Geology and Vertebrate Paleontology of Western and Southern North America

Edited By Xiaoming Wang and Lawrence G. Barnes

Contributions in Honor of David P. Whistler
Paleomagnetism of the Oligocene and Miocene Lincoln Creek and Astoria formations, Knappton, Washington

Donald R. Prothero,1,2 Jonathan M. Hoffman,3 and James L. Goedert2,4

ABSTRACT. The upper Oligocene Lincoln Creek Formation and the lower Miocene Astoria Formation, exposed on the north bank of the Columbia River near Knappton, Washington, have long been important localities for marine fossils. Oriented magnetic samples were taken at low tide from 12 sites spanning the exposed parts of both formations and analyzed by both thermal and alternating field demagnetization. The characteristic remanence was held primarily in magnetite, with minor amounts of goethite overprinting. Both reversed and normal polarities were obtained, and they passed a reversal test for stability. The rocks show a mean direction of $D = 67.2, I = 62.5, k = 5.8, a_95 = 11.3$, which suggests almost $77 \pm 11$ degrees of clockwise tectonic rotation, consistent with other results reported for the region, but they show no significant latitudinal translation. The lower part of the Lincoln Creek Formation is reversed in polarity, followed by a short normal magnetozone. The contact between the two formations is covered, but the available exposures of the Astoria Formation are entirely reversed in polarity. On the basis of the presence of late Oligocene molluscan faunas (*Liracassis apta* Zone) and correlation with the magnetic stratigraphy of the Lincoln Creek Formation at Canyon River on the south flank of the Olympic Mountains, we correlate the Knappton section of the Lincoln Creek Formation with either Chrons C7Ar–C6Cn2r (25.7–23.3 Ma) or C7r–C6Cn2r (25.4–23.3 Ma). The age of the Astoria reversed magnetozone is poorly constrained, and it could be as young as 20 Ma (million years before present). The locations of key fossil horizons within this stratigraphic sequence are discussed.

INTRODUCTION

Fossiliferous rocks of the Lincoln Creek and Astoria formations near the now-defunct cement plant and sawmill at the abandoned town site of Knappton, Washington, are exposed at low tide on the north bank of the Columbia River, across from Astoria, Oregon (Fig. 1). They were first mapped by Weaver (1937), later mapped in more detail by Wells (1979, 1989), and described further by Moore (1984a). According to Moore (1984a), several different fossiliferous levels are within the Lincoln Creek sequence. The lowest, Unit I (LACMIP 5844; Natural History Museum of Los Angeles County, Department of Invertebrate Paleontology), contains abundant goose-neck barnacles, which were described by Zullo (1982). Unit II (LACMIP 5843) contains many decapod crustaceans (not yet described). Unit III (LACMIP 5852) contains glass sponges described by Rigby and Jenkins (1983). Unit IV (LACMIP 5842) is known as the *Aturia* bed because of the abundance of the nautiloid *Aturia* (Bronn, 1838). Fossils from the Lincoln Creek Formation near Knappton have also been illustrated, described, or both in a number of other reports (e.g., Rathbun, 1926; Miller, 1947; Moore, 1984b, 1988; Squires, 1989; Goedert and Squires, 1993; Squires and Goedert, 1994), as well as in a brief summary of the fish fossils by Welton (in Moore, 1984a:7).

In the overlying Astoria Formation are several LACM localities, including the type locality of the desmatophocine otarioid pinniped *Desmatophoca brachycephala* Barnes, 1987. Fossil crabs have also been reported from the Astoria Formation near Knappton (Berglund and Goedert, 1992; Schweitzer and Salva, 2000). Not only are the Knappton localities the source of many of Los Angeles County, Department of Invertebrate Paleontology, contains abundant goose-neck barnacles, which were described by Zullo (1982). Unit II (LACMIP 5843) contains many decapod crustaceans (not yet described). Unit III (LACMIP 5852) contains glass sponges described by Rigby and Jenkins (1983). Unit IV (LACMIP 5842) is known as the *Aturia* bed because of the abundance of the nautiloid *Aturia* (Bronn, 1838). Fossils from the Lincoln Creek Formation near Knappton have also been illustrated, described, or both in a number of other reports (e.g., Rathbun, 1926; Miller, 1947; Moore, 1984b, 1988; Squires, 1989; Goedert and Squires, 1993; Squires and Goedert, 1994), as well as in a brief summary of the fish fossils by Welton (in Moore, 1984a:7).

In the overlying Astoria Formation are several LACM localities, including the type locality of the desmatophocine otarioid pinniped *Desmatophoca brachycephala* Barnes, 1987. Fossil crabs have also been reported from the Astoria Formation near Knappton (Berglund and Goedert, 1992; Schweitzer and Salva, 2000). Not only are the Knappton localities the source of many
important specimens in the LACM (Natural History Museum of Los Angeles County) collections, but they could also be of historical importance as well. Some of the first fossils from the West Coast of North America, collected by J.D. Dana with the Wilkes Exploring Expedition, might have been found in Knappton outcrops (Weaver, 1942:76).

However, the ages of these strata and fossils are still not well constrained. Zullo (1982) assigned the Lincoln Creek sequence to the upper part of the \textit{Liracassis apta} Zone (Moore, 1984b, 1988) and suggested that it is earliest Miocene in age. She indicated that most of the mollusks belong to the Juanian Molluscan Stage (of Addicott, 1976a, 1976b), although the assemblage has strong resemblances to the overlying early Miocene Pillararian Stage. Squires and Goedert (1994) assigned the sequence a tentative age range of latest early Oligocene to earliest late Oligocene on the basis of the presence of specimens of \textit{Liracassis} Moore, 1984b, that appear to be transitional between \textit{Liracassis rex} (Tegland, 1931) and \textit{L. apta} (Tegland, 1931).

In the last two decades, considerable progress has been made in dating the marine rocks of the Pacific Northwest. Through the use of planktonic microfossils and magnetic stratigraphy, most of the key sections have now been dated and correlated to the global timescale of Berggren et al. (1995). The longest, most complete section through the Lincoln Creek and Astoria formations, at Canyon River on the southern Olympic Peninsula of Washington, was studied by Prothero and Armentrout (1985). The type section of the Juanian Molluscan Stage in the Pysht Formation (Durham, 1944) was studied by Prothero et al. (2001c), and the type section of the Pillararian Stage in the Clallam Formation was studied by Prothero and Burns (2001). Correlative sections in the Yaquina Formation and Nye Mudstone in Oregon were studied by Prothero et al. (2001b), and in the overlying Astoria Formation by Prothero et al. (2001a). With the use of these sections as standards, it should now be possible to further refine the age of the Knappton localities with magnetic stratigraphy.

**METHODS AND MATERIALS**

The stratigraphic section follows the measurements of George Moore (personal communication) and the descriptions and photographs in Moore (1984a). A map of the localities is shown in Figure 2. Samples were collected during low tide in the summer of 2001 with the use of simple hand tools to recover oriented blocks of rock (three samples per site to obtain site statistics). Oriented cores were then drilled from the blocks with a drill press or prepared from smaller pieces of rock with Zircar aluminum oxide ceramic. The samples were measured on a 2G cryogenic magnetometer at the California Institute of Technology with the use of an automatic sample changer. After measurement of natural remanent magnetization (NRM), each sample was demagnetized in alternating fields (AFs) of 25, 50, and 100 gauss to determine the coercivity behavior (and magnetite content) of the samples and demagnetize any multidomain grains before their remanence was baked in. After AF demagnetiza-
tion, each sample was then thermally demagnetized at 50°C steps from 200° to 600°C to remove any chemical remanence held by iron hydroxides such as goethite and to determine whether any remanence held by hematite remained after the Curie point of magnetite (580°C) had been exceeded.

About 0.1 g of powdered rock from several samples was subjected to increasing isothermal remanent magnetization (IRM) to determine their IRM acquisition behavior, and thus the relative abundance of magnetite or hematite. They were also AF demagnetized twice: once after having acquired an IRM produced in a 100-mT (milli-tesla) 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), which indicates whether single or multidomain grains are present.

Fossils of taxa mentioned in the text are deposited in the collections of the LACM, the UWBM (Burke Museum of Natural History and Culture), or both.

ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AF</td>
<td>Alternating fields</td>
</tr>
<tr>
<td>IRM</td>
<td>Isothermal remanent magnetization</td>
</tr>
<tr>
<td>LACM</td>
<td>Department of Vertebrate Paleontology, Natural History Museum of Los Angeles County, Los Angeles, California USA</td>
</tr>
<tr>
<td>LACMIP</td>
<td>Natural History Museum of Los Angeles County, Department of Invertebrate Paleontology locality</td>
</tr>
<tr>
<td>NRM</td>
<td>Natural remanent magnetization</td>
</tr>
<tr>
<td>UWBM</td>
<td>Burke Museum of Natural History and Culture, University of Washington, Seattle, Washington USA</td>
</tr>
</tbody>
</table>

RESULTS

Orthogonal demagnetization ("Zijderveld") plots of representative samples are shown in Figure 3. In most samples, there is a dramatic response to AF demagnetization, suggesting that the remanence is held largely in a low-coercivity mineral such as magnetite, although the slight decrease in magnetization in the first AF steps suggests a minor overprinting by an iron hydroxide such as goethite. The abrupt decrease in intensity at 200°C (above the dehydration temperature of goethite) suggests the removal of a high-coercivity remanence held in iron hydroxides. In a few samples (e.g., Fig. 3C), thermal demagnetization at 200°C removed a slight overprint to reveal a stable reversed direction. In nearly every sample,
Figure 3  Orthogonal demagnetization plots of representative samples from the Lincoln Creek and Astoria formations (tilt-corrected). Solid squares indicate horizontal component; open squares indicate vertical component. First four AF steps are NRM, 25, 50, and 100 gauss, followed by thermal steps of 200, 300, 350, 400, 450, 500, 550, and 600°C. Each division = $10^{-5}$ emu.
the remanence was 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, with minor chemical overprinting by goethite or other iron hydroxides.

Representative IRM acquisition analyses are shown in Figure 4. Most samples showed near saturation at 300 mT, suggesting that the 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.

Most of the samples showed a direction pointed southwest and up at NRM and showed only a single component of magnetization, which decayed steadily to the origin (Fig. 3A and 3B). Because these data are dip-corrected, this is clearly a reversed direction that has undergone clockwise rotation. A few samples (Fig. 3C) had a slight overprint but showed the characteristic reversed and rotated direction by 300°C. Two sites (Fig. 3D) pointed east and down from NRM to 600°C, which is a normal direction with clockwise rotation. Thus, it is apparent that the direction is a primary or characteristic remanence and not an overprint or later magnetic component.

This is confirmed by the reversal test (Fig. 5). The mean for the five normal samples was $D = \ldots$
108.4, $I = 39.2, k = 22.7, \alpha_{95} = 16.4$; the mean for the 30 reversed samples was $D = 233.7, I = -64.4, k = 6.1, \alpha_{95} = 11.8$. These directions, although not directly opposite one another, show overlapping circles of confidence, so they are antipodal within confidence limits (Fig. 5). Clearly, these directions are primary or characteristic directions, and not modern normal overprints, in that they are largely reversed and show a rotation consistent with that seen elsewhere in this area in rocks of this age. Inverting the reversed directions through the origin, the mean for the formation was $D = 67.2, I = 62.5, k = 5.8, \alpha_{95} = 11.3$.

Once the overprinting had been removed and a stable component was isolated, each direction was summarized by the least squares method of Kirschvink (1980) and averaged with Fisher (1953) statistics (Table 1). Each site was then ranked according to the scheme of Opdyke et al. (1977). Of the 12 sites, seven were statistically separated from a random distribution at the 95% confidence level (Class I sites of Opdyke et al., 1977). Two sites had only two usable samples, so no site statistics could be calculated (Class II sites of Opdyke et al., 1977). The remaining three sites showed a clear polarity preference, but the third sample was divergent (Class III sites of Opdyke et al., 1977).

The magnetic polarity stratigraphy is shown in Figure 6. The lower 100 m of the sampled section of the Lincoln Creek Formation is entirely reversed in polarity, including sites containing the gooseneck barnacle bed (Unit I of Moore, 1984a; = LACMIP 5844) and the decapod crustacean bed (Unit II of Moore, 1984a; = LACMIP 5843). The next 70 m of section are normal in polarity. The interval from 250 m to approximately 500 m in the section was covered by landslides, so it could not be sampled for paleomagnetic analysis. It includes the Aturia locality (Unit IV; = LACMIP 5842). From 500 m to more than 600 m in the section, the exposed outcrop of Astoria Formation is entirely reversed in polarity, including localities LACMIP 5863 and LACMIP 5864 and the type locality of the desmatophocine otarioid pinniped *Desmatotheca brachycephala* Barnes, 1987.

**DISCUSSION**

A tentative correlation of this stratigraphic section with the global timescale of Berggren et al. (1995) and the Pacific Coast timescale of Prothero (2001) is shown in Figure 7. The presence of *Liracassis apta* and other Juanian Stage mollusks places the Lincoln Creek part of the section in the late Oligocene, and Moore (1984a) indicated that some of the other mollusks suggest affinities with those of the early Miocene Pillarian Stage, so she argued that the Knappton Lincoln Creek molluscan fauna is late Juanian in age. In the Canyon River section of the Lincoln Creek and Astoria formations (Prothero and Armentrout, 1985), the *L. apta* (Moore, 1984b) Zone (and Juanian Stage) spans magnetic Chrons C10n–C6Cr; this is also true of the type Juanian section in the Pysh Formation (Prothero et al., 2001c). Thus, the best correlation of the long reversed interval followed by the short normal magnetozone of the Knappton Lincoln Creek section is either Chrons C7r–C7n, or C7Ar–C7An (Fig. 7).

The long talus-covered interval stratigraphically higher than site 8 (Fig. 6) makes the remaining correlations less certain. It could potentially obscure several magnetic polarity changes, so when the reversed section of the Astoria Formation is encountered, it is difficult to decide which of the many reversed early Miocene intervals best correlate with it. If the covered interval is a long one, or if the section has hidden unconformities, this reversed interval of Astoria Formation could correlate with...
Astoria beds as young as C5Br (15–16 Ma), as shown by magnetostratigraphic analysis of the Astoria Formation in the Newport, Oregon, area (Prothero et al., 2001a). However, several specimens of *Aturia angustata* Conrad, 1848, have been found at LACMIP 5863 (encompassing our sites 9 and 10), low in the Astoria Formation. According to Moore and Moore (2002) this nautiloid became
Two possible correlations of the Lincoln Creek and Astoria formations at Knappton to the global and local timescale (following Prothero [2001] and Berggren et al. [1995]), and to the magnetostratigraphy of the Lincoln Creek and Astoria formations at Canyon River (after Prothero and Armentrout, 1985).
extinct approximately 17 Ma, so we know that sites 9 and 10 are at least that old. Furthermore, fragments of the pectinid bivalve *Verticocena fucanus* (Dall, 1909), a zonal mollusk for the Pillar Stage (Addicott 1976a, 1981), have also been found at LACMIP 5863. Farther east, and higher in the Astoria Formation, LACMIP 5864 (encompassing our sites 11 and 12) marks the stratigraphically lowest occurrence, locally, of the gastropod *Fulgoraria* (Miopleiona) *indurata* (Conrad, 1849). According to Addicott (1976a) this would also mark the lower boundary of the Pillar Stage, although it also occurs in the middle Miocene Newportian Stage.

On the basis of correlations with the type Pillarian section in the Clallam Formation (Prothero and Burns, 2001), we suggest that the Astoria Formation east of Knappton best corresponds to one of the reversed intervals in Chron C6C: C6C1r, C6C2r, or later reversed intervals. We suggest that the Knappton section of the uppermost Lincoln Creek and Astoria formations is temporally equivalent to at least the lower part of the original (and now concealed) type section of the Astoria Formation, approximately 10 km to the south, in the city of Astoria, Oregon. It is significant that Dall and Harris (1892) divided the exposures of the Astoria Formation at Astoria, Oregon, into three stratigraphically successive members (Astoria shale, *Austria* bed, and Astoria sandstone), and this would apply equally well to the section that is exposed at Knappton, Washington. Additionally, Addicott (1976a, 1976c) and Moore and Addicott (1987) referred the lower part of the original type section of the Astoria Formation to the Pillarian Stage. On the basis of correlations with the type section of the Pillar Stage in the Clallam Formation (Prothero and Burns, 2001), we suggest that the Lincoln Creek and Astoria formations sections at Knappton best corresponds to one of the reversed intervals in Chron C6C: C6C1r, C6C2r, or later reversed intervals. We cannot precisely date the very top of the section, but we know that it must have an age between 15 and 23 Ma.

The mean direction *D* = 67.2°, *I* = 62.5°, *k* = 5.8, *α95* = 11.3 suggests about 77 ± 11 degrees of clockwise tectonic rotation compared with the Oligocene cratonic pole of Diehl et al. (1983) and corrected according to Demarest (1983). The nearest basement rock, the Eocene Crescent Volcanics Domain 7 (of Wells and Coe, 1985; Table 1), has a clockwise rotation of 65 ± 17°, and is thus statistically indistinguishable from our results. South of Knappton, in northern Oregon, rotations of 74 ± 5° were found in the upper Eocene–lower Oligocene Keasy Formation (Prothero and Hankins, 2000) and of 72 ± 11° in the lower Oligocene Pittsburg Bluff Formation (Prothero and Hankins, 2001). Thus, our rotational results are consistent with those of similar age reported in the nearest studies to the north and south.

The mean inclination of 62.5 ± 11° suggests a paleolatitude of 46°, which is virtually identical to its present latitude of 46°17′N. Thus, there is no indication in these rocks of any significant northward translation since the early Miocene (as expected for such young rocks after the emplacement of most of the Cascades and their basement terranes).

**ACKNOWLEDGMENTS**

We thank George Moore and Ellen Moore for the use of their unpublished stratigraphic section and for comments on the manuscript. Joseph Kirschvink provided access to his paleomagnetics laboratory. We acknowledge Lawrence G. Barnes, Ellen Moore, and two anonymous reviewers for helpful comments on the paper. This research was supported by a grant to D.R.P. from the Donors of the Petroleum Research Fund of the American Chemical Society, and by NSF grant EAR00-00174.

**LITERATURE CITED**


Received 3 April 2003; accepted 21 May 2007.