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Chronology of the Wasatchian Land-Mammal Age (Early Eocene): Magnetostratigraphic Results from the McCullough Peaks Section, Northern Bighorn Basin, Wyoming[1]

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ABSTRACT

The McCullough Peaks section of the Willwood Formation in the northern Bighorn Basin, Wyoming, has produced a rich fossil record of early Eocene mammals spanning much of the Wasatchian land-mammal age. The Wasatchian is an especially significant period in mammalian evolution since it marks the first appearance of several modern orders of mammals including Perissodactyla, Artiodactyla, and true Primates. Magnetostratigraphic analysis of paleosol horizons in the McCullough Peaks region is used to correlate Wasatchian land-mammal zones to the geomagnetic polarity time scale. A total of 135 paleomagnetic samples were analyzed from 37 levels in a 1480 m section that ranges from Wasatchian zone Wa-0 (earliest Sandcouleean subage) to the base of zone Wa-7 (earliest Lostcabinian subage). Progressive thermal demagnetization of samples from red (B type) and mottled red/gray (AB type) soil horizons provides the most reliable results. The characteristic magnetization is carried by hematite with unblocking temperatures between 400°C and 680°C. Fine-grained hematite and magnetite are also present and carry a strong present-day overprint. Magnetostratigraphic correlation indicates that Wasatchian zone Wa-0 (earliest Sandcouleean subage) to middle zone Wa-5 (*Bunophorus* interval-zone) correlate with Chron C24r, middle zone Wa-5 to middle zone Wa-6 (Lysitean subage) correlate with Chron C24n.3n, late zone Wa-6 correlates with Chron C24n.2, and early zone Wa-7 (Lostcabinian subage) correlates with Chron C24n.1r. These results indicate that the last zone, Wa-7 (Lostcabinian subage), may represent as much as one-half of the Wasatchian land-mammal age, while earlier zones Wa-0 to Wa-6 (Sandcouleean-Lysitean subages) together span only 2.4 m.y. of early Eocene time.

Introduction

The lower Eocene Willwood Formation in the Bighorn Basin is characterized by repeated highly fossiliferous red and gray mudstones (paleosol horizons) interbedded with channel sandstones and sheet sandstone complexes (Van Houten 1944; Neasham and Vondra 1972; Bown and Kraus 1981, 1987). The Willwood Formation outcrops in a 1480 m stratigraphic section in the McCullough Peaks region of the northern Bighorn Basin (figure 1). Fossil mammals have been collected from this area for more than 80 years, making it one of the best known records of early Cenozoic mammalian evolution. In recent years 4496 fossil mammals have been catalogued from 160 localities at 105 different levels in the McCullough Peaks section. These fossil collections indicate that the McCullough Peaks section lies within the Wasatchian land-mammal age (figure 2) and ranges from zone Wa-0 (earliest Sandcouleean subage) to the base of zone Wa-7 (earliest Lostcabinian subage). The combination of extensive exposure and well-constrained biostratigraphy makes the McCullough Peaks an excellent area to correlate Wasatchian faunal zones to the geomagnetic polarity time scale (GPTS). Correlation of mammalian faunal zones to the GPTS has proven important in linking the marine and terrestrial stratigraphic records and in establishing the geochronology of land-mammal ages. An independent chronology for these faunal zones is essential for studies of the timing and rate of early Cenozoic mammalian evolution (Gingerich 1993; Clyde and Gingerich 1994).

Previous magnetostratigraphic analyses of Paleocene and Eocene sections in western North America (Butler et al. 1981, 1987; Rapp et al. 1983; Flynn 1986) have correlated the Tiffanian, Clarkforkian, earliest Wasatchian, and early Bridgerian

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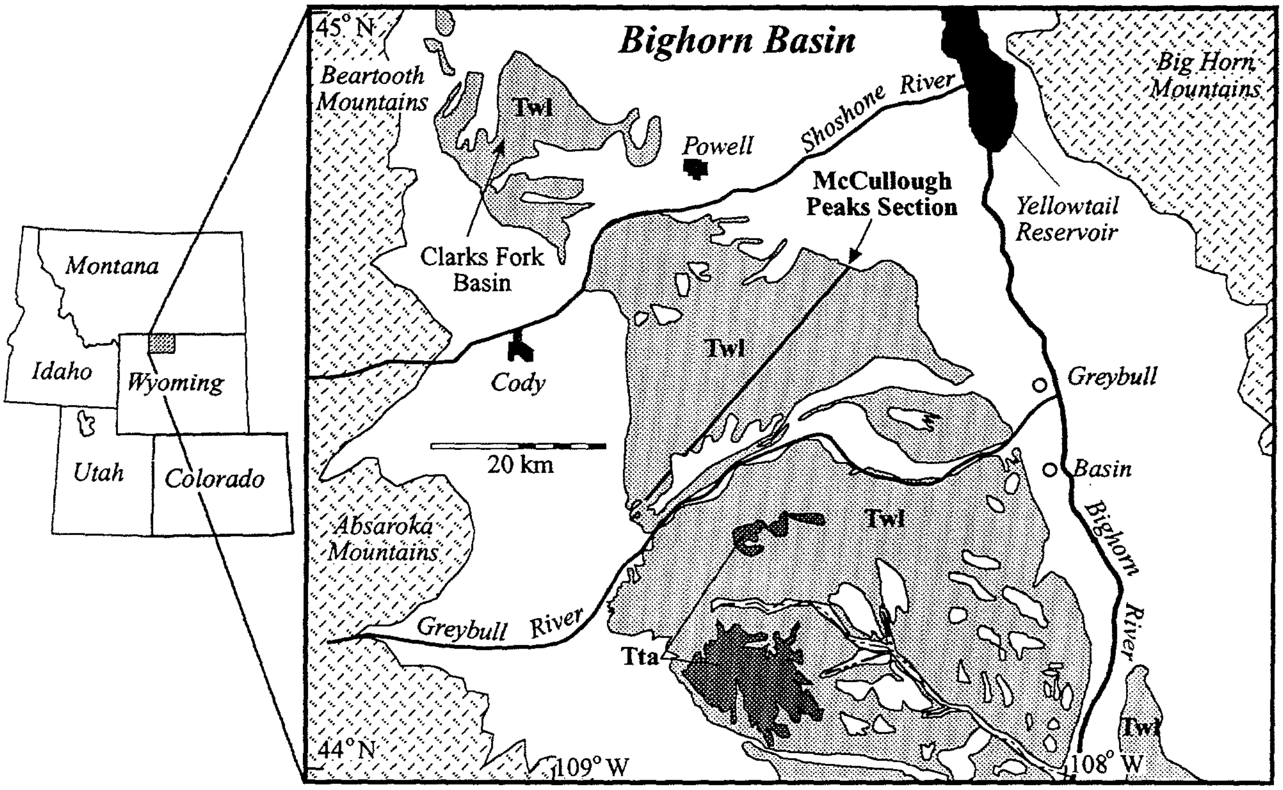

Figure 1. Geologic map of the northern Bighorn Basin, Wyoming (adapted from Love and Christiansen, 1985). Light gray (Twl) and dark gray (Tta) show the outcrop pattern of the lower Eocene Willwood and Tatman formations, respectively.

land-mammal ages to the GPTS. Butler et al. (1981) analyzed various sections in the northern Bighorn Basin and contiguous Clarks Fork Basin and correlated late zone Ti-5 (Tiffanian land mammal age) and early zone Cf-1 (Clarkforkian land mammal age) to Chron C25n and late zone Cf-1 (Clarkforkian land mammal age) through zone Wa-4 (Wasatchian) to Chron C24r. Flynn (1986) correlated an early Bridgerian (~ zone Br-1) fauna from the East Fork Basin of Wyoming to Chron C21n or C22n. These correlations suggest that Wasatchian faunal zones Wa-4 through Wa-7 should include Chrons C24n, C23r, C23n, and C22r, but these have not yet been found in Wasatchian strata. This study extends magnetostratigraphic analysis further upward in the Wasatchian land-mammal age in an attempt to correlate the rest of the Wasatchian faunal zones to the GPTS.

Paleomagnetic Sampling and Sample Behavior

Three or more oriented hand samples were collected from 37 different horizons in the McCullough Peaks section and cut into approximately 8 cm^3 cubes for paleomagnetic analysis. A total of 135 samples were analyzed for this study. Preliminary investigations of the magnetic properties of these rocks indicated that surface weathering may alter the iron-rich minerals to geothite, so special care was taken to remove all weathered material from the surface before taking samples. Samples were collected from A (gray) soil horizons, AB (mottled gray/red) soil horizons, and B (red) soil horizons (as defined by Retallack 1988). Orientations of hand samples were made in the field using a Brunton compass. Magnetization of these rocks is too weak to significantly deflect compass readings. Bedding is essentially horizontal and no bedding corrections were required. Sampling was concentrated in the upper half of the section since the lower half overlaps with the Big Sand Coulee section of Butler et al. (1981).

Progressive thermal and alternating field (af) demagnetizations were performed on pilot samples from both the A (gray) and B (red) soil horizons using a Schonstedt TSD-1 thermal demagnetizer and a SI-4 af demagnetizer. Remanence measurements were made on a three-axis cryogenic magnetometer (2G) in the magnetically shielded paleomagnetic laboratory at the University of Michigan.

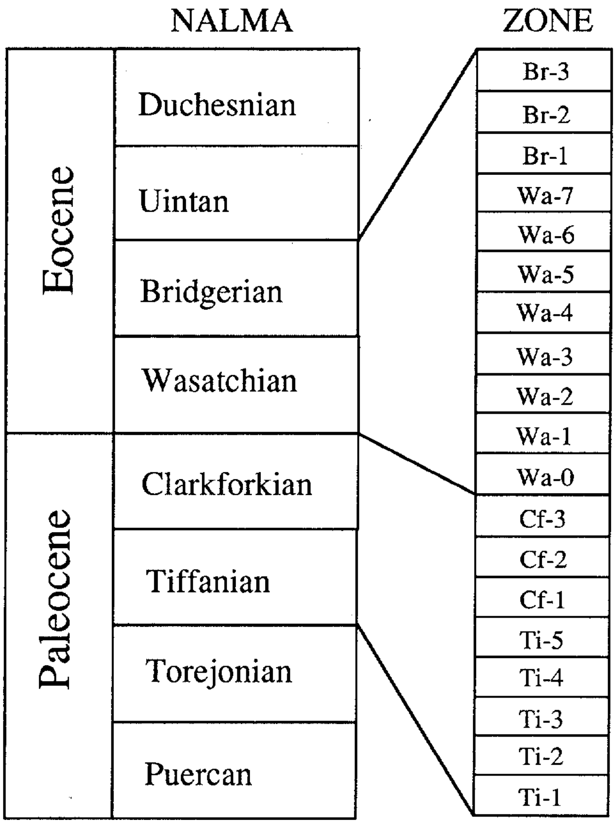

Figure 2. Schematic diagram showing North American Land Mammal Ages (NALMA) and associated faunal zones. The McCullough Peaks section ranges from Wasatchian faunal zone Wa-0 to Wa-7.

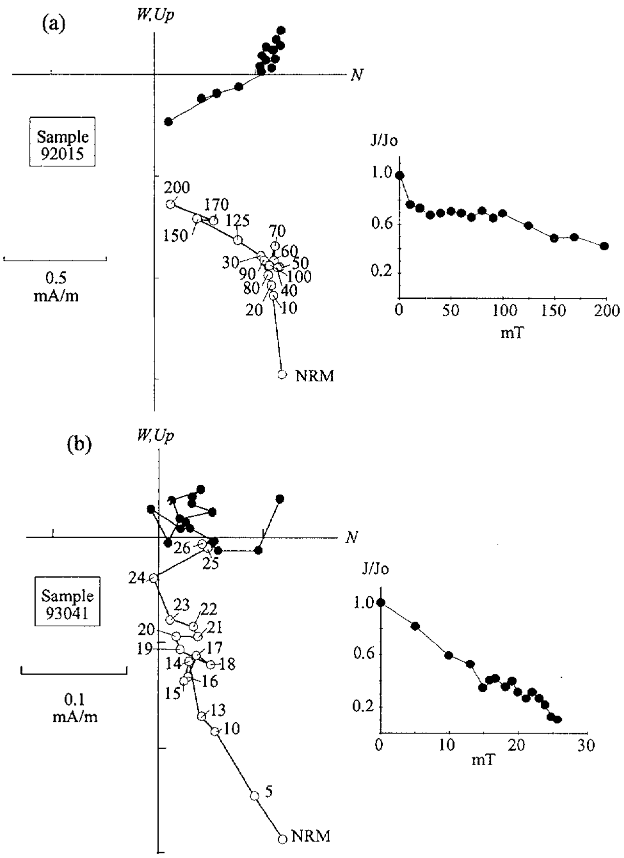

Figure 3. Representative Zijderveld (1967) diagrams and intensity plots of alternating field (af) demagnetization. In the Zijderveld diagrams, the open (solid) circles show vector endpoints in the vertical (horizontal) plane. In the intensity plots Jo is the intensity of the natural remanent magnetization prior to demagnetization. (*a*) Demagnetization of a B (red) soil horizon sample to a peak af field of 200 mT. (*b*) Demagnetization of an A (gray) soil horizon sample to a peak af field of 26 mT.

Alternating fields up to 200 mT failed to demagnetize the natural remanence magnetization (NRM) in several test samples (figure 3*a*). Conversely, thermal demagnetization proved to be the more effective technique for isolating the remanence components (figure 4*a*–*d*).

Based on pilot-sample results, the remaining samples were thermally demagnetized (10–20 steps) up to a maximum temperature of 680°C. Remanence components were determined by least-squares analysis (Kirschvink 1980). Remanence directions were then grouped into two categories depending on the maximum angular deviation (MAD). Category I directions had MAD angles less than 15°. Category II directions had MAD angles between 15°C and 20°C. Mean directions and their surrounding statistical distributions were calculated following the method described by Fisher (1953). At several sites, the overlapping unblocking spectra of the magnetic components obscured any linear demagnetization trends and, in these cases, the progression of remanence directions along the great circle path from the overprinting direction to a reversed characteristic direction (figure 5) was used to augment the category I and category II results.

The magnetic mineralogy was determined from the acquisition of isothermal remanent magnetization (IRM) up to a peak field of 1.2 T, and from thermal demagnetization of three mutually orthogonal IRMs of varied intensity (Lowrie 1990). In the latter experiments, the applied fields were 1.2 T, 0.4 T, and 0.15 T.

Magnetic Results

Samples from the A (gray) soil horizons exhibited weak NRM intensities less than 0.5 mA/m. AF demagnetization of these samples showed a low coercivity magnetization with a mean destructive field

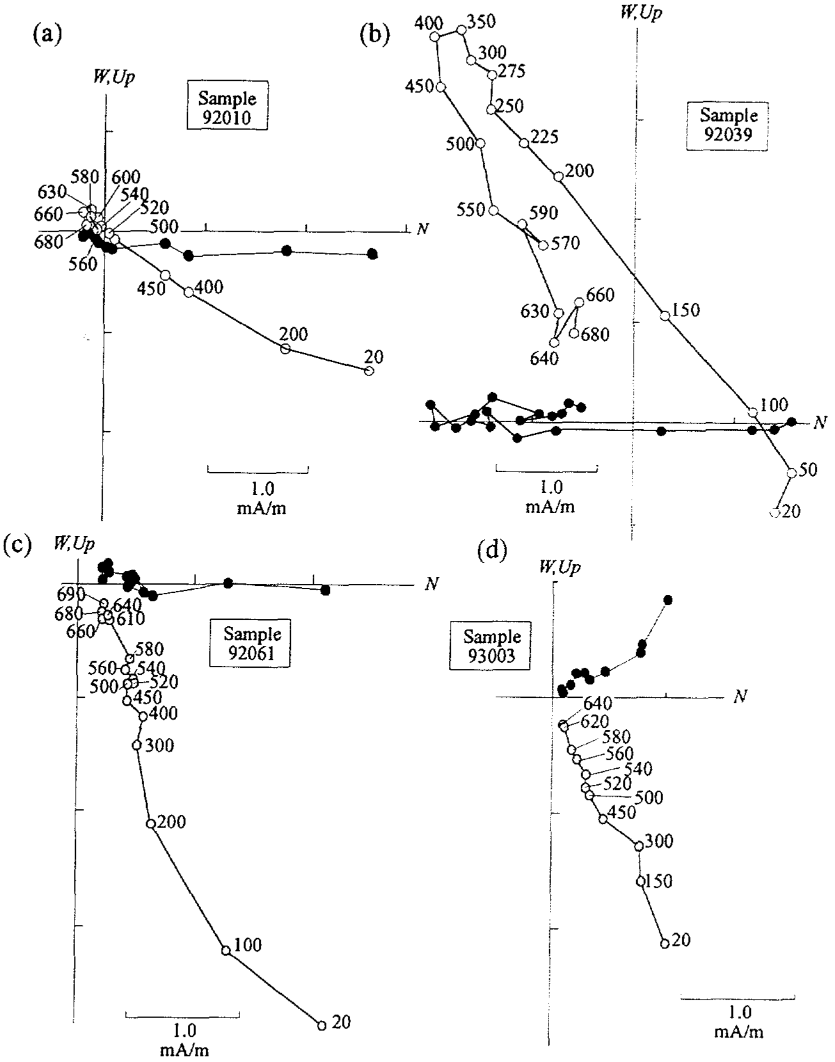

Figure 4. Representative Zijderveld (1967) diagrams of thermal demagnetization. The symbols are the same as those in figure 3. (*a*) and (*b*) Demagnetization of a present-day magnetization overprinting a reversed polarity characteristic magnetization. (*c*) and (*d*) Demagnetization of a present-day magnetization overprinting a normal polarity characteristic magnetization.

of less than 15 mT (figure 3*b*). Upon thermal demagnetization, magnetizations became very weak and unstable and often showed strong viscous relaxation of the remanence directions. No reliable magnetizations with high coercivities or high unblocking temperatures were obtained from the A (gray) soil horizon samples.

IRM acquisition and thermal demagnetization of a multi-component IRM (figure 6*a* and 6*b*) indicates that the A (gray) soil horizon samples contain a significant fraction of magnetite (IRM saturation below 0.2 T and unblocking temperature up to 585°C) and accessory hematite (IRM not saturated at 1.2 T and unblocking temperatures near 680°C).

In contrast, NRM intensities of the AB (mottled red/gray) and B (red) soil horizon samples were significantly stronger than the A (gray) soil horizon samples, ranging between 1.0 mA/m and 6.0 mA/m. Thermal demagnetization of these samples revealed two remanence components: (1) a secondary magnetization parallel to the present-day earth's field (PDF) with unblocking temperatures up to 550°C, and (2) a characteristic remanent magnetization (ChRM) with high unblocking temperatures between 400°C and 680°C (figure 4*a* to 4*d*). IRM and thermal demagnetization of a multi-component IRM indicate that these samples are dominated by high-coercivity hematite with a trace amount of magnetite (figure 6*a* and 6*c*). These results, coupled with the thermal demagnetization of the NRMs, suggest that the ChRM is carried by coarser-grained hematite and that the overprint direction is carried either by magnetite or by fine-grained, pigmentary hematite.

Category I and category II ChRMs were obtained from 64 samples. These ChRMs form two groups of directions (figure 7). Half (32) show south-southeast declinations with shallow to moderate

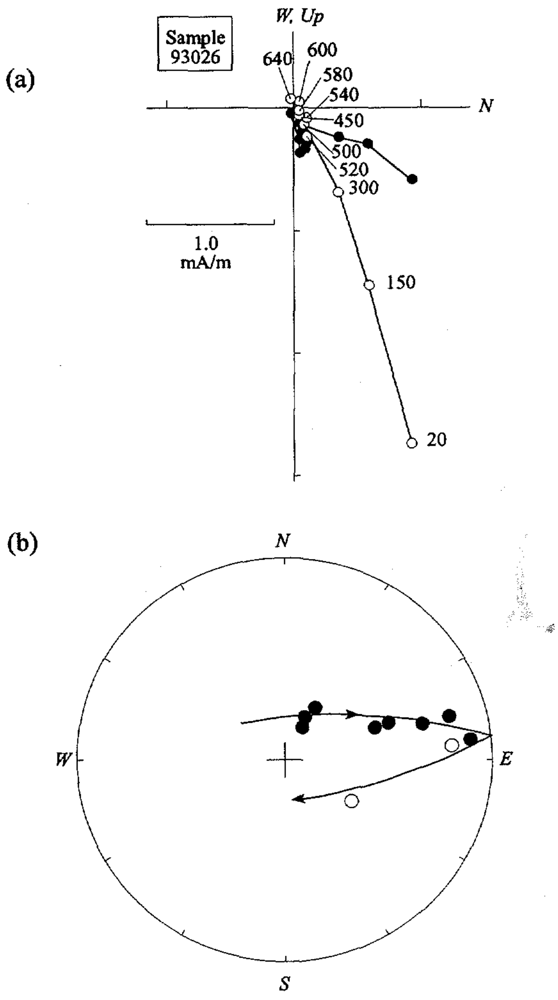

Figure 5. (*a*) Thermal demagnetization of a sample that did not yield a category I or category II line but was used for great circle analysis. Symbols are the same as in figure 3. (*b*) Equal area projection showing a great-circle fit to the directions during progressive thermal demagnetization. The directions move from the present-day field direction toward a reversed polarity Eocene direction. Open (closed) symbols lie on the upper (lower) hemisphere of the projection.

upward inclinations while the remaining ChRMs show N-NW declinations with moderate downward inclinations. The PDF overprinting directions for these samples are toward the N-NE with moderate to steep inclinations.

Recognition of the south and upward ChRM is straightforward because it is nearly antipodal to the overprinting magnetization. As the PDF overprint is progressively demagnetized, the magnetization directions migrate toward a south and upward direction. The large scatter around the mean direction probably reflects incomplete removal of the PDF overprint. In contrast, identification of the north and down ChRM is more problematic given that it is nearly parallel to the PDF overprint. Isolation of this ChRM direction was primarily accomplished by fitting lines to the demagnetization trajectories over the same range of demagnetization temperatures that unblocked the south and upward ChRM. Figure 7 shows that this method was successful. The mean of the north and downward group of ChRM is statistically distinct from the mean of the PDF overprint directions.

These two groups of ChRM directions appear to be antipodal and similar to the expected Eocene direction for the Bighorn Basin ($D = 349°$, $I = 63°$) based on the Eocene reference pole for North America (Diehl et al. 1983). The reversal test (McFadden and McElhinny 1990) is positive and can be classified as type C if all the category I and category II directions are used, and type B if just the category I directions are used. These results indicate that both normal and reversed polarity directions of Eocene age are preserved in the Willwood Formation paleosols in the McCullough Peaks and thus can be used as the basis for correlation between biostratigraphic zones of the region and chronological ages from the GPTS. These results are similar to those of Nick et al. (1991), who found an early, synsedimentary magnetization of hematite in paleosol horizons within the Black Prince Limetone (Pennsylvanian) of Arizona.

Characteristic remanent magnetizations for samples that exhibited stable demagnetization behavior are plotted against stratigraphic level in figure 8 along with the ranges of some biostratigraphically important taxa. The McCullough Peaks section is characterized by a total of eight polarity zones. The first level is characterized by normal polarity (A+) and is followed by a 950 m interval of reversed polarity (B−). The next 350 m is characterized by normal polarity (C+ and E+), except for a single poorly defined reversed site (D−?) at 965 m. The next 100 m is characterized by a reversed interval (F−) and a normal interval (G+), and the final 80 m is characterized by reversed polarity (H−). The pattern of reversals exhibited by these polarity zones can be used in conjunction with other stratigraphic and chronometric data to correlate the associated Wasatchian faunal zones to the GPTS.

Correlation to The Geomagnetic Polarity Time Scale

The favored correlation of McCullough Peaks' magnetic zones to magnetic anomalies of the GPTS is shown in figure 9. The long reversed polar-

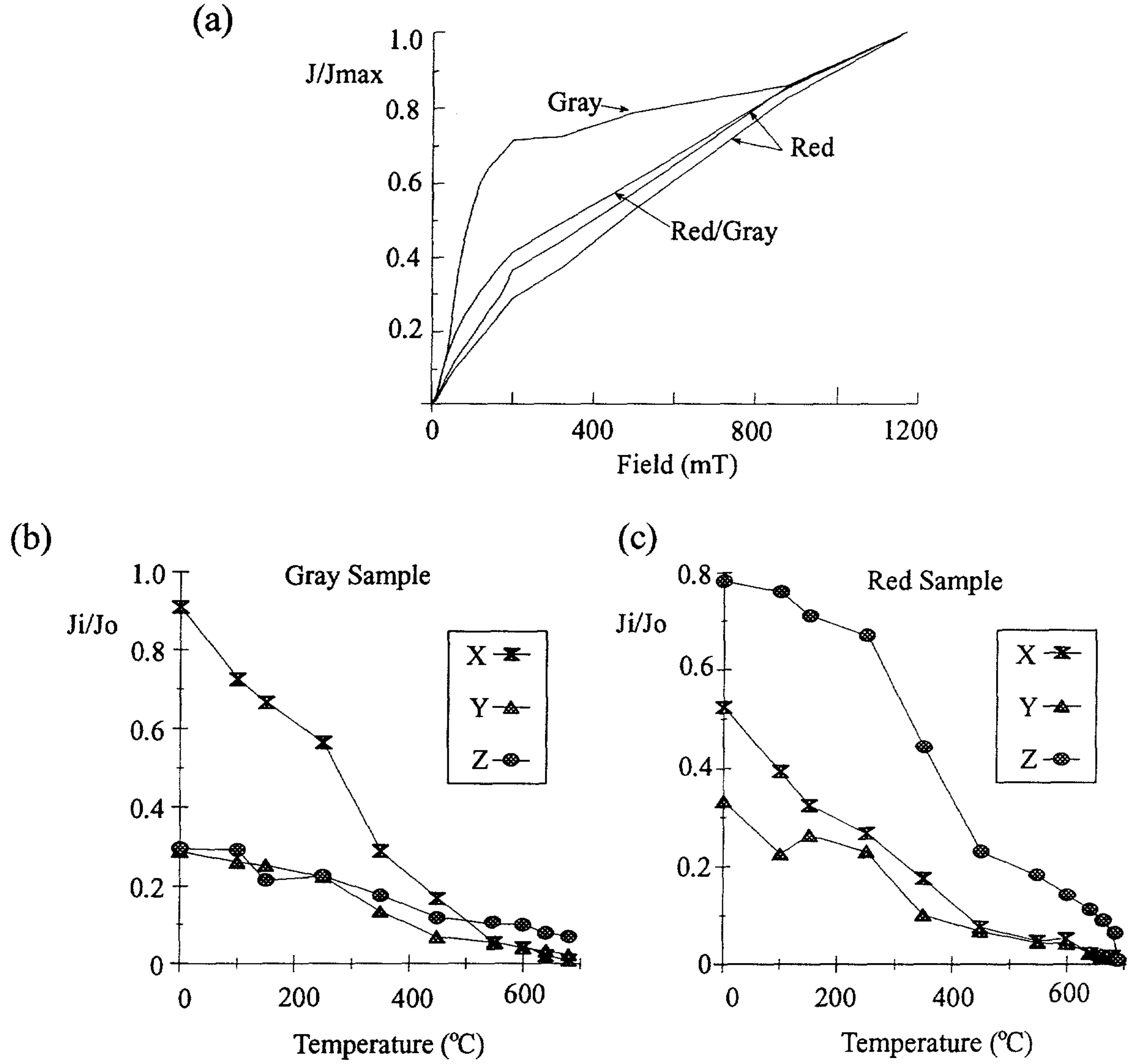

Figure 6. (*a*) Acquisition of an isothermal remanent magnetization (IRM) normalized to the peak magnetization for representative A (gray) soil horizon, AB (gray/red) soil horizon and B (red) soil horizon samples. (*b*) and (*c*) Intensity diagrams showing thermal demagnetization of a three component IRM applied along the X, Y, and Z axes of the samples; 1.20 T along Z, 0.40 T along Y and 0.15T along X. The magnetization for each axis is normalized to the resultant IRM intensity. In (*b*), the magnetization is carried by magnetite which is indicated by the dominant low-field IRM along X that is unblocked by 580°C. In (*c*), the magnetization is carried by hematite which is indicated by the dominant high-field IRM along Z that is unblocked at 680°C.

ity zone at the bottom of the McCullough Peaks section (B−) is correlated with Chron C24r. This correlation is straightforward for a variety of reasons. The Paleocene-Eocene boundary in terrestrial North American sections has traditionally been recognized by the first appearance of Perissodactyla, Artiodactyla, and true Primates (Gingerich 1989; Gunnell et al. 1993). These first occur in zone Wa-0. The Paleocene-Eocene boundary is also marked by a distinct geochemical signal in both marine (Stott et al. 1990) and terrestrial sections (Koch et al. 1992). The base of the McCullough Peaks section has characteristic Wa-0 taxa, including the first appearance of Perissodactyla, and it has the Wa-0 geochemical excursion (Koch and Zachos unpub. data). Thus the base of the McCullough Peaks section can be regarded as the paleocene-Eocene boundary. Although the exact placement of the Paleocene-Eocene boundary in terrestrial sections is controversial (cf. Rea et al. 1990; Wing et al. 1991; Koch et al. 1992 and Gunnell et al. 1993), the resolution of that problem will

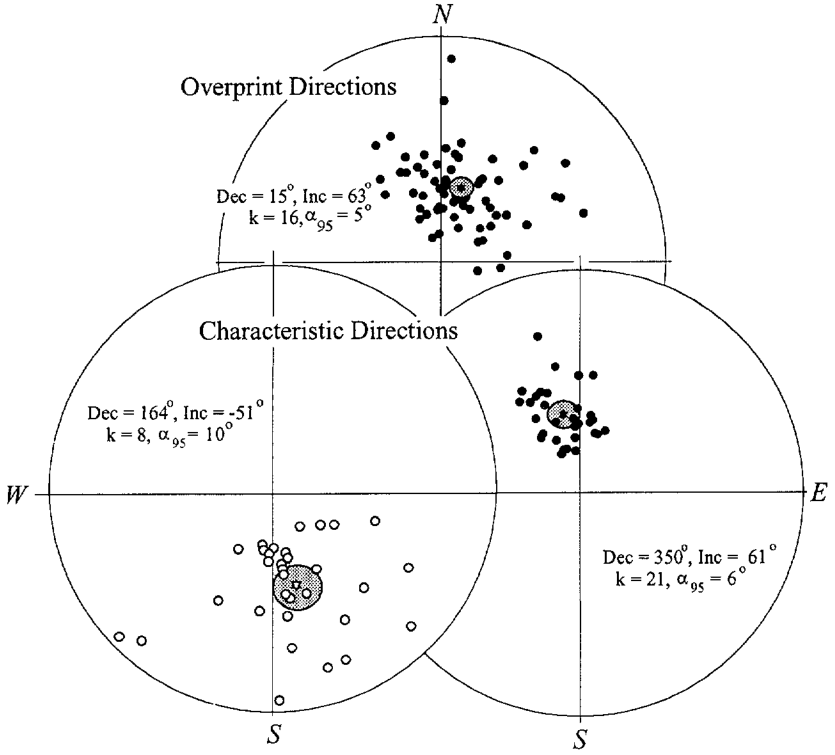

Figure 7. Equal area projections of the overprint directions as well as the normal and reversed polarity characteristic magnetizations. The open (closed) symbols represent sample directions on the upper (lower) hemisphere of the projection. The stars are the mean direction for each group. The shaded ellipses represent the 95% confidence regions around each mean (Fisher 1953).

not affect these results. The time scale of Cande and Kent (1992) located the Paleocene-Eocene boundary within Chron C24r. Butler et al. (1981) also correlated the early Wasatchian to Chron C24r in their study of the adjacent Clarks Fork Basin. It is worthy of note that the lowest interval in the McCullough Peaks section is characterized by normal polarity (A+) and may correspond to the enigmatic Oldhaven event that Townsend and Hailwood (1985) reported at the Paleocene-Eocene boundary in the London Basin (see also Rapp et al. 1983).

Correlation of the upper magnetic zones in the McCullough Peaks section is less straightforward due to the complexity of Chron C24 and the existence of several short-term reversals during this interval. However, a radiometric age of 52.8 ± 0.3 Ma (Wing et al. 1991) for the early Lostcabinian (zone Wa-7) provides an important and independent temporal constraint. In the McCullough Peaks section, the base of the Lostcabinian lies in a reversed polarity zone (H−) that follows a short normal zone (G+) and a short reversed zone (F−). The time scale of Cande and Kent (1992) shows that 52.8 Ma lies in the middle of Chron C24n, which is characterized by a series of short reversals. Correlation of E+ in the McCullough Peaks section with Chron C24n.3n in the GPTS suggests that C+ is also part of Chron C24n.3n. F− is then correlated to Chron 24n.2r, G+ is correlated to Chron C24n.2n, and H− is correlated to Chron C24n.1r. This interpretation assumes that D−, which is poorly characterized, does not represent an actual reversal. Although other correlations for these upper magnetic zones cannot be ruled out without further sampling of the entire Lostcabinian and early Bridgerian, the correlation presented here seems the most likely, based on the observed pattern of reversals and the Wing et al. (1991) radiometric age. More important to this study however, is that the transition from B− to C+ clearly represents the Chron C24r to Chron C24n transition in the GPTS.

Magnetostratigraphy of Wasatchian Faunal Zones

Numerous faunal zonations for the Wasatchian land-mammal age have been proposed over the past 80 years (figure 10). Granger (1914) described the general sequence of Wasatchian faunas in the Bighorn and Clarks Fork basins. He recognized four distinct faunal "members" within the Wasatchian: Sand Coulee, Gray Bull, Lysite, and Lost Cabin. Wood et al. (1941) considered Granger's Sand Coulee as an indistinguishable part of their Gray Bull. Schankler (1980) proposed a different classification based on three points of faunal turnover ("biohorizons") in the Elk Creek section of the central Big-

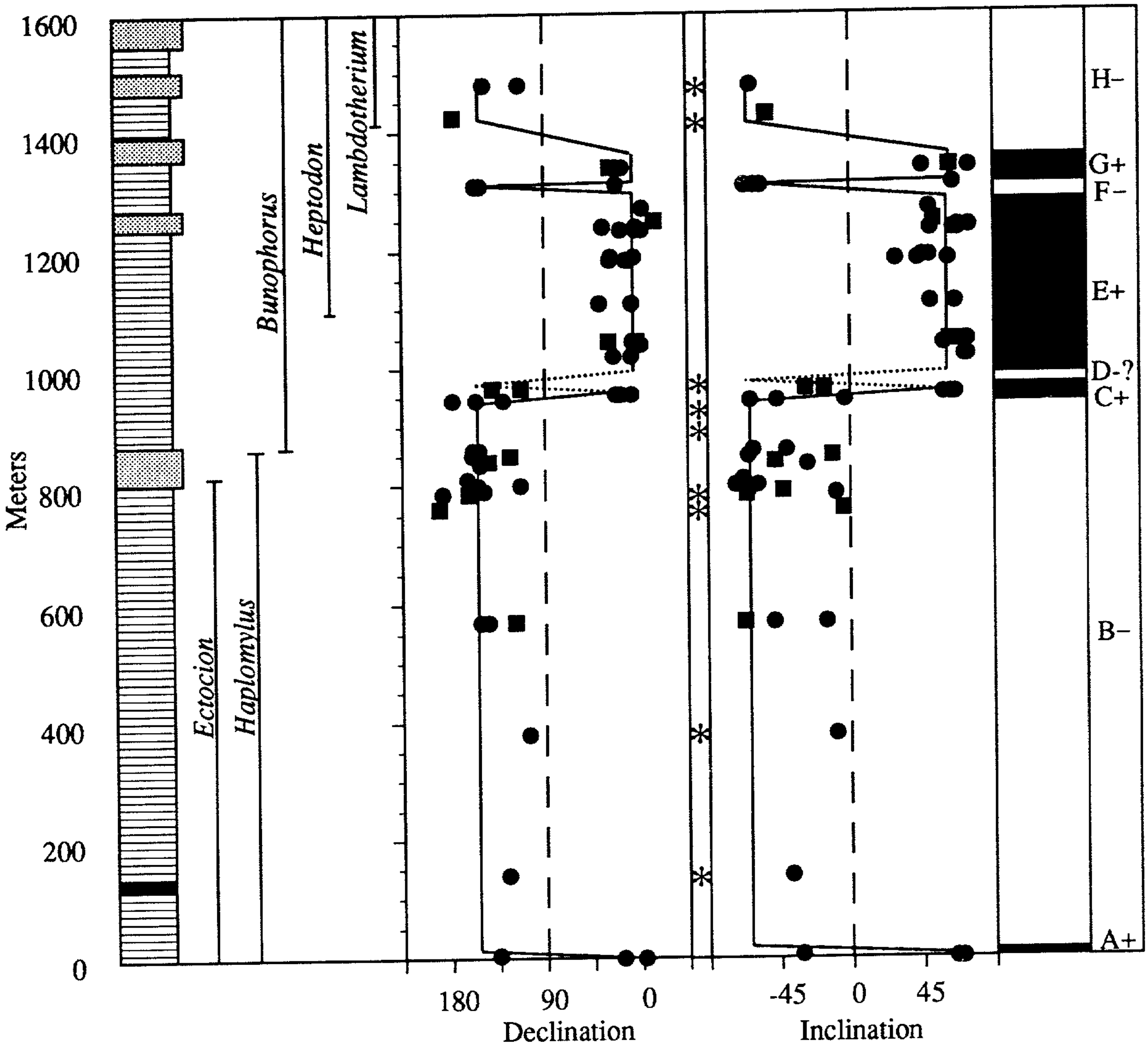

Figure 8. Declination and inclinations of sample characteristic remanent magnetizations (ChRM) are plotted against stratigraphic level in the McCullough Peaks section. Category I lines (solid circles) are lines fit with a maximum angular deviation (MAD) of less than 15°. Category II lines (solid squares) are those fit with a MAD of between 15° and 20°. Asterisks mark levels where great circle determinations were used on samples with obscured linear demagnetization trends due to overlapping unblocking spectra. Simplified lithological description and the stratigraphic ranges of some biostratigraphically important taxa are given at the left. Hatched pattern represents stacked paleosols with interbedded channel sandstones, light shading represents sandstone complexes and black represents carbonaceous shales. Polarity zonation is shown at the right with the black zones representing normal (north and down) polarity and white zones representing reversed (south and up) polarity.

horn Basin. More recently, Gingerich (1983, 1989, 1991) proposed a classification consistent with Granger's and Schankler's that divides the Wasatchian age into eight distinct zones based on first appearances of *Hyracotherium, grangeri* (Wa-0), *Cardiolophus radinskyi* (Wa-1), *Arfia shoshoniensis* (Wa-2), *Homogalax protapirinus* (Wa-3), *Hyracotherium pernix* (Wa-4), *Bunophorus estagicus* (Wa-5), *Heptodon calciculis* (Wa-6), *Lambdotherium primaevum* (Wa-7). Using first appearances of these taxa in the McCullough Peaks section, zones within the Wasatchian land-mammal age can be correlated to the magnetic polarity stratigraphy presented here (figure 10). Zone Wa-0 (earliest Sandcouleean subage) to middle zone Wa-5 (*Bunophorus* interval-zone) falls within Chron C24r, middle zone Wa-5 to middle zone Wa-6 (Lysitean subage) correlates with Chron C24n.3n, late zone Wa-6 entails Chron C24n.2r and Chron C24n.2n, and the beginning of zone Wa-7 (Lostcabinian sub-

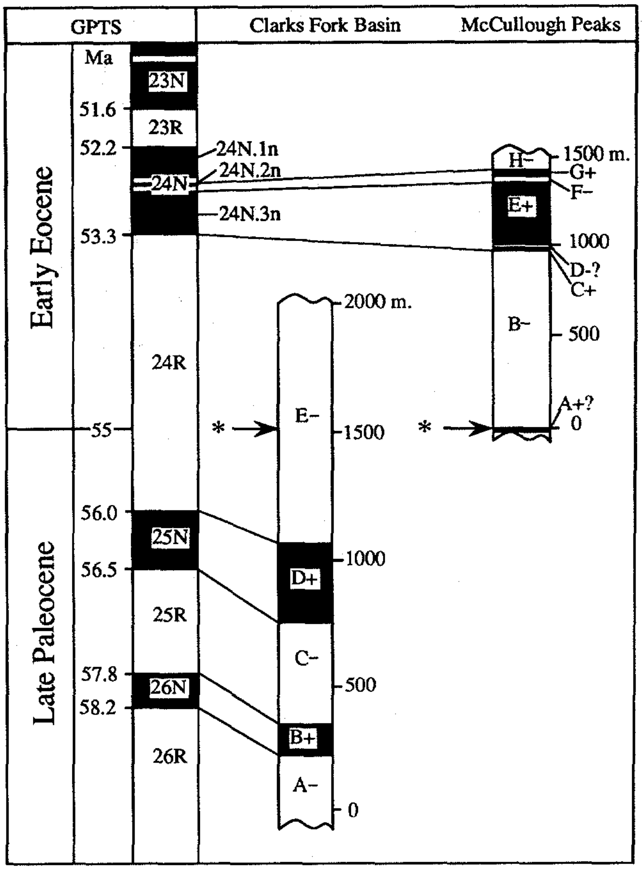

Figure 9. Correlation of the McCullough Peaks polarity zones to the geomagnetic polarity time scale (GPTS) of Cande and Kent (1992). Clarks Fork Basin section is from Butler et al. (1981). Asterisks mark the first appearance of Perissodactyla and the Paleocene-Eocene geochemical excursion of Koch et al. (1992). See text for basis of correlation.

age) falls within Chron C24n.1r. These correlations, coupled with the correlation of an early Bridgerian fauna to Chron C21n or C22n (Flynn 1986), indicate that Chrons C24n.1n, C23r, C23n, and C22r probably all lie within zone Wa-7 (Lostcabinian subage).

Chronometric Calibration

Radiometric calibration provides a means to determine how much geological time is associated with different land-mammal zones. Cande and Kent (1992) placed the Paleocene/Eocene boundary at 55 Ma, and the top of Chron C24n.2 (correlated here to latest zone Wa-6) at 52.6 Ma. The Wasatchian/Bridgerian boundary has been radiometrically dated to approximately 50 Ma (Krishtalka et al. 1987; p. 91–95), making the entire Wasatchian approximately 5 m.y. long. Assuming that our correlation to the GPTS is correct and that the Clarkforkian-Wasatchian boundary is equivalent to the Paleocene-Eocene boundary elsewhere, then zone Wa-7 (Lostcabinian subage) represents approximately one-half of the entire Wasatchian land-mammal age. Wing et al. (1991) suggested that the Lostcabinian represents the last two-fifths of Wasatchian time, and the paleomagnetic results presented here suggest that it spans even more of the Wasatchian. Zone Wa-7 appears to represent as much time as all seven earlier zones, Wa-0 through Wa-6 combined. If zone Wa-0 represents a relatively short interval of time, on the order of 0.20–0.25 m.y. (because it is only, at most, 40 m thick; Gingerich 1989), then each of the six remaining zones represent, on average, about 0.4 m.y. The first half of Wasatchian time is represented by much more sediment than the second half in the Bighorn Basin, which suggests a significant decline in Laramide tectonism and sediment accumulation here during the later part of the early Eocene.

Conclusions

Paleomagnetic analysis of paleosols in the McCullough Peaks section of the Willwood Formation (lower Eocene) indicates that hematite carries a stable remanent magnetization in the B (red) and AB (gray/red) soil horizons. Thermal demagnetization of these samples resulted in a nearly antipodal distribution of ChRM directions similar to the expected Eocene direction for this area. Magnetostratigraphic analysis of the McCullough Peaks section suggests that zone Wa-0 (earliest Sandcouleean subage) to middle zone Wa-5 (*Bunophorus* interval-zone) correlates with Chron C24r, middle zone Wa-5 to middle zone Wa-6 (Lysitean subage) correlates with Chron C24n.3n, late zone Wa-6 correlates with Chron C24n.2 and earliest zone Wa-7 (Lostcabinian subage) correlates with Chron C24n.1r. Radiometric calibration indicates that zone Wa-7 (Lostcabinian subage) represents approximately one-half of the entire Wasatchian land-mammal age and that the interval from zone Wa-0 (earliest Sandcouleean subage) to the end of zone Wa-6 (latest Lysitean subage) represents only 2.4 m.y. of early Eocene time.

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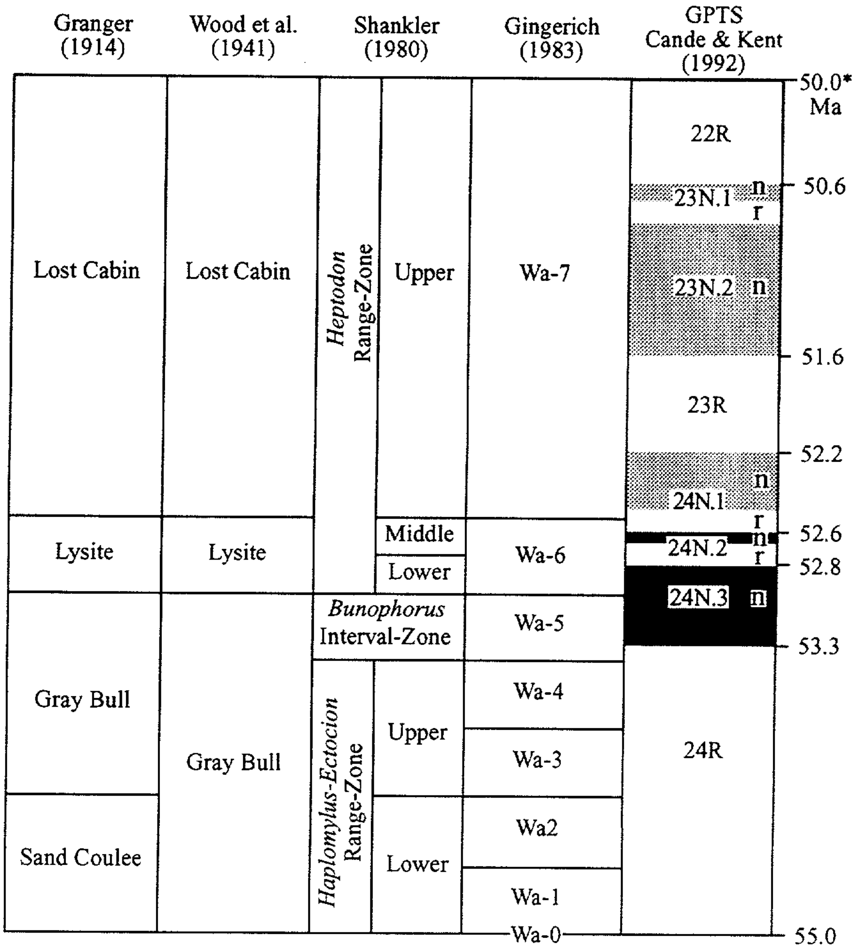

Figure 10. Chronology of Wasatchian faunal zones based on the magnetostratigraphic analysis presented here. The polarity time-scale shows the results from this study (black and white chrons) as well as the inferred correlation of the Lostcabinian to the GPTS (gray and white chrons). The Lostcabinian (zone Wa-7) represents approximately one-half of the entire Wasatchian land-mammal age. Age of 50 Ma for the Wasatchian-Bridgerian boundary (asterisk) is from Krishtalka et al. (1987, p. 91–95); other ages are from Cande and Kent (1992).

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