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Preliminary magnetostratigraphy of the John Day Formation, Oregon, and the North American Oligocene-Miocene boundary

by DONALD R. PROTHERO and JOHN M. RENSBERGER*

with 7 figures and 1 table

Abstract. Magnetostratigraphic studies of the Oligocene and Miocene John Day Formation, east-central Oregon, produce a polarity pattern spanning Chrons 6C.2r to 8r (24 to 28.2 Ma). This polarity pattern allows the first direct correlation of the changes in terrestrial mammal-bearing sequences with marine sections. Based on magnetostratigraphy, the Oligocene-Miocene boundary falls in the latest Arikareean (top of the *Entoptychus-Gregorymys* Concurrent-range Zone) in North American terrestrial sequences.

Kurzfassung. Magnetostratigraphische Studien der oligo-miozänen John Day Formation (östliches Zentral-Oregon) ergaben eine Polaritätsskala, welche zwischen 6C.2r und 8r Chrons (24–28,2 Ma) liegt. Dieses Ergebnis erlaubt zum ersten Male eine direkte Korrelation von kontinentalen, Säugetier-führenden Sedimenten mit marinen Abfolgen.

Auf Grund der Magneto-Stratigraphie ist die Grenze Oligozän/Miozän in den kontinentalen Abfolgen Nordamerikas innerhalb des späten Arikareean zu ziehen (Oberkante der *Entoptychus-Gregorymys*-Zone).

Introduction

Worldwide climatic changes in the late Oligocene and early Miocene are currently under intense study. The multi-institution Cenozoic Paleoceanography project (CENOP) has produced a detailed climatic record of early Miocene changes in world temperature, sea level, deep water circulation, and global ice volume (KELLER & BARRON 1983). The Oligocene-Miocene transition was a time of rising sea level, warming and moderating temperatures, and rediversification of planktonic biotas after Oligocene extinctions. Near the Oligocene-Miocene boundary, the circum-Antarctic current developed, accelerating the formation of cold Antarctic bottom water. This eventually led to major mid-Miocene Antarctic glaciation (KELLER & BARRON 1983, KENNETT 1977).

Prior to the present study, it was impossible to make direct correlations of worldwide climatic change recorded in marine sediments with events observed in non-marine sections.

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Scattered radiometric dates on non-marine sections (Tedford et al., in press) gave indirect correlations, but resolution was poor. Even the placement of the Oligocene-Miocene boundary in North American mammal-bearing sections has changed from the Whitneyan-Arikareean boundary (Wood et al. 1941) to near the top of the Arikareean North American land mammal "age" (Tedford et al., in press). The Whitneyan-Arikareean boundary is now believed to be about 29 Ma in age, or late Oligocene (Prothero et al. 1982).

Magnetostratigraphy provides the ideal tool for direct correlation of marine and non-marine sections. The most complete and fossiliferous section of Arikareean rocks in North America is the John Day Formation of east-central Oregon. The detailed lithostratigraphy and mammalian biostratigraphy of these rocks are described elsewhere (Fisher & Rensberger 1972, Rensberger 1971, 1973). The John Day Formation, as defined by Fisher & Rensberger (1972), has four members (Fig. 1). The lowermost Big Basin Member has a deep reddish stain due to hematite, and was not sampled. Although it is relatively thin and poorly exposed, it spans much of the Oligocene (Fisher & Rensberger 1972), and would probably not yield a usable magnetostratigraphic pattern. The fossiliferous volcaniclastic zeolitized Turtle Cove Member is characterized by a green color. It is overlain by the unzeolitized Kimberly Member, which has a gray or tan color. The contact between these units is a diagenetic color change, and thus is noticeably time transgressive (Fisher & Rensberger 1972). The Kimberly Member is unconformably overlain by the Haystack Valley Member, which is characterized by an abundance of channel sandstones. In the summer of 1983, the senior author and three assistants collected paleomagnetic samples from four stratigraphic sections which together span the formation in the type area. Two sections (Picture Gorge 7 and Picture Gorge 29) can be directly tied by the Picture Gorge Ignimbrite (Fisher & Rensberger 1972). Haystack 8 covers the gap in the middle of the *Entoptychus-Gregorymys* Concurrent-range Zone between Picture Gorge 7 and Picture Gorge 36 (Fig. 1). Correlations between individual *Entoptychus* species show that the record of the Arikareean is essentially complete except for the very top of the *Entoptychus-Gregorymys* Concurrent-range zone. The upper part of the *Entoptychus-Gregorymys* Concurrent-range zone (found in Picture Gorge 36) is overlain by the unconformity between the Kimberly and Haystack Valley Members. The Haystack Valley Member contains the rodent *Mylagaulodon*, which is indica-

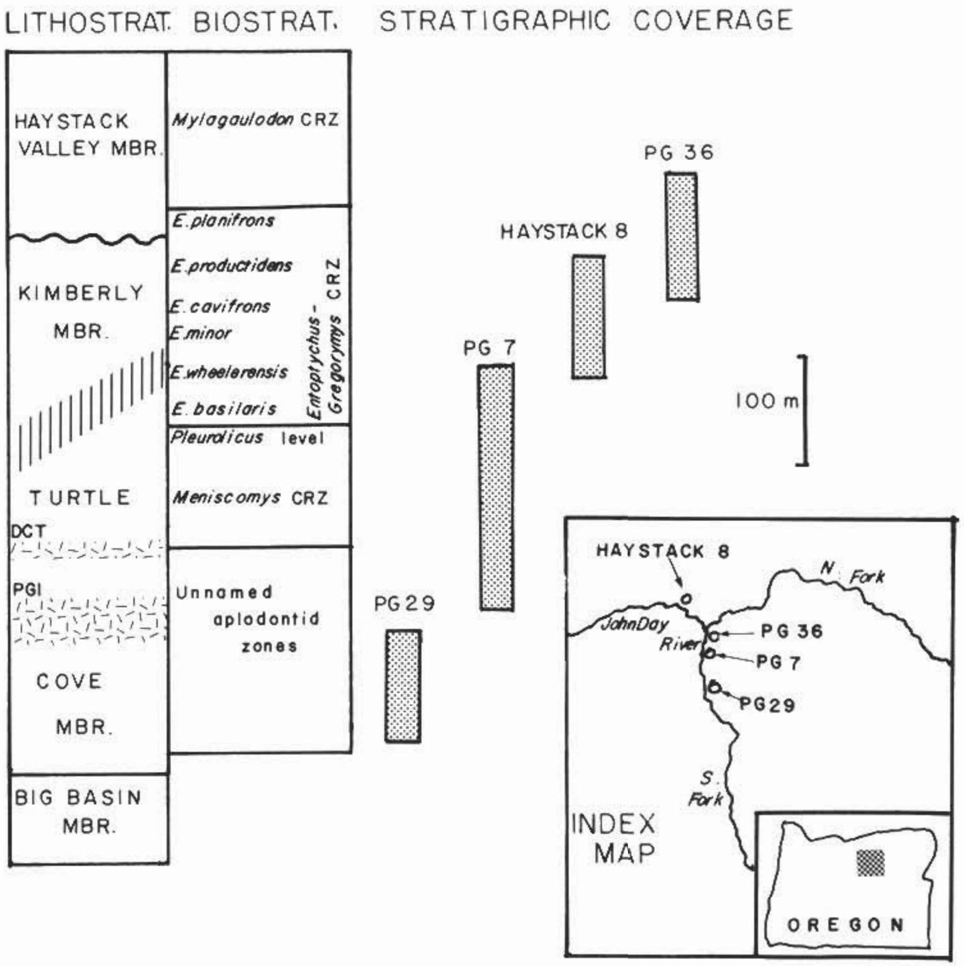

Fig. 1. Lithostratigraphy, biostratigraphy, stratigraphic coverage and index map of magnetostratigraphic sections sampled in this study. Abbreviations: CRZ = Concurrent-range Zone; DCT = Deep Creek Tuff; PG = Picture Gorge sections; PGI = Picture Gorge Ignimbrite.

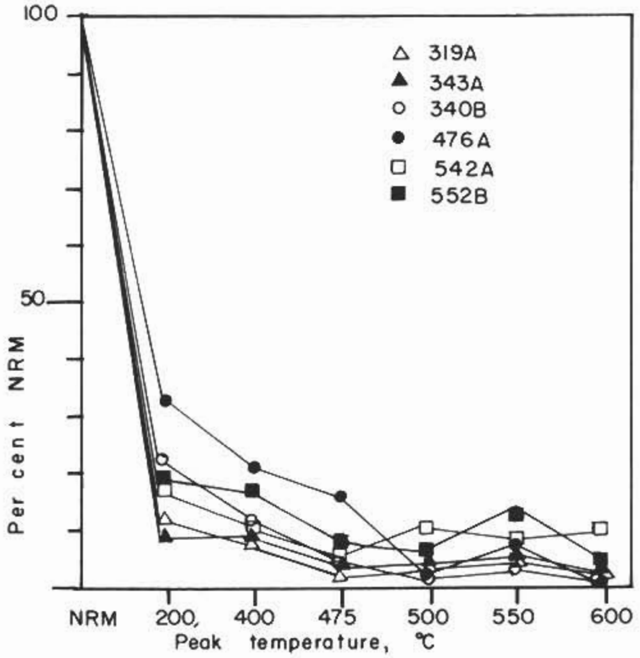

Fig. 2. Thermal demagnetization curves of six representative samples.

tive of the early Hemingfordian land mammal "age" (early Miocene). Thus, the John Day Formation gives an almost continuous record of the Arikareean and early Hemingfordian land mammal "ages".

Paleomagnetic analysis

Three oriented block samples were collected at each site, using simple hand tools. Sites were spaced at 1.7 m intervals over 411 m of section, resulting in 239 sites and 717 individual paleomagnetic samples. Samples were trimmed on a band saw and measured on a cryogenic magnetometer at the South Dakota School of Mines. Mean natural remanent magnetization (NRM) intensity for 38 pilot samples was 1.4×10^{-4} Gauss. The samples did not respond to alternating field demagnetization, even up to 1000 oersteds, indicating that the remanence is carried by a high-coercivity mineral, such as hematite. After stepwise thermal demagnetization (Fig. 2), the intensity dropped sharply at only 200 °C to about 10–20% of NRM in most samples. By 600 °C, mean intensity of magnetization was 4.3×10^{-6} Gauss. Directional behavior, as illustrated by Zijderveld plots (Fig. 3), showed that a reversed component was first apparent at demagnetization temperatures of 500–550 °C. This suggests that the characteristic remanence is carried by a mineral with a high blocking temperature, such as hematite.

Previous studies (FISHER & RENSBERGER 1972, FISHER 1966, HAY 1963) reported magnetite, but no hematite, in samples of the John Day Formation. Examination of polished sections in reflected light showed that some of this material is specular hematite, which is apparently the carrier of the characteristic remanence. Since there is no evidence of remanence carried by magnetite (as indicated by the lack of response to alternating field demagnetization), the magnetite grains must be too large, and are probably multi-domain grains. During thermal treatment, green specimens from the Turtle Cove Member changed to a tan color. This is probably due to diagenetic changes in the clay celadonite, which presumably dewaters to some other phyllosilicate at elevated temperatures (R. L. HAY, pers. commun.). This diagenetic change certainly deserves further study, but since this color change is not due to a magnetic mineral, it should have no effect on the remanence.

Since reversed behavior is apparent at temperatures of 500 °C and above, all samples were initially demagnetized at 550 °C. Many samples were treated again at 600 °C to obtain better clustering of results. Cleaned sample directions were then averaged using the methods of FISHER (1953), and their significance calculated (WATSON 1956). The hierarchical site classification of OPDYKE et al. (1977) was used. Class I sites (OPDYKE et al. 1977) are significantly removed from a random distribution at the 95% confidence level. 24 normal and 16 reversed sites were statistically significant Class I sites. Class III sites do not pass the significance test, but two out of three samples show a clear preference for one polarity. The majority of the sites were Class III, since it was common for one of the three samples to behave aberrantly. The reason for this is not clear, but it may be related to the difficulty of demagnetizing and

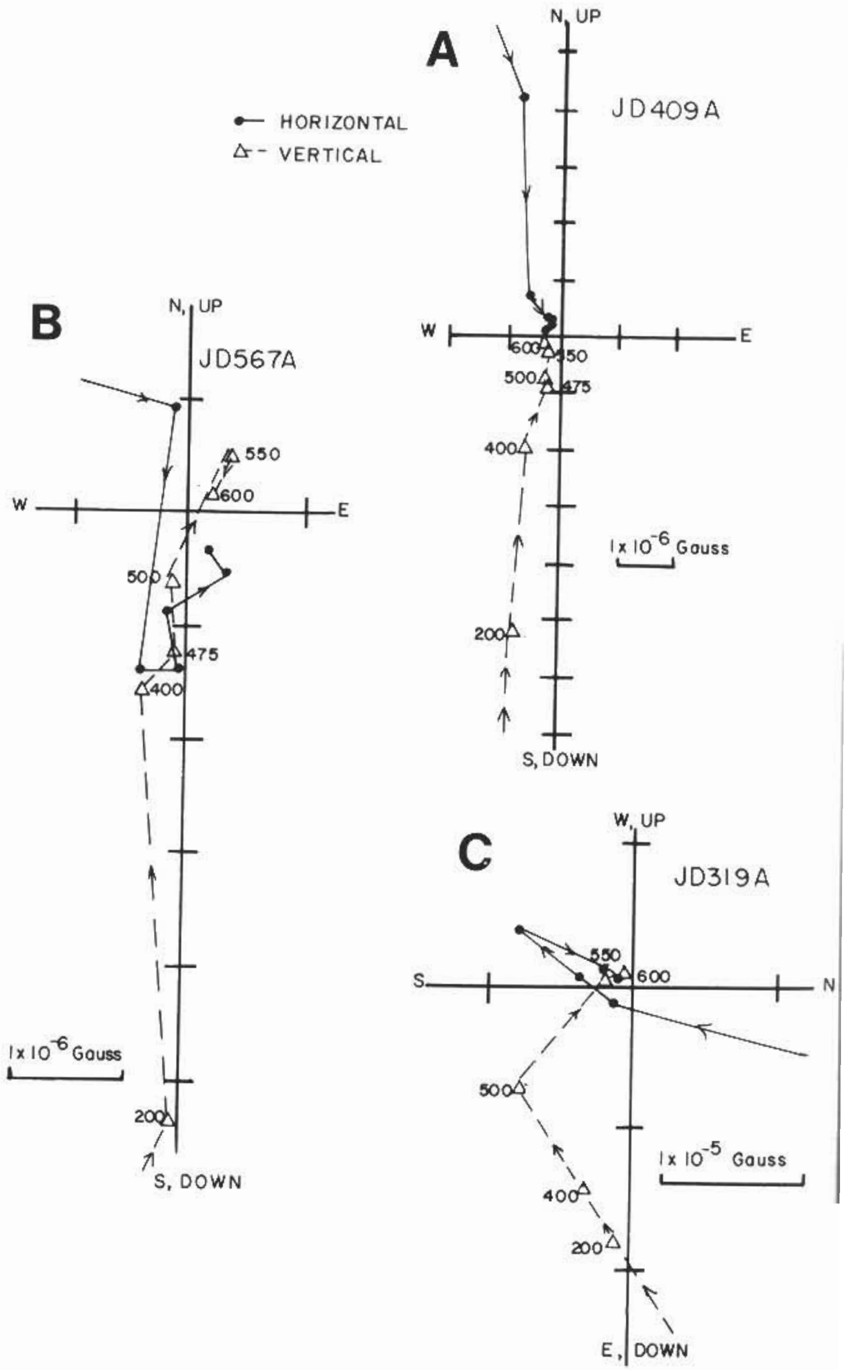

Fig. 3. Vector demagnetization (Zijderveld) plots of three representative samples. (A) Normal sample JD409A. (B) Reversed sample JD567A, which first showed reversed behavior at 550 °C. (C) Reversed sample JD319A, which first showed reversed behavior at 500 °C. Labeled increments are in degrees Centigrade. NRM vector is off scale on all plots, and therefore omitted.

measuring samples at such elevated temperatures. At this point, such a weak signal remains that some sort of noise (probably from viscous remanence) would be relatively noticeable and difficult to completely eliminate. Sites which were completely scattered and showed no polarity preference, or which gave very low virtual geomagnetic pole (VGP) latitudes, were considered indeterminate. They are shown by an "x" in Fig. 5, and were not connected to the other sites in the polarity plot.

The virtual geomagnetic poles of all Class I sites were averaged and plotted in a stereographic projection (Fig. 4). The means for all significant normal and reversed sites (Table 1) are not antipodal, but their ellipses of confidence overlap considerably. Both mean directions are significant, using the randomness test of Watson (1956). The mean direction for the entire John Day Formation (averaging the normal and inverted reversed means) in in good agreement with the directions for the overlying middle Miocene Columbia River basalts (Watkins & Baksi 1974) and the underlying late Eocene Clarno Formation (Beck et al. 1978). The Columbia River basalts show a clockwise tectonic rotation of 2–12 (Magill & Cox 1980), and the rotation of the Clarno Formation is slightly greater. The John Day results (Fig. 4) suggest an even greater rotation, but the margin of error is so large that little significance can be attached to this pole position. Indeed, the confidence ellipses of the normal and reversed site means even encompass the pole position for the stable North American craton at 25 Ma (Irving 1979).

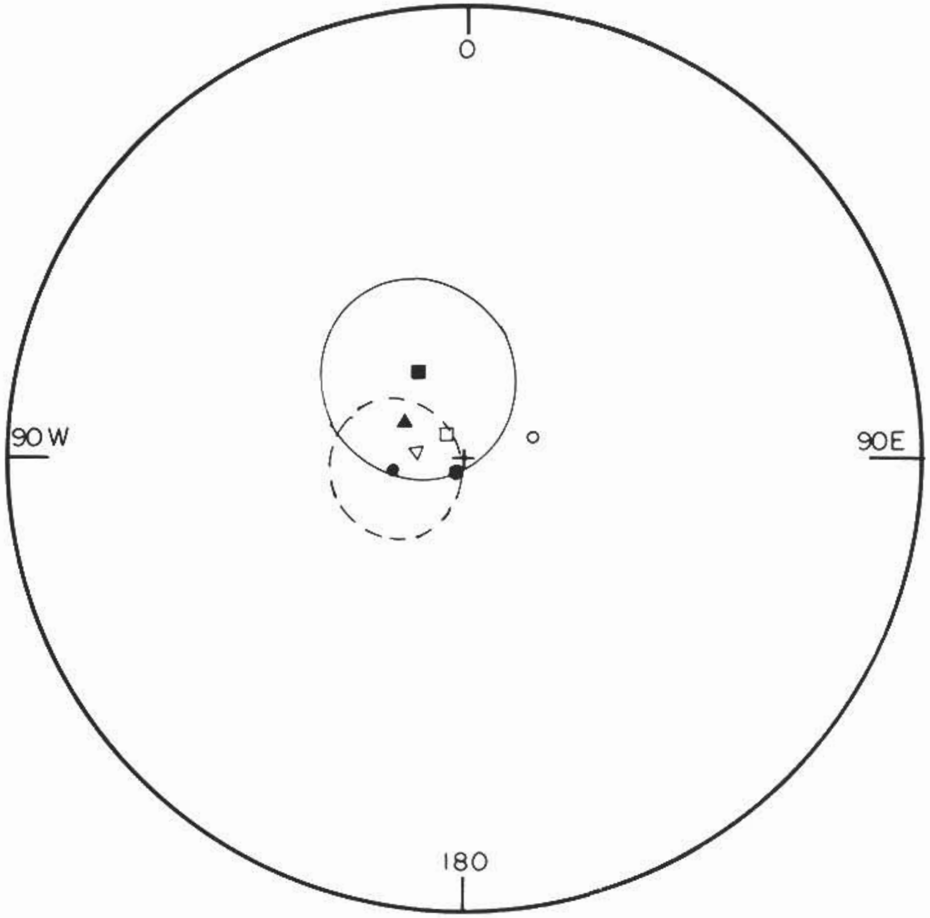

Fig. 4. Stereographic projection of pole positions. Solid square and solid ellipse: mean and ellipse of confidence of Class I normal sites (see Table 1). Solid circle and dashed ellipse: mean and ellipse of confidence of reversed sites (inverted). Open circle: mean of reversed sites (before inversion). Solid triangle: mean of Class I normal and inverted reversed means. Solid hexagon: pole position for North American craton at 25 m.y.B.P. (Irving 1979). Open square: pole position for middle Miocene Columbia River basalts (Watkins & Baksi 1974). Open triangle: pole position for late Eocene Clarno Formation (Beck et al. 1978).

Table 1 Comparison of pole positions.

Pole	N	Latitude	Longitude	K	α_{95}
Mean, John Day Fm.		77.5	296.0		
Mean, Class I normal sites, John Day Fm	24	72.2	327.0	3.86	18.2
Mean, Class I reversed sites, John Day Fm.	16	–76.9	70.9	8.26	13.6
Clarno Fm. (Beck et al. 1978)	13	80.5	274.0	14.4	11.3
Columbia River basalts (Watkins & Baksi 1974)	14	84.2	315.8	45.9	5.9
North American craton (Irving 1979)	21	87.0	162.0	66.0	4.0

Correlation

The polarity pattern (Fig. 5) can be tentatively correlated with the magnetic polarity timescale. In the late Oligocene, the Chron 6r (Harland et al. 1982) reversed interval is distinctive in its length (Fig. 6). It spans 1.3 million years, from 24.2 to 25.5 million years ago (Berggren, Kent & Flynn 1984). The John Day sequence shows an unusually long zone of reversed polarity from the middle of the *Meniscomys* Concurrent-range Zone to the upper part of the *Entoptychus-Gregorymys* Concurrent-range Zone (Fig. 5). This interval appears to be Chron 6r, based on its great length and the age constraints of the section (Fig. 7). Above this interval as a short section of normal polarity which appears to be Chron 6C.3. Beneath Chron 6r are three zones of normal polarity which seem to represent Chrons 7, 7A, and 8. Beneath Chron 8 are about 30 m of predominantly reversed rock that may represent Chron 8r. The Picture Gorge Ignimbrite, which falls at the top of Chron 8, is radiometrically dated at 26.0 Ma (Evernden et al. 1964). This date is in reasonable agreement with the paleomagnetics (Fig. 7), since normal error estimates on mid-Tertiary dates are in the order of a million years.

A radiometric date of 21.9 Ma for the top of the Harrison Formation (Tedford et al., in press), a position generally taken as representing the upper boundary of the Arikareean, suggests that an unconformity of about 2 million years separates the top of the *Entoptychus-*

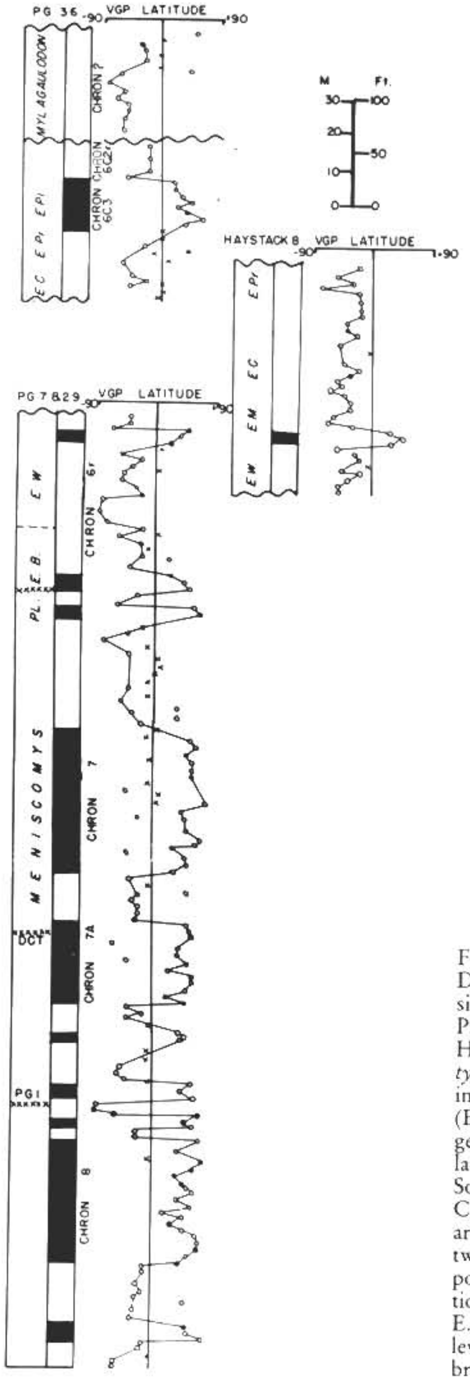

Fig. 5. Composite magnetostratigraphy of the John Day Formation. Sections shown in Fig. 1 are composited as follows: below PGI (Picture Gorge Ignimbrite is Picture Gorge 29; above it is Picture Gorge 7. PG 7 and Haystack 8 are linked by the co-occurrence of *Entoptychus wheelerensis* (E.W.). Haystack 8 overlaps PG 36 in the co-occurrence of *E. cavifrons* and *E. productidens* (E.C.-E.Pr.). Magnetic polarity plotted as virtual geomagnetic pole (VGP) latitude, so that positive VGP latitudes indicate normal polarity, negative are reversed. Solid circles are significant Class I sites; open circles are Class III sites (OPDYKE et al. 1977). Indeterminate sites are shown by an "x". Only polarity zones composed of two or more consecutive sites of the same determinate polarity are connected by the solid line. Other abbreviations: DCT = Deep Creek Tuff; PL = *Pleurolicus* level; E.B. = *Entoptychus basilaris* level; E.M. = *E. minor* level; E.Pl. = *E. planifrons* level; xxxxx = tuff or ignimbrite level.

Gregorymys Concurrent-range Zone from the rest of that zone in the John Day Formation (Fig. 7). The Haystack Valley Member, which contains the *Mylagaulodon* Concurrent-range Zone, as well as the uppermost part of the *Entoptychus-Gregorymys* Concurrent-range Zone, unconformably overlies the Kimberly Member and was deposited during regional uplift in late John Day time. This unconformity is also represented in the Rocky Mountains (RENSBERGER 1981), where the faunal discontinuity is greater than in the John Day Formation. In

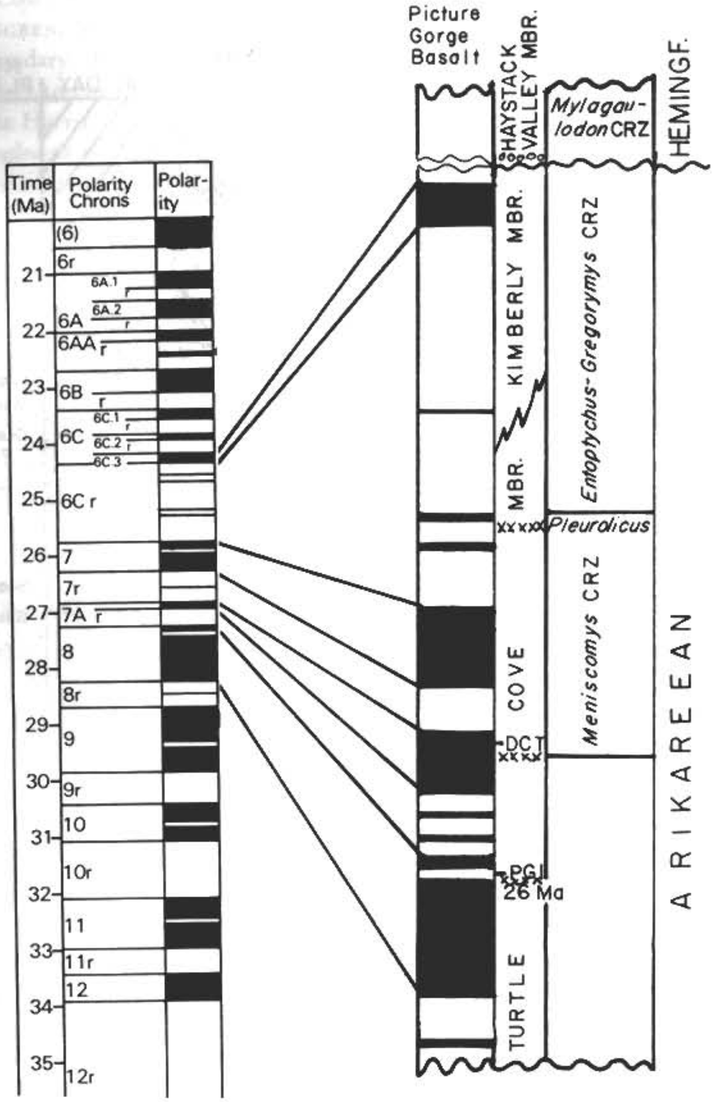

Fig. 6. Correlation of John Day magnetostratigraphy with the magnetic polarity timescale. Chron terminology after HARLAND et al. (1982).

the John Day Formation, the greatest faunal discontinuity apparently occurs within the Haystack Valley Member. At Picture Gorge 36, where the upper part of the paleomagnetic profile was taken, the uppermost part of the *Entoptychus-Gregorymys* Concurrent-range Zone is apparently missing and the early Hemingfordian *Mylagaulodon* Concurrent-range zone extends to the base of the Haystack Valley Member. Thus, the magnitude of the chronologic gap and the correlation of the uppermost reversed interval with the several reversed intervals of the Hemingfordian remain uncertain.

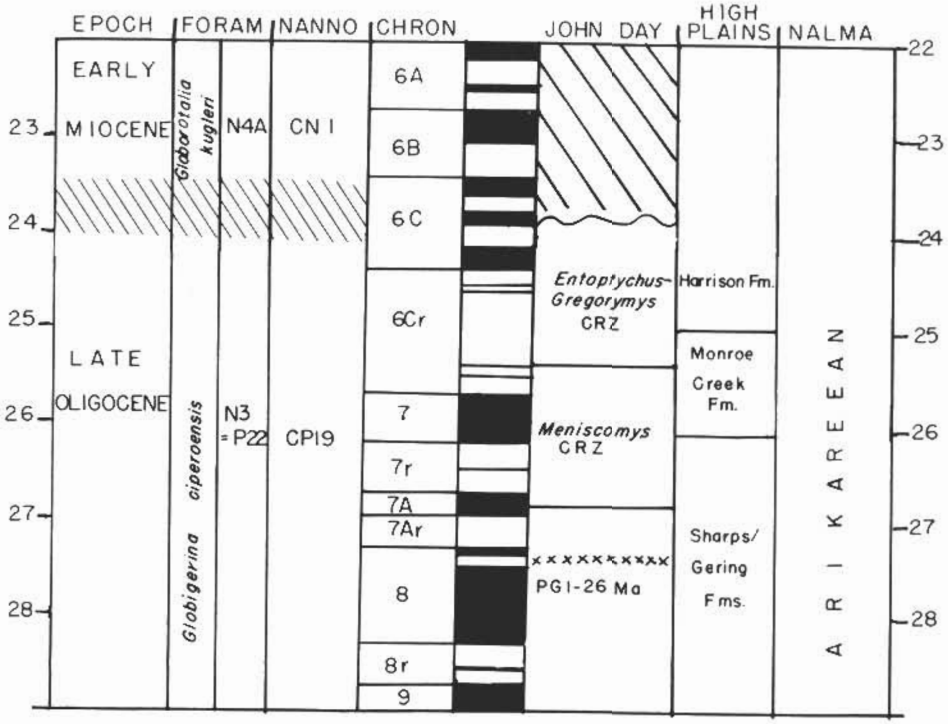

Fig. 7. Correlation of the John Day magnetostratigraphy with other chronologies. North American land mammal "ages" (NALMA) after TEDFORD et al. (in press) Zonation of Foraminifera (Foram.) and calcareous nannoplankton (Nanno.) after BERGGREN, KENT & FLYNN (1984). Correlation with High Plains after FISHER & RENSBERGER (1972).

Recent studies (BERGGREN, AUBRY & HAMILTON 1983, BERGGREN, KENT & VAN COUVERING 1984) of the magnetostratigraphy and biostratigraphy of marine sections place the Oligocene-Miocene boundary (as recognized by the first appearance of *Globorotalia kugleri* and the base of nannofossil zone CN 1) within Chron 6C.2r. This suggests an age of 23.7 Ma for the Oligocene-Miocene boundary (BERGGREN, KENT & FLYNN 1984). In North America, this would place the Oligocene-Miocene boundary just beneath the unconformity near the middle of the Picture Gorge 36 section. Recently, SRINIVASAN & KENNETT (1983) have proposed that the Oligocene-Miocene boundary is associated with the first appearance of *Globoquadrina dehiscens*, which first appears somewhat later than *Globorotalia kugleri* in planktonic zone N4. Paleomagnetic evidence (BERGGREN, AUBRY & HAMILTON 1983, BERGGREN, KENT & VAN COUVERING 1984) places this boundary between Chron 6B and 6C. This would mean that the Oligocene-Miocene boundary is somewhat younger than Chron 6C.2r, and therefore lies within the hiatus between the *Entoptychus-Gregorymys* Concurrent-range Zone and the *Mylagaulodon* Concurrent-range Zone. For the present, however, we will follow the interpretation of BERGGREN, KENT & VAN COUVERING (1984) of the position of the Oligocene-Miocene boundary. In North American continental sections, the base of the Miocene occurs at the very top of the *Entoptychus-Gregorymys* Concurrent-range Zone and somewhere within of the Harrison Formation in the Great Plains. Further work in progress on the magnetostratigraphy of the Great Plains Arikareean (R. M. HUNT & B. J. MACFADDEN, personal communication) will resolve the precise position of the base of the Miocene in High Plains sections.

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