-54.4	5.2	61.0
11	3	27.1	51.4	51.5	17.4
12	3	335.1	73.1	32.2	22.1
13	3	8.5	44.3	18.9	29.2
14	2	356.7	42.5	3.6	180.0
15	3	19.9	21.5	7.1	50.0
16	3	182.9	-50.4	18.8	29.3
17	3	161.2	-56.7	4.0	72.6
19	3	29.5	52.1	17.2	30.6
20	3	13.8	35.6	24.4	25.5
21	3	226.4	-55.1	5.0	62.1
22	3	235.1	-40.0	106.8	12.0
23	2	188.2	-29.7	6.6	123.5
24	3	170.5	-64.6	6.0	55.3
25	3	219.0	-35.3	6.9	50.8
26	2	179.2	-21.3	65.8	31.3
27	3	194.52	-50.8	4.4	67.5
28	2	13.6	52.6	7.4	112.3
29	3	24.9	47.4	26.8	24.3
30	3	12.1	59.2	5.1	61.2

TABLE 1—Summary of site statistics (cont.)

SITE NUMBER	N	D	I	k	α_{95}
31	3	33.3	40.1	19.4	28.8
32	3	348.5	56.5	15.7	32.3
33	3	357.6	58.2	29.8	23.0
34	3	349.3	34.2	11.7	37.8
35	3	359.4	57.2	12.0	37.2
36	2	22.0	50.3	15.2	69.4
37	3	359.9	42.7	29.1	23.3
38	3	207.9	-45.1	13.2	35.4
39	3	10.3	46.3	14.9	33.2
40	3	13.9	36.8	12.4	36.6
41	3	6.3	12.6	119.2	11.3
42	2	9.6	36.6	8.5	101.2
43	3	155.4	-40.2	4.4	67.8
44	3	201.7	-37.5	6.1	54.9
45	2	209.8	-42.4	5.3	177.9
46	3	165.8	-38.4	6.7	51.8
47	3	178.5	-33.6	3.7	75.7
48	3	185.2	-62.0	3.8	75.1
49	3	153.3	-33.4	25.2	25.1
50	2	23.0	53.2	69.4	30.4
51	3	9.8	36.9	4.4	67.3
52	3	352.0	31.2	6.0	55.5
53	3	199.4	-71.6	17.8	30.1
54	3	136.7	-52.0	3.0	89.7
55	3	351.3	49.8	10.1	41.0
56	3	249.2	-49.3	6.4	53.4
57	2	209.1	-42.0	8.2	103.3
58	3	204.8	-31.2	8.4	45.4
59	3	211.9	-43.7	9.8	41.8
60	3	178.6	-38.5	7.3	49.4
61	2	173.4	-30.0	6.5	126.2
62	3	193.0	-37.3	3.1	87.1
63	3	3.7	42.3	61.5	15.9
64	3	47.8	41.1	21.3	27.4
65	3	327.8	42.5	5.2	61.0
66	3	3.0	54.4	6.9	51.2
67	3	334.5	57.1	6.8	51.3
68	3	168.9	-24.9	7.2	49.6