

MAGNETIC POLARITY STRATIGRAPHY AND BIOSTRATIGRAPHY
OF PALEOCENE AND LOWER EOCENE CONTINENTAL DEPOSITS,
CLARK'S FORK BASIN, WYOMING¹

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ABSTRACT

Paleomagnetic samples were collected at 273 sites within a 2012 m continental sedimentary sequence in the Clark's Fork Basin near Powell, Wyoming. The lower 1158 m is in the Polecat Bench Fm while the upper 854 m is within the Willwood Fm. Although significant secondary components of magnetization were present, alternating-field demagnetization to 300 oe peak field revealed the polarity of the primary component of the natural remanent magnetism. A well-defined polarity zonation is observed. The Polecat Bench Fm is dominantly of reversed polarity but does contain two normal polarity zones. The Willwood Fm in this section is entirely of reversed polarity. Abundant Tiffanian, Clarkforkian, and Wasatchian faunas indicate that the age range of the sediments is from late Paleocene through early Eocene. These age constraints, along with the characteristic polarity sequence, allow the magnetic polarity sequence to be correlated with the magnetic polarity time scale. The section correlates with the magnetic polarity time scale from the reversed polarity interval preceding anomaly 26 chron into the reversed polarity interval preceding anomaly 24 chron. Tiffanian fossils are found in sediments deposited during the reversed polarity interval preceding anomaly 26 chron up into sediments deposited during anomaly 25 chron. Clarkforkian faunas occur in sediments deposited during anomaly 25 chron into the base of the overlying reversed polarity zone. Wasatchian faunas are found within sediments deposited during the reversed polarity interval preceding anomaly 24 chron. The Paleocene/Eocene boundary occurs in the Clark's Fork Basin in the reversed polarity interval preceding anomaly 24. These data indicate that the age of anomaly 24 chron is early Eocene rather than late Paleocene.

INTRODUCTION

The Clark's Fork Basin (fig. 1) is the type area of the transitional Paleocene-to-Eocene Clarkforkian Land Mammal Age. In the Clark's Fork Basin, sediments of Clarkforkian age rest directly on a thick sequence of sediments yielding late Paleocene faunas of Tiffanian age. Rocks of Clarkforkian age are overlain by lower Eocene sediments yielding mammals of Wasatchian age. Taken together, sediments of Tiffanian, Clarkforkian, and Wasatchian ages in the Clark's Fork Basin are the most complete, most richly fossiliferous sequence of continental sediments spanning the Paleocene-Eocene boundary known anywhere in the world.

Magnetostratigraphic studies of terrestrial sedimentary sequences containing important

vertebrate faunas are of considerable importance in establishing the geochronology of land mammal ages. Establishment of the magnetic polarity sequence in sections containing diagnostic vertebrate faunas and correlation of the resultant sequence to the magnetic polarity time scale allows the faunas to be placed within an independent chronologic framework. This chronologic framework is not dependent upon local lithostratigraphic limits or stage of evolution. Combined magnetostratigraphic and biostratigraphic studies of mammalian fossil bearing sequences thus help to establish the temporal limits of land mammal ages and allow more accurate determination of rates of evolution and dispersal of land mammals.

Previous magnetic polarity stratigraphic and biostratigraphic studies in the San Juan Basin of New Mexico have established the placement of the Puercan (early Paleocene) and Torrejonian (middle Paleocene) Land Mammal Ages within the magnetic polarity

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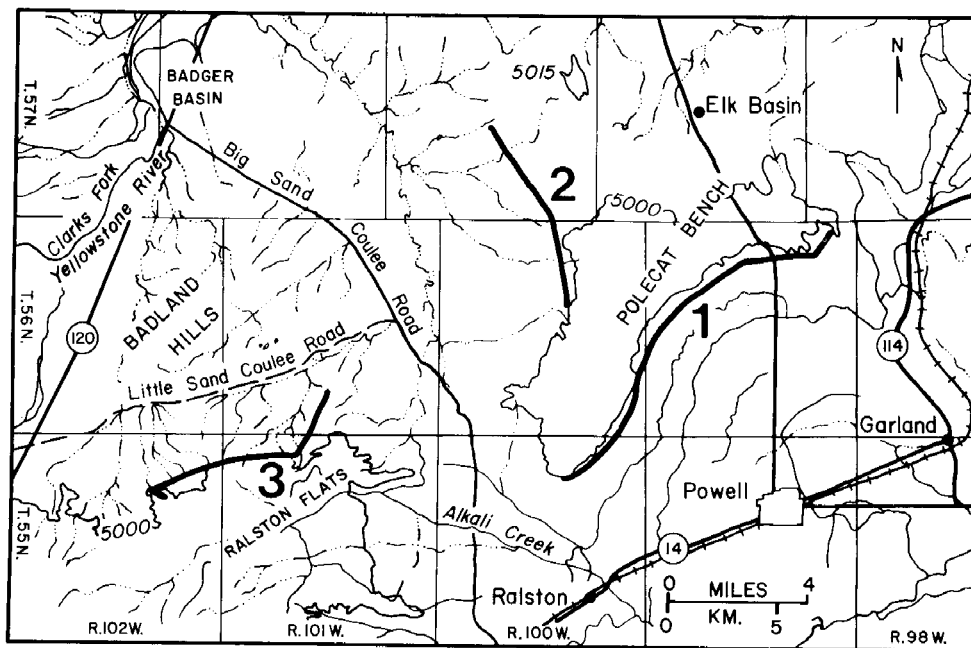


Fig. 1. — Index map of Clark's Fork Basin with locations of paleomagnetic sections. Township and range boundaries and major physiographic features are illustrated. Bold lines are used to illustrate the locations of the paleomagnetic sections. Number 1 is Polecat Bench South, 2 is Polecat Bench Northwest, and 3 is Big Sand Coulee.

time scale (Lindsay et al. 1978, 1980; Taylor and Butler 1980). Magnetic polarity stratigraphy of the North Horn Formation of Dragon Canyon, Utah has allowed determination of the relationship of Dragonian faunas to Puercan and Torrejonian faunas (Tomida and Butler 1980). Continuation of this effort to place North American Land Mammal Ages within the magnetic polarity time scale requires establishment of the magnetic polarity zonation in a sedimentary sequence containing younger vertebrate faunas. The continental deposits of the Clark's Fork Basin, northwestern Wyoming provide an excellent sequence of Paleocene and lower Eocene sediments containing abundant vertebrate fossils. This paper reports the results of paleomagnetic polarity and biostratigraphic study of this sedimentary sequence. The major objective of this work was to establish the magnetic polarity sequence in the Paleocene and lower Eocene deposits of the Clark's Fork Basin and

thereby establish the placement of the Tiffanian, Clarkforkian, and Wasatchian Land Mammal Ages within the magnetic polarity time scale.

BIOSTRATIGRAPHY

The first significant collections of fossil mammals from the Clark's Fork Basin were made by William J. Sinclair and Walter Granger in 1911 and 1912. The recognized two new mammalian faunal horizons, the Clark Fork beds and the basal Wasatchian Sand Coulee beds, respectively, below more typical "Wasatch" early Eocene horizons (Sinclair and Granger 1912; Granger 1914). Collections from these transitional Paleocene-to-Eocene Clark Fork and early Eocene Sand Coulee faunal horizons were augmented by Jepsen (1930). Jepsen also documented the presence of a Tiffany-equivalent late Paleocene faunal zone in the Clark's Fork Basin, and middle Paleocene Torrejon-equivalent and early Paleocene Puerco-

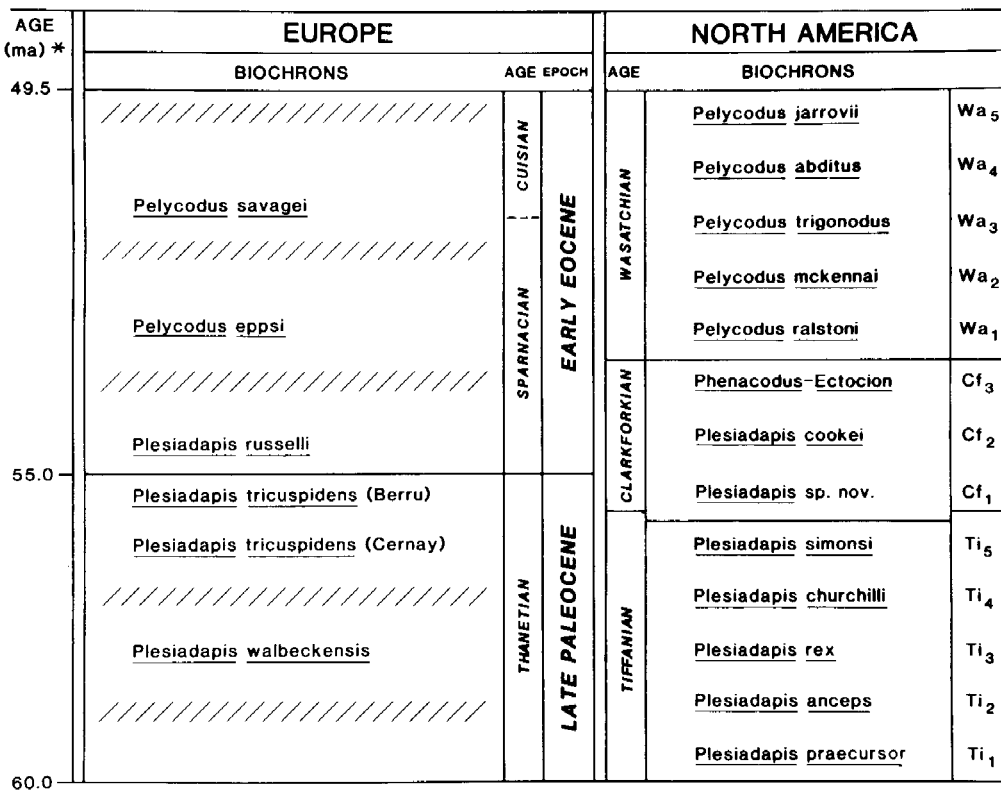


Fig. 2. - Correlation of European and North American land mammal faunas and ages, based on *Plesiadapis* and *Pelycodus* biochrons (Gingerich 1976, 1980; Rose 1980). Hatchures indicate missing section in European sequence, North American sequence is virtually complete. Average duration of each biochron in North America is approximately 0.8 million years. Radiometric ages from Berggren et al. (1978).

quivalent faunal zones on the southeast flank of Polecat Bench, stratigraphically below the Tiffany-equivalent faunal interval. Later Wood et al. (1941) recognized these faunal (e.g., Tiffany, Torrejon, and Puerco) zones as North American Cenozoic provincial land mammal ages. The faunas of the two earliest Cenozoic land mammal ages are still represented in the Clark's Fork-Polecat Bench area principally by two quarry samples: e.g. from the Mantua Quarry (Puercan) and the Rock Bench Quarry (Torrejonian). These are exposed near the base of the Polecat Bench Formation (Jepsen 1940, equals the Fort Union Formation of some authors) on the southeast side of Polecat Bench in a sandstone sequence that

has not yielded reliable paleomagnetic determinations.

Fossils diagnostic of Tiffanian, Clarkforkian, and Wasatchian land mammal ages occur in the Clark's Fork Basin and adjacent Bighorn Basin in a thick sequence of fluvial sediments of the Polecat Bench and Willwood Formations (Van Houten 1944). These three land mammal ages can be subdivided into a sequence of 13 biostratigraphic zones or biochrons (Gingerich 1976, 1980) based on the evolution of the abundant primates *Plesiadapis* and *Pelycodus* (see fig. 2). Biochrons Ti₂ through Wa₃ are all represented by local ranges of diagnostic taxa in one continuous sequence on Polecat Bench and in the Clark's Fork Basin.

The Paleocene-Eocene boundary was originally defined ambiguously by Schimper (1874), and consequently several different boundaries are presently recognized by different authors. Vertebrate paleontologists generally place the boundary at the base of the Sparnacian in the Paris Basin, (e.g., Russell 1968; base of planktonic foraminiferal zone P5). Invertebrate paleontologists sometimes place the boundary at the base of the London Clay (e.g., Curry et al. 1978, at base of zone P6a), or at the base of the Ypresian (Berggren 1972; base of zone P6b) between the Sparnacian and Cuisian (e.g., Hay and Mohler 1967; base of zone P8). Paleobotanists sometimes place the boundary at the top of the Paris Basin Cuisian (Schorn 1971, base of zone P9 or P10). In recent years there has been progress toward agreement on placement of the Paleocene-Eocene boundary at the base of the Sparnacian (Pomerol 1969; Gingerich 1975; Berggren et al. 1978), recognizing the profound change in mammalian faunas that occurs between the *Conglomerat de Cernay* (Thanetian) and the *Conglomerat de Meudon* (Sparnacian). However, there is by no means universal agreement regarding placement of this boundary. In this paper we follow Russell (1968), Pomerol (1969), and others in regarding the base of the Sparnacian in the Paris Basin as the base of the Eocene.

In the Paris Basin the basal Sparnacian mammalian fauna of Meudon differs from older Thanetian faunas (at Cernay and Berru) in having a larger, more advanced species of *Plesiadapis* (*P. russelli*), and the earliest Rodentia, Perissodactyla, oxyaenid Creodonta, and genus *Coryphodon* known from Europe. By comparison with North American faunas the Meudon fauna is equivalent to the Clarkforkian, implying that the North American Clarkforkian Land Mammal Age is early Eocene in age (Gingerich 1976). Recent biostratigraphic work in the Clark's Fork Basin indicates the presence of a zone (Cf₁) that was not known before. Based on a species of *Plesiadapis*, this new basal Clarkforkian

zone (Cf₁) correlates with the Thanetian locality of Berru in the Paris Basin, while the overlying *Plesiadapis cookei* zone (Cf₂) correlates with Meudon and the basal Sparnacian. Thus, the Thanetian-Sparnacian (Paleocene-Eocene) boundary in Europe appears to coincide with the boundary between Cf₁ and Cf₂ in the Clark's Fork Basin (Rose 1980). These relationships are shown diagrammatically in figure 2.

PALEOMAGNETIC ANALYSIS

At least three oriented block samples were collected at each of the 273 paleomagnetic sites. Collection and sample preparation techniques are described in Johnson et al. (1975). Paleomagnetic sites were biased towards the finest lithologies and least weathered outcrops available. Most sites were in dark claystone or fine siltstone, and red beds in the Willwood Formation were avoided. Measurements of remanent magnetization were done using a cryogenic magnetometer (Superconducting Technology, C-102) with noise level of $\sim 1 \times 10^{-7}$ gauss·cm³. A Schonstedt GSD-1 single-axis demagnetizer was used for performing alternating-field (AF) demagnetization.

Intensities of natural remanent magnetization (NRM) are low in both the Polecat Bench and Willwood Formations. Mean NRM intensities following AF demagnetization in 300 oe peak field are 3×10^{-7} gauss in the Polecat Bench Formation and 6.5×10^{-7} gauss in the Willwood Formation. Representative progressive AF demagnetization data are illustrated in figure 3. In the progressive demagnetization experiments, all three samples from the site studied were subjected to progressive demagnetization and the site mean intensity and direction were determined following each AF treatment. The site means are plotted in figure 3. This technique was found helpful in analyzing the progressive demagnetization behavior of these weakly magnetized sediments.

Figure 3a (PB203) illustrates a common AF demagnetization behavior observed for sites with a primary NRM of reversed

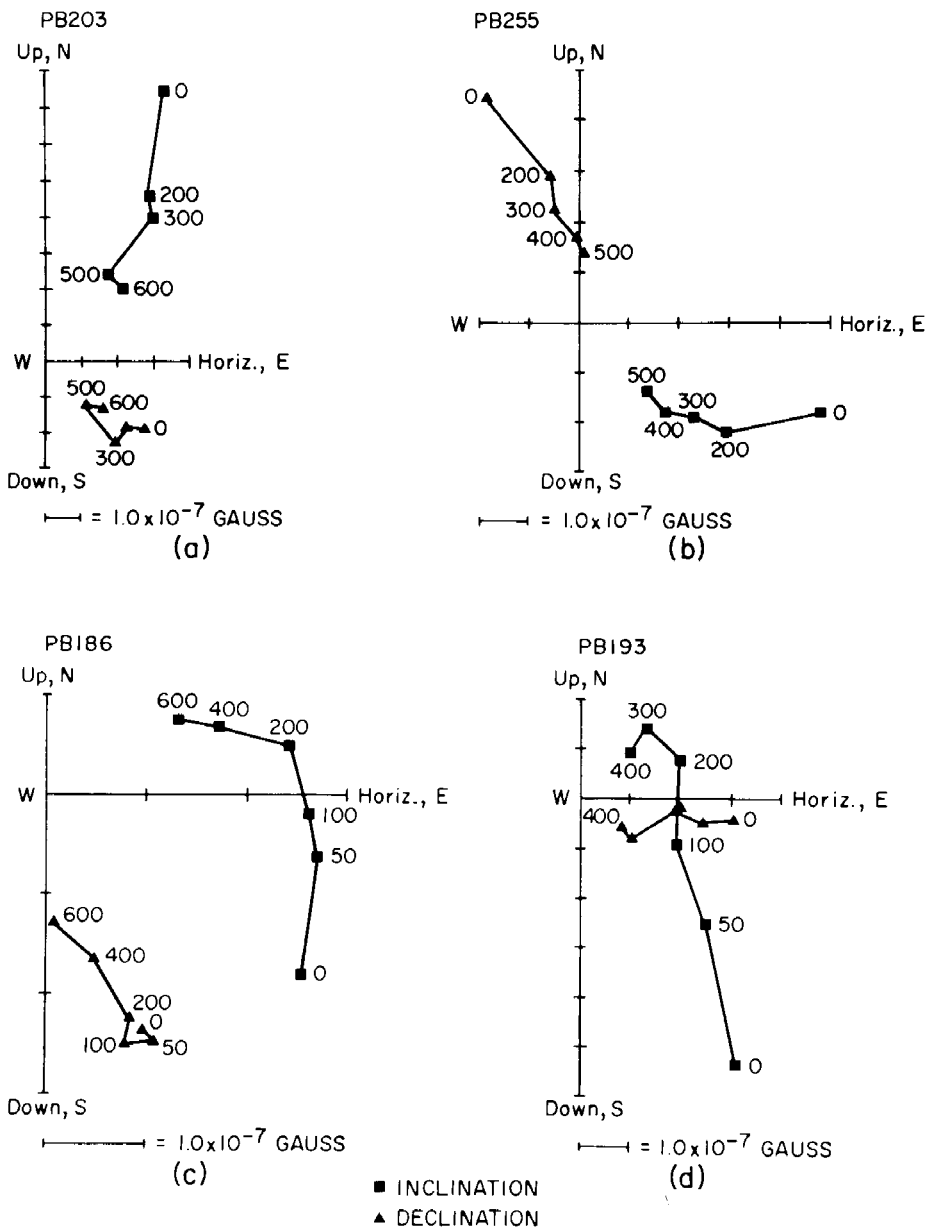


Fig. 3. - Vector demagnetization diagrams. The diagrams are a modification of the Zijdeveld diagram. Squares are used to plot vertical versus horizontal components while triangles illustrate the projection of the magnetization vector on the horizontal plane. Numbers adjacent to data points indicate the peak demagnetizing field in oersteds. Scale of axes in units of remanent magnetization intensity is illustrated at base of figure.

polarity (negative inclination and southerly declination). A basic trend toward the origin with little directional change is observed during demagnetization. A considerable portion of the NRM of this site resides in the 0 to 500 oe remanent coercivity range. Site PB255 (fig. 3*b*) illustrates the progressive AF demagnetization of a site with a primary component of normal polarity (positive inclination and northerly declination). The vector demagnetization diagram shows the desired trend toward the origin following a directional shift between 0 and 200 oe peak field. Again a large proportion of the NRM has remanent coercivity in the 0 to 500 oe range.

Sites PB186 and PB193 (figs. 3*c* and 3*d*, respectively) show a progressive AF demagnetization behavior frequently observed in sites with a primary NRM of reversed polarity. Large directional changes are observed between 0 and 200 oe peak demagnetizing field. This is followed by stabilization of the direction and decrease in intensity of the remaining NRM. Because of the low NRM intensity, it is sometimes difficult to establish the desired linear trend toward the origin of the vector demagnetization diagram at AF fields higher than 400 oe. However, it is fairly clear that the NRM of these sites is of two components. The low coercivity component erased below 200–300 oe is almost certainly a secondary viscous component. This secondary component is almost always of normal polarity and usually is of larger amplitude in the coarser grained samples. The more stable primary components for sites PB186 and PB193 are of reversed polarity and significant proportions of these primary components are contained in the 200 to 600 oe coercivity range.

The AF demagnetization behaviors observed for these samples are similar to those observed for samples from the San Juan Basin (Lindsay et al. 1980). The carrier of the primary NRM has a large proportion of its remanent coercivity spectrum within the 200 to 600 oe interval. This property is commonly observed in sediments where the

primary NRM is a depositional remanence (DRM) carried by detrital magnetite or titanomagnetite. Although polished sections of these fine-grained sediments are difficult to prepare, the few polished sections which have been successfully prepared show magnetite (or titanomagnetite) as the dominant opaque mineral. Isothermal remanence (IRM) acquisition experiments have been performed on one sample from each of 45 sites. In most cases, almost all the IRM is acquired in magnetizing fields less than 3000 oe, with little or no additional IRM acquired at higher magnetizing fields. This behavior is consistent with the other observations indicating that magnetite (or titanomagnetite) is the dominant ferromagnetic mineral. The IRM acquisition data further indicate the absence of high coercivity minerals such as hematite. No correlations between magnetic properties and polarity of primary NRM have been observed. More detailed rock-magnetic and thermomagnetic analyses of these sediments are planned. However, the basic conclusion that the primary NRM is a depositional remanence acquired penecontemporaneous with deposition seems secure.

As illustrated by the progressive AF demagnetization results, determination of the polarity of the primary component required AF demagnetization to at least 300 oe peak field. The NRM of each sample was measured before demagnetization and following AF demagnetization at 200 and 300 oe peak fields. Sites for which significant directional change was observed between 200 and 300 oe were subsequently demagnetized at 400 oe peak field in order to assure that the polarity of the primary NRM could be confidently determined. This additional demagnetization was necessary for less than 10% of the sites. This procedure provided the motion of the site mean direction during progressive AF demagnetization, as well as the final cleaned direction, for determination of the polarity of the primary component. Unambiguous polarity determination was possible for almost all sites.

Site mean directions were calculated by the technique of Fisher (1953), and Watson's (1956) test for randomness was also performed. Statistical parameters of all sites were examined to establish which sites contained grouping of sample NRM vectors which exceeded that expected for selection from a random population at the 95% confidence level. Passage of this test requires $R \geq 2.62$ for $N = 3$ and is a rather stringent test for such weakly magnetized rocks. In the Polecat Bench Formation, 116 of the 169 sites passed this test while 62 of the 104 sites in the Willwood Formation passed the test. No data were rejected as a result of this statistical analysis. However, polarity assignments for sites passing the test are felt to be more confident than those with less well clustered directions of NRM. Accordingly, sites whose clustering is significantly different from random at the 95% confidence level are given more weight in interpretation of the polarity zonation.

POLECAT BENCH SOUTH

The most complete stratigraphic record of late Paleocene mammalian faunas is on the south side of Polecat Bench (fig. 4). The base of the section is the Cretaceous-Tertiary boundary, immediately underlying Mantua Quarry. The fauna from Mantua Quarry is early Paleocene (Puercan) in age (Jepsen 1930). Some 65 m above the level of Mantua Quarry on the east side of Polecat Bench is Rock Bench Quarry, yielding a fauna of middle Paleocene age (Torrejonian, Jepsen 1930). The Mantua Quarry level can be traced to the southeast of Polecat Bench, 2 km south of Mantua Quarry itself, where our section begins.

The only early Tiffanian fauna in the Polecat Bench section is from locality 263, 175 m above the level of the Cretaceous-Tertiary boundary. This locality yields *Plesiadapis anceps* (Gingerich 1976), establishing its age as early Tiffanian (Ti_2). Three middle Tiffanian faunas including *Plesiadapis rex* are now known from localities 262, 261, and 243 on the southeast side of Polecat

Bench. These localities span the stratigraphic interval from 280–425 m above the base of the section.

Late Tiffanian faunas are known from three levels. Localities 239 and 228 are early late Tiffanian (Ti_4) in age, yielding *Plesiadapis churchilli*. Locality 239 is also known as the Airport locality (Gingerich 1975; it is now clear that, through an error in mapping, some specimens in the Princeton University collection of 1928 published as coming from this locality were actually collected from the middle Tiffanian several miles to the east). Localities 85 and 86 are higher stratigraphically, at level 840 m, and they yield a late Tiffanian fauna including a specimen referable to *Plesiadapis fodinatus* or possibly its descendant *Plesiadapis dubius*. This specimen indicates a very late Tiffanian age (Ti_5 , probably late Ti_5) for these localities.

Clarkforkian faunas are found in the interval from 975 m to 1490 m (975 to 1520 m in the section measured by Gingerich 1976; this slight discrepancy is in total thickness only and there is no significant difference in the relative spacing or sequence of localities). Two localities, 83 and 78, span the early Clarkforkian (Cf_1) from levels 975 to 1130 m. The lowest of these includes both *Esthonyx* and *Coryphodon*, genera that first appear in North America in the early Clarkforkian. *Plesiadapis cookei* is found from locality 74 (level 1160 m) to locality 65 (level 1300 m). These span the middle Clarkforkian (Cf_2). Late Clarkforkian (Cf_3) faunas are found in the interval from 1400 to 1490 m. These include localities 72, 70, etc.

The beginning of the Wasatchian is marked by the first appearance of Perissodactyla (*Hyracotherium*), Artiodactyla (*Diacodexis*), modern primates (*Pelycodus*), and hyaenodontid Creodonta (*Arfia*). These new forms first appear at the same stratigraphic level, level 1500 m in figure 4, where they dominate the fauna from their first introduction. Sediments of Wasatchian age are only present at the very southwest end of Polecat Bench. Localities 67, 69, 68, and others are all

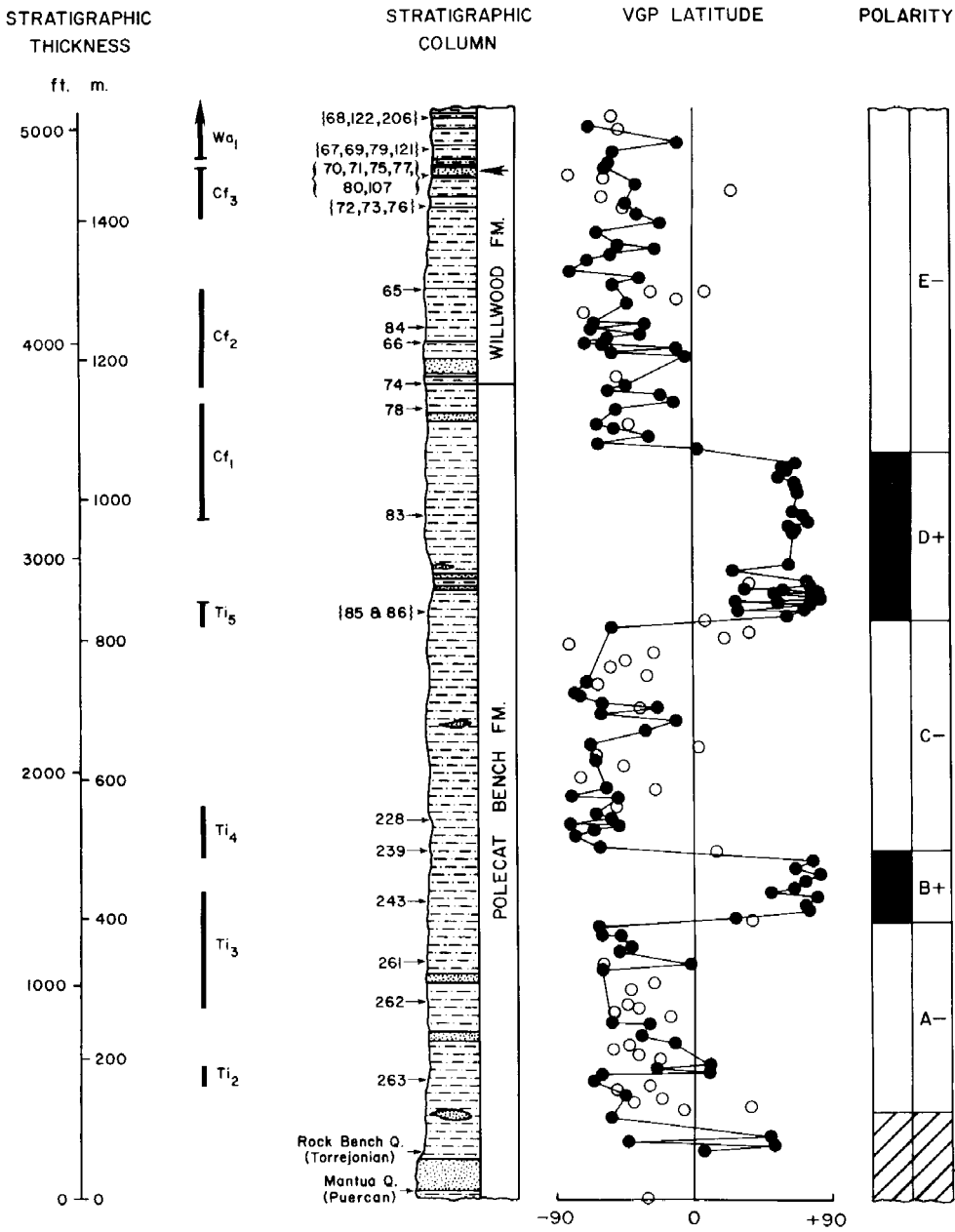


Fig. 4. — Polecat Bench South Section. Stratigraphic column, virtual geomagnetic pole (VGP) latitude, and interpreted polarity column are plotted against stratigraphic thickness. Numbers to left of stratigraphic column are University of Michigan Museum of Paleontology vertebrate fossil localities. Heavy vertical lines to left of lithologic column indicate local range zones of mammal species diagnostic of vertebrate biochronology. Solid circles in VGP plot designate sites with grouping of NRM vectors which is significantly removed from selection from a random population at the 95% confidence level. Open symbols are from sites with poorer clustering. Dot pattern in stratigraphic column indicates sandstone, dot-dash pattern indicates alternating silts and clays, solid lines indicate red beds. Arrow to right of stratigraphic column indicates the location of the boundary sandstone.

earliest Wasatchian (Wa_1). No higher levels are present on Polecat Bench.

Site mean virtual geomagnetic pole (VGP) latitudes following AF demagnetization are plotted for the Polecat Bench South section in figure 4. Also illustrated is the interpreted polarity column. Negative VGP latitude indicates reversed polarity and positive VGP latitude indicates normal polarity. Although some sites with reversed primary components do not reach high negative VGP latitudes because of secondary normal polarity overprints which are not easily erased, the motion of the site mean directions during demagnetization are clearly toward reversed polarity. Thus, we can confidently assign a reversed polarity to the primary NRM.

We have not designated polarity zones in the lower 100 m of this section. This is because we do not believe that the results in this interval are reliable. Lithologies in this stratigraphic level are dominated by sandstones and weathering of the outcrop is quite deep in this area. Also, we do not observe a coherent pattern of VGP latitudes which are distributed into stratigraphic intervals of positive and negative VGP latitudes. Above the 100 m level we observe coherent patterns of VGP latitudes which clearly define the polarity zonation. Polarity zones are designated using the labeling system of Alvarez et al. (1977).

The polarity zones from the Clark's Fork Basin described in this paper should be referred to using the prefix "Powell." The basal polarity zone in the section would be designated "Powell A-." This nomenclature is analogous to that used by Alvarez et al. (1977) and is in keeping with recent recommendations regarding magnetostratigraphic nomenclature (*Geology*, 1979, v. 7, p. 578-583). However, where the context makes it clear that the polarity zones being discussed are from the present study, the prefix Powell may be dropped.

Reversed polarity zone A- is ~300 m in thickness and is overlain by normal polarity zone B+ which has a thickness of ~100 m. The Airport fossil locality is at a stratigraphic level near the base of reversed polarity zone

C- which has a thickness of ~350 m. The overlying normal polarity zone D+ has a thickness of ~250 m. Reversed polarity zone E- extends to the top of this section. This magnetozone contains the contact between the Polecat Bench and Willwood Formations near its base and the boundary sandstone near the top of the section (shown by arrow in lithologic column of fig. 4).

POLECAT BENCH NORTHWEST

Late Paleocene faunas are also known from the northwest side of Polecat Bench. The most productive locality is Princeton Quarry (Jepsen 1930; Jepsen and Woodburne 1969). This quarry has yielded a large sample of late Tiffanian (Ti_5) mammals, including the primate *Plesiadapis fodinatus*. Locality 144 is approximately 100 m above the level of Princeton Quarry (fig. 5), and it also yields a late Tiffanian fauna. Jepsen and Woodburne (1969) described a specimen of *Hyracotherium* said to come from this locality, but there is some reason to doubt locality documentation with the specimen and repeated collecting at locality 144 in recent years has failed to turn up any additional specimens of *Hyracotherium*. Localities 178 and 191 are approximately 300 m above the level of Princeton Quarry. Both of these yield a Tiffanian fauna, but locality 178 also includes the new species of *Plesiadapis* characteristic of the early Clarkforkian. Thus localities 178 and 191 on the west side of Polecat Bench are latest Tiffanian (late Ti_5) and should be closely correlative with localities 85 and 86 on the east side of Polecat Bench.

The two polarity zones of this section are quite well defined by the pattern of VGP latitudes illustrated in figure 5. A site with good clustering and positive VGP is found at the 300 m level, but this site showed consistent motion towards reversed polarity during demagnetization. Thus, the positive VGP latitude of this site should not be taken to indicate the presence of a thin normal polarity zone. The basal 350 m of the section are of reversed polarity while the upper 160 m are normal polarity. These

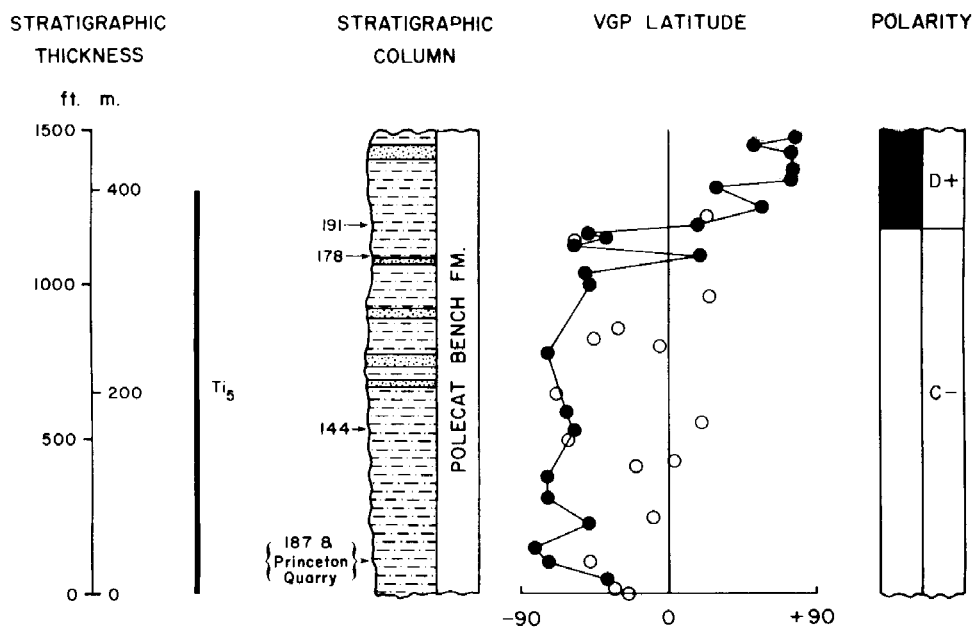


Fig. 5. — Polecat Bench Northwest Section. Labels as in figure 4.

polarity zones are labeled C- and D+, respectively, for reasons explained below.

BIG SAND COULEE SECTION

The Clarkforkian-Wasatchian boundary is marked lithologically by a sheet sandstone unit that can be traced west of Polecat Bench for some 25 km across the Clark's Fork Basin (Kraus 1980). Numerous fossil mammal localities are now known both above and below this sandstone. Our paleomagnetic section of the Clark's Fork Basin Wasatchian begins below the boundary sandstone at late Clarkforkian (Cf₃) locality 60 and proceeds up the south side of the west fork of Big Sand Coulee.

The first 100 m above the Clarkforkian-Wasatchian boundary sandstone in Big Sand Coulee (fig. 6) includes localities 27, 26, and 4, all of which yield *Pelycodus ralstoni* indicating an early Wasatchian (Wa₁) age. The next interval, from 100 to about 400 m above the base of the Wasatchian, includes localities 151, 96, 35, 114, and others, yielding *Pelycodus mckennai*. This interval is also early Wasatchian (Wa₂). Localities

more than 400 m above the Clarkforkian-Wasatchian boundary in Big Sand Coulee, such as locality 112, yield *Pelycodus trigonodus*, indicating a middle Wasatchian (Wa₃) age. No mammalian faunas younger than middle Wasatchian have been found in the Clark's Fork Basin.

An increased proportion of sand in the Big Sand Coulee Section has evidently resulted in an increased occurrence of normal polarity overprints on the paleomagnetic samples in this section. However, the pattern observed for the well clustered sites quite clearly indicates that the entire 650 m of this section has a primary NRM of reversed polarity. A single well clustered site near the top of the section has a high positive VGP latitude. However, the odd mean direction observed ($I = +18^\circ$, $D = 6^\circ$) is not a good indicator of normal polarity and the inclination consistently shallowed during the progressive demagnetization. Therefore, this site is not a reliable indicator of a primary NRM of normal polarity. The data are thus interpreted as defining a single 650 m thick reversed polarity zone in the

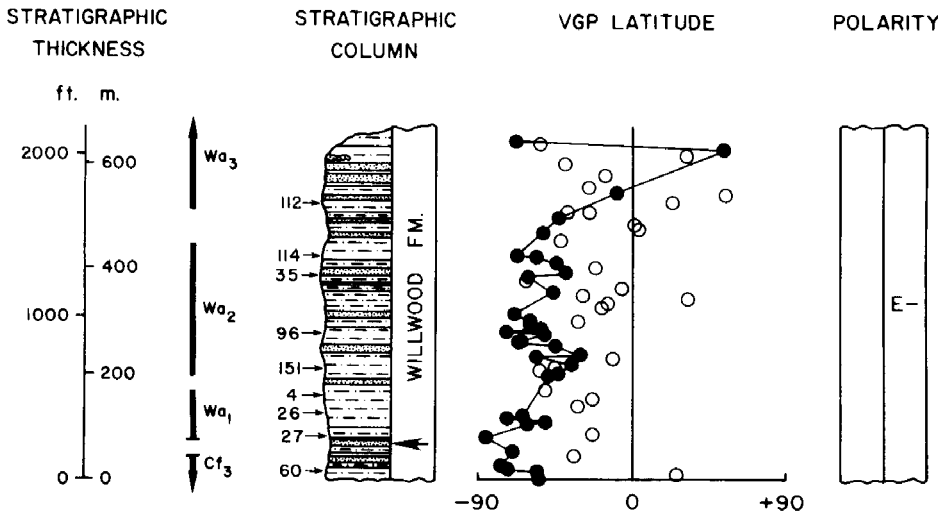


Fig. 6. - Big Sand Coulee Section. Labels as in figure 4.

Big Sand Coulee section. The E- label of this polarity zone is explained below.

TIFFANY SECTION - BIOSTRATIGRAPHY

One of the most important late Paleocene faunas in North America is from 7-8 km north of Tiffany, Colorado. This Tiffany fauna, on which the Tiffanian land mammal age was originally based, comes from a stratigraphic interval approximately 100 m thick with the Mason Pocket Quarry near its base (Granger 1917). The fauna from Mason Pocket consists predominantly of small mammals (Simpson 1935). It includes *Nannodectes gidley* and *Chiromyoides caesor*, and on the basis of these records the Mason Pocket fauna is regarded as late Tiffanian (Ti₄) in age (Gingerich 1976). Most other localities in the vicinity of Tiffany are stratigraphically higher than Mason Pocket. These include localities yielding the *Phenacodus* and other large mammals described by Simpson (1935), the large *Oxyaena* described by Van Valen (1966), and *Chiromyoides potior* described by Gingerich (1976). Large *Oxyaena* and *Chiromyoides potior* first appear in the Bighorn Basin of Wyoming in the *Plesiadapis simonsi* zone (Ti₅), and it is probable that some, if not all, of the Tiffany fauna from levels above Mason

Pocket is correlative with the local range zone of *Plesiadapis simonsi* in the Bighorn Basin, i.e. (Ti₅). Thus, faunally the Tiffany beds encompass only the later part (Ti₄ and Ti₅) of the Tiffanian Land Mammal Age.

The paleomagnetic data shown in figure 7 for the Mason Pocket section clearly indicate that the entire 150 m section is of reversed polarity. The relationship of this reversed zone A- to the Big Horn Basin section is addressed in the following discussion. This polarity zone should be designated Mason A-. The prefix "Mason" follows Simpson's designation of the fossil locality as Mason Pocket and is also derived from the proximity of this section to Mason Peak.

COMBINED CLARK'S FORK BASIN SECTION

Figure 8 illustrates how the three paleomagnetic sections from Clark's Fork Basin are related. The Polecat Bench South and Big Sand Coulee sections are correlated both lithostratigraphically and biostratigraphically. The sandstone complex within the Willwood Formation known as the boundary sandstone occurs near the top of the Polecat Bench South section and near the base of the Big Sand Coulee section. This lithostratigraphic correlation between the two sections

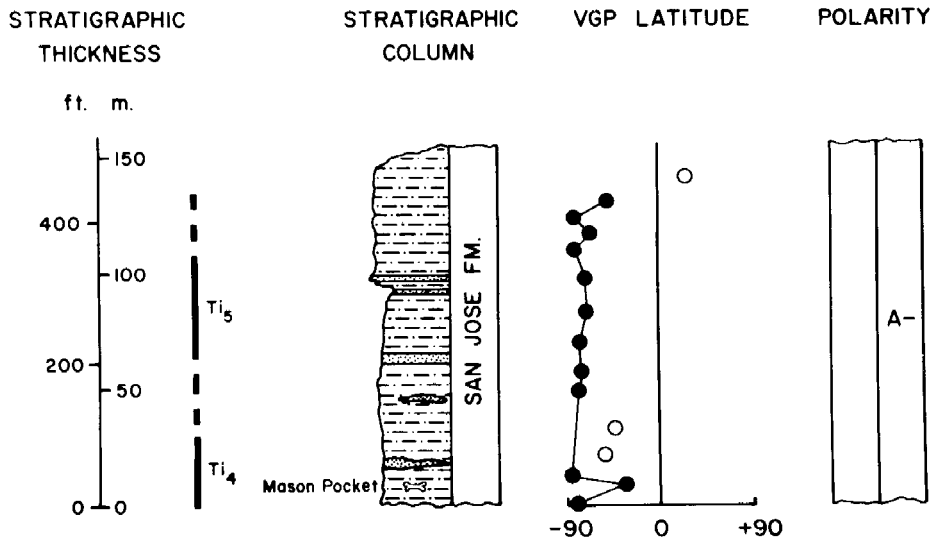


Fig. 7. — Mason Pocket Section. Labels as in figure 4.

is illustrated by the arrows connecting the sections. Additionally, the biostratigraphic boundary between Clarkforkian faunas and Wasatchian faunas occurs at this same stratigraphic level in both the Polecat Bench and Big Sand Coulee sections. Thus, the correlation shown in figure 8 between these two sections is strongly supported by both lithostratigraphic and biostratigraphic evidence. The two sections have considerable overlap, so that there is little danger of having missed a thin magnetic polarity zone. It is therefore clear that reversed polarity zone E- of the Polecat Bench South section is continued in the Big Sand Coulee section. Accordingly, the reversed zone in Big Sand Coulee is labeled E-.

Correlation of the Polecat Bench Northwest section to the Polecat Bench South section is also illustrated in figure 8. This correlation is based on magnetostratigraphic and faunal evidence. Tiffanian fossils occur within magnetozone C- in both sections. Latest Tiffanian localities 85 and 86 occur at the top of C- in the Polecat Bench South section while localities 191 and 198 of the Polecat Bench Northwest contain a latest Tiffanian fauna and are also found at the top of the reversed zone C- in that section.

The respective reversed and normal polarity zones C- and D+ of these two sections obviously correlative and the base of the I zone provides an accurate determination of the stratigraphic relationships between the two sections. No other correlation of the magnetic polarity zones is possible without violating the clearly defined biostratigraphic relationships in the two sections.

The magnetic polarity zonation of the complete stratigraphic interval sampled in the Clark's Fork Basin is shown at the right-hand side of figure 8. To the right of this magnetic polarity column are shown stratigraphic intervals within which faunal localities assigned to the Tiffanian, Clarkforkian, and Wasatchian Land Mammal A occur. The Wasatchian extends above the present section since even the youngest Wasatchian fauna in the Big Sand Coulee section is middle Graybullian. The boundary between the Paleocene and Eocene epochs is placed between zones Cf₁ and Cf₂. The observed magnetic polarity sequence consists of one reversed and one normal polarity zone below the reversed zone C- which contains the Tiffanian localities. This reversed zone is then followed by normal polarity zone D+ which in turn is overlain by the 200

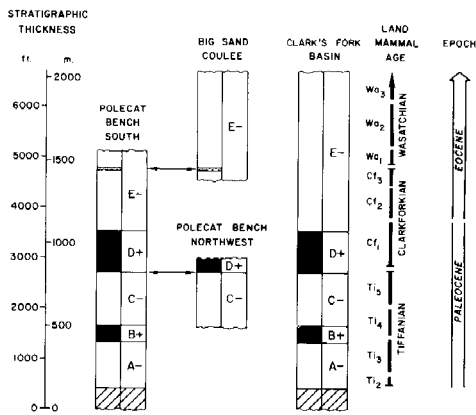


Fig. 8. — Combined Clark's Fork Basin sections. Dot pattern in Polecat Bench South and Big Sand Coulee sections indicate the level of the boundary sandstone. Arrows connecting sections illustrate the correlations between the sections. See text for details. Combined section is labeled Clark's Fork Basin. Bold vertical lines to right of combined section indicate the local range zones of mammal species diagnostic for vertebrate biochrons in Tiffanian, Clarkforkian, and Wasatchian land mammal ages.

thick reversed polarity zone E-. Clarkforkian faunas occur in the basal portion of E- while Wasatchian faunas occur in the upper portion. The biostratigraphic and paleomagnetic data of the three sampled sections have thus provided a consistent and well defined magnetic polarity and biostratigraphic sequence. The next step in analysis of the data is correlation of this magnetic polarity sequence to the magnetic polarity time scale.

We note that the magnetic polarity data from the Paleocene age lower part of the San Jose Formation of the San Juan Basin (fig. 7) is consistent with the Clark's Fork Basin sequence. The Mason Pocket locality in the San Juan Basin is contained within a reversed polarity zone. All of the late Tiffanian localities in the Big Horn Basin are contained within or adjacent to reversed polarity zone Powell C-. These data strongly suggest that Big Horn Basin polarity zone Powell C- and the reversed polarity zone of the lower San Jose Formation containing the Mason Pocket locality (Mason A-) are

correlative recordings of the same reversed polarity interval. The absence of any normal polarity zones in the Mason Pocket section makes more precise correlation impossible.

DISCUSSION AND INTERPRETATIONS

Before attempting to correlate the Clark's Fork Basin polarity sequence to the magnetic polarity time scale, we must discuss the choice of time scale used. In recent years, the most widely used magnetic polarity time scale for the Cenozoic has been that of LaBrecque et al. (1977). This time scale was derived from analyses of marine magnetic anomalies and was a revision of the original magnetic anomaly time scale of Heirtzler et al. (1968). However, an increasing body of biostratigraphic evidence from DSDP cores points to the need for revision of the Paleogene portion of the magnetic polarity time scale. For example, Berggren et al. (1978) noted that invertebrate biozonation observed in cores from DSDP site 39 (Sclater et al. 1974) indicate that anomaly 24 chron should be placed at the Paleocene/Eocene boundary rather than in the mid to upper Paleocene as in the LaBrecque et al. (1977) time scale. (In keeping with the recommendations of the IUGS International Subcommittee on Stratigraphic Classification and the IUGS/IAGA Subcommittee on a Magnetic Polarity Time Scale, time intervals of the magnetic polarity time scale are referred to by attaching the suffix "chron." Thus, "anomaly 24 chron" refers to the interval of time within which the geomagnetic was entirely or dominantly of normal polarity and during which oceanic crust produced by seafloor spreading was entirely or dominantly of normal magnetic polarity. This oceanic crustal magnetization produces a magnetic anomaly which is referred to as magnetic anomaly number 24 or, more commonly, as anomaly 24.)

Ness et al. (1980) have critically evaluated a large body of data pertaining to the development and present status of marine magnetic anomaly time scales. They have developed a magnetic polarity time scale which incorporates recent DSDP data and

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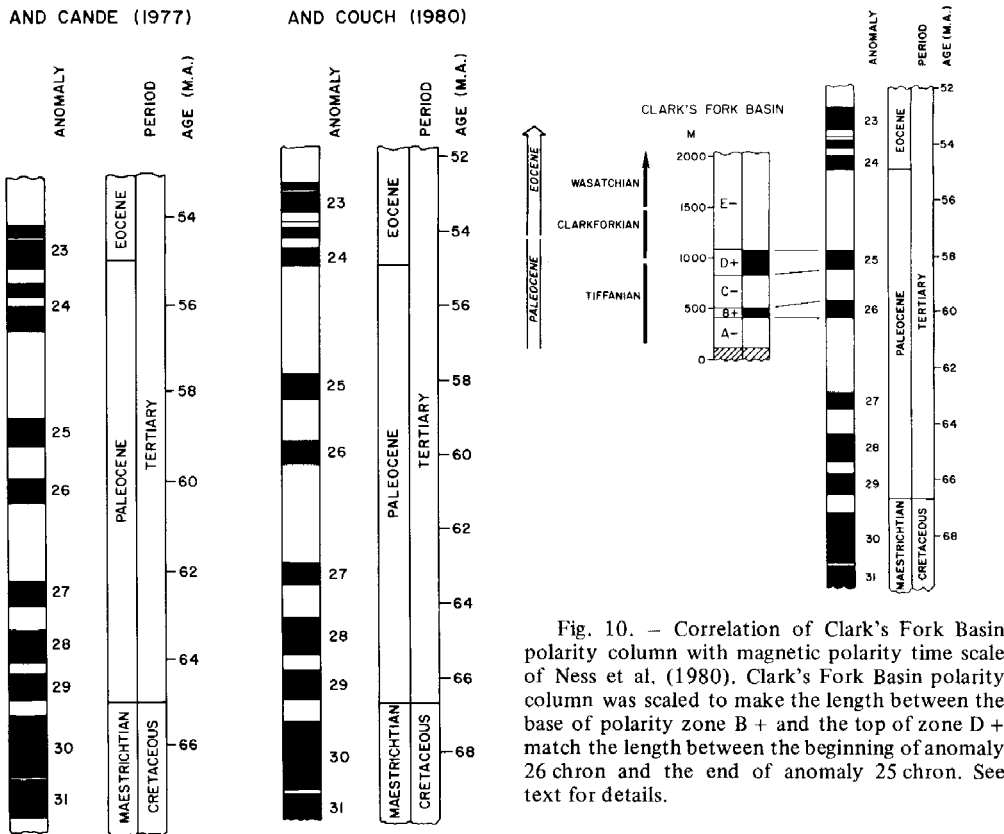


Fig. 9. - Comparison of magnetic polarity time scales. Upper Cretaceous to lower Eocene portions of the magnetic polarity time scales of LaBrecque et al. (1977) compared to time scale of Ness et al. (1980).

also incorporates changes to the geologic time scale necessitated by the revised K^{40} decay constant. The resulting polarity time scale greatly reduces the systematic discrepancies between the ages of magnetic anomalies in the LaBrecque et al. (1977) time scale and the ages determined by invertebrate biozonations in DSDP cores, especially in the Late Paleocene and Early Eocene. Figure 9 illustrates the Late Cretaceous, Paleocene, and Early Eocene portions of these two magnetic polarity time scales. We feel that the advantages of the time scale by Ness et al. (1980) are sufficiently compelling to adopt it as the

best available magnetic polarity time scale. The major difference between these time scales is that anomaly 24 chron is placed just above the Paleocene/Eocene boundary in the Ness et al. time scale, whereas the time scale of LaBrecque et al. had placed anomaly 24 in the Late Paleocene. The basic polarity sequence is, of course, quite similar.

Figure 10 illustrates the correlation of the magnetic polarity and biostratigraphic sequence from the Clark's Fork Basin with the magnetic polarity time scale of Ness et al. (1980). This correlation is based on several lines of evidence.

Magnetic polarity zonation and biostratigraphy of the San Juan Basin sediments in New Mexico provide constraints to correlation of the Clark's Fork Basin with the polarity time scale. Early and middle Paleocene faunas (e.g., Puercan and Torrejonian land mammal ages) in the San Juan Basin

Fig. 10. - Correlation of Clark's Fork Basin polarity column with magnetic polarity time scale of Ness et al. (1980). Clark's Fork Basin polarity column was scaled to make the length between the base of polarity zone B + and the top of zone D + match the length between the beginning of anomaly 26 chron and the end of anomaly 25 chron. See text for details.

occur within the interval of the magnetic polarity time scale from, and including, anomalies 26, 27, and 28 (Lindsay et al. 1978, 1980). Middle Paleocene Torrejonian faunas in the San Juan Basin occur within the normal polarity zone correlative with magnetic anomaly 26 chron and the underlying reversed polarity zone. Torrejonian faunas are ancestral to late Paleocene Tiffanian faunas, therefore Tiffanian faunas in the Clark's Fork Basin (e.g., magnetozone B+) cannot be correlated with any normal polarity interval older than anomaly 26 chron.

Given these constraints, the most logical correlation of the Clark's Fork magnetic polarity sequence is that shown in figure 10, with magnetic polarity zone B+ correlated with anomaly 26 chron and magnetic polarity zone D+ correlated with anomaly 25 chron. The polarity sequence of two closely spaced normal polarity intervals preceded and followed by long reversed polarity intervals is a rather unique sequence observed between anomalies 24 and 27. This sequence closely matches the Clark's Fork Basin magnetic polarity sequence. No other correlation can be made without severe abuse to either the magnetostratigraphic or biostratigraphic data.

The resulting placements of Tiffanian, Clarkforkian, and early Wasatchian land mammal ages within the Clark's Fork Basin section are illustrated in figure 10. Tiffanian faunas occur within sediments deposited during the reversed polarity interval preceding anomaly 26 up into the sediments deposited during anomaly 25 chron. Clarkforkian faunas occur within sediments deposited during anomaly 25 chron and the early portion of the reversed polarity interval following anomaly 25 chron. Wasatchian faunas occur in the upper portion of this same reversed polarity interval. The Paleocene/Eocene boundary is placed near the base of the reversed polarity interval preceding anomaly 24 chron.

As one will note when comparing our Clark's Fork Basin correlations to those of the San Juan Basin, there is a discrepancy in the correlation of early and middle

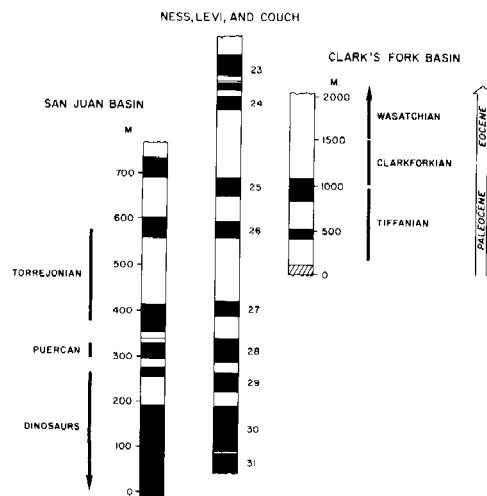


Fig. 11. — Comparison of San Juan Basin and Clark's Fork Basin polarity sequences with the magnetic polarity time scale. Local stratigraphic limits of Puercan and Torrejonian mammals are shown by heavy vertical lines adjacent to San Juan Basin polarity sequence while local stratigraphic limits of Tiffanian, Clarkforkian, and Wasatchian mammals are shown by heavy vertical lines adjacent to the Clark's Fork Basin polarity sequence.

Tiffanian faunas in the Clark's Fork Basin and the middle and late Torrejonian faunas in the San Juan Basin. Both faunal intervals are correlated with anomaly 26 chron and the underlying reversed polarity interval. These correlations are shown in figure 11, along with the magnetic polarity time scale of Ness et al. (1980). A slight overlap of faunal correlation between these two areas might be expected, but this overlap seems excessive (e.g., at least half of both land mammal ages are seen as temporally equivalent). The temporal discrepancy could indicate that faunal correlations between the northern and southern Rocky Mountains during the Paleocene are discordant, or that barriers to faunal exchange between the northern and southern Rocky Mountains in the Paleocene were sufficient to retard dispersal between those areas during that time. Neither of the above explanations can be

defended on the basis of other presently available evidence.

We believe the magnetic polarity correlation shown in figure 10 is reliable (e.g., Tiffanian land mammal age in the Clark's Fork Basin is correlative with anomaly 26 chron) because of the excellent match of the Clark's Fork Basin magnetic sequence with the magnetic polarity time scale between the interval of anomalies 24 and 27 plus the uncomplicated, well-exposed section in the Clark's Fork Basin. Two of the authors (RFB and EHL) also believe that the correlation of the San Juan Basin polarity sequence with the polarity time scale shown in figure 11 is also correct. However, PDG is not comfortable with the implied time equivalence of late Torrejonian faunas of the San Juan Basin and early Tiffanian faunas in the Clark's Fork Basin.

We reject the interpretation of Lerbekmo et al. (1979) for correlation of the San Juan Basin polarity sequence with the magnetic polarity time scale. Assignment of the magnetozone yielding Puercan fossils (anomaly 28 according to Lindsay et al. 1980, anomaly 29 according to Lerbekmo et al. 1979) to anomaly 29 would require placing Torrejonian fossils from the San Juan Basin within anomaly 27 and the underlying reversed polarity interval. Such an assignment would in turn imply drastic changes in sedimentation rate prior to and following anomaly 27. The implied changes cannot be justified on the basis of lithology of the Nacimiento Formation in the San Juan Basin.

We have attempted alternative correlations of the San Juan Basin sequence to the polarity time scale but have found that alternatives cause more problems than they solve. We note that the placement of Torrejonian within the magnetic polarity time scale is not an issue in the debate regarding the magnetostratigraphy through the Cretaceous/Tertiary boundary of the San Juan Basin (e.g., Alvarez and Vann 1979; Fassett 1979; Lindsay et al. 1979*a, b*). Placement of Torrejonian within the magnetic polarity time scale is dependent

primarily on the magnetic polarity and biostratigraphic data from Kutz Canyon, San Juan Basin (Taylor and Butler 1980) and is unaffected by arguments regarding the placement of Puercan and extinction of dinosaurs within the polarity time scale.

At present we do not have a satisfactory explanation of the apparent overlap between the early Tiffanian of the Clark's Fork Basin with the late Torrejonian of the San Juan Basin. We can only hope that further study will resolve the apparent conflict.

A somewhat unexpected feature of this correlation to the magnetic polarity time scale is that the Clark's Fork Basin section extends significantly into the Wasatchian without encountering a normal polarity zone correlative with anomaly 24 chron. Given the correlation of Clarkforkian and Wasatchian with the Sparnacian and Ypresian of Europe, it is highly unlikely that Wasatchian (and thereby the Paleocene/Eocene boundary) has been misplaced in geologic time. The Wasatchian is firmly placed in the early Eocene. Rather than adjusting the position of Wasatchian within geologic time, adjustment of the geologic age of anomaly 24 chron is indicated. Anomaly 24 chron is most likely younger than the basal Eocene age given on the magnetic polarity time scale of Ness et al. (1980), although we have not yet determined how much younger. Adjustment in the age of anomaly 24 chron to younger than basal Eocene is in concert with invertebrate paleontological data from DSDP cores which indicate that anomaly 24 chron is at least as young as basal Eocene (Berggren et al. 1978). Although slight revision may be required, the magnetic polarity and biostratigraphic data from the Clark's Fork Basin indicate that the magnetic polarity time scale of Ness et al. (1980) is a significant improvement over the earlier polarity time scale of LaBrecque et al. (1977).

CONCLUSIONS

Paleomagnetic study of the Polecat Bench and Willwood formations in the Clark's Fork Basin has established a reliable

magnetic polarity stratigraphy for these continental sediments. The magnetic polarity sequence, in concert with the abundant vertebrate faunas, allows a clear correlation of the polarity sequence to the magnetic polarity time scale. The polarity sequence from the Clark's Fork Basin correlates with the magnetic polarity time scale from the reversed polarity interval preceding anomaly 26 chron into the reversed polarity interval preceding anomaly 24 chron.

Vertebrate faunas belonging to the Tiffanian Land Mammal Age occur from the reversed polarity zone correlated with the reversed polarity interval preceding anomaly 26 chron up into the normal polarity zone which correlates with anomaly 25 chron. Clarkforkian faunas occur from within the normal polarity zone correlated with anomaly 25 chron up into the succeeding reversed polarity zone. All Wasatchian faunas in this section occur within the reversed polarity

zone which is correlated with the long reversed polarity interval between anomaly 25 chron and anomaly 24 chron. The boundary between the Paleocene and Eocene epochs occurs early within the reversed polarity interval preceding anomaly 24 chron. These data indicate that anomaly 24 chron is lower Eocene rather than late Paleocene.

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REFERENCES CITED

- Alvarez, W.; Arthur, M. A.; Fischer, A. G.; Lowrie, W.; Napoleone, G.; Premoli Silva, I.; and Roggenthen, W. M., 1977, Upper Cretaceous-Paleocene magnetic stratigraphy of Gubbio, Italy. V. Type section for the Late Cretaceous-Paleocene geomagnetic reversal time scale: *Geol. Soc. America Bull.*, v. 88, p. 383-389.
- Alvarez, W., and Vann, D. W., 1979, Comment on biostratigraphy and magnetostratigraphy of Paleocene terrestrial deposits, San Juan Basin, New Mexico: *Geology*, v. 7, p. 66-67.
- Berggren, W. A., 1972, A Cenozoic time-scale, some implications for regional geology and paleobiogeography: *Lethaia*, v. 5, p. 195-215.
- ; McKenna, M. C.; Hardenbol, J.; and Obradovich, J. D., 1978, Revised paleogene polarity time scale: *Jour. Geology*, v. 86, p. 67-81.
- Curry, D.; Adams, C. G.; Boulter, M. C.; Dille, F. C.; Eames, F. E.; Funnell, B. M.; and Wells, M. K., 1978, A correlation of Tertiary rocks in the British Isles: *Geol. Soc. London Spec. Report*, v. 12, p. 1-72.
- Fassett, J. E., 1979, Comment on biostratigraphy and magnetostratigraphy of Paleocene terrestrial deposits, San Juan Basin, New Mexico: *Geology*, v. 7, p. 69-70.
- Fisher, R. A., 1953, Dispersion on a sphere: *Roy. Soc. (London) Proc.*, v. A217, p. 295-305.
- Gingerich, P. D., 1975, What is type Paleocene? — discussion: *Am. Jour. Sci.*, v. 275, p. 894-895.
- 1976, Cranial anatomy and evolution of early Tertiary Plesiadapidae (Mammalia, Primates): *Univ. Michigan Pap. Paleont.*, v. 15, p. 1-40.
- 1980, Evolutionary patterns in early Cenozoic mammals: *Ann. Rev. Earth Planet. Sci.*, v. 8, p. 407-424.
- Granger, W., 1914, On the names of lower Eocene faunal horizons of Wyoming and New Mexico: *Bull. Amer. Mus. Nat. Hist.*, v. 33, p. 201-207.
- 1917, Notes on Paleocene and lower Eocene mammal horizons of northern New Mexico and southern Colorado: *Bull. Amer. Mus. Nat. Hist.*, v. 37, p. 821-830.
- Hay, W. W., and Mohler, H. P., 1967, Calcareous nannoplankton from early Tertiary rocks at Pont-Labau, France and Paleocene-early Eocene correlations: *Jour. Paleont.*, v. 41, p. 1505-1541.
- Heirtzler, J. R.; Dickson, G. O.; Herron, E. M.; Pittman, W. C., III.; and LePichon, X., 1968, Marine magnetic anomalies, geomagnetic field reversal, and motions of the ocean floor and continents: *Jour. Geophys. Res.*, v. 73, p. 2119-2136.
- IUGS International Subcommittee on Stratigraphic Classification and IUGS/IAGA Subcommittee on a Magnetic Polarity Time Scale, 1979, Magnetostratigraphic polarity units — A supplementary chapter of the ISSC Inter-

- national Stratigraphic Guide: Geology, v. 7, p. 578-583.
- Jepsen, G. L., 1930, Stratigraphy and paleontology of the Paleocene of northeastern Park County, Wyoming: Amer. Phil. Soc. Proc., v. 69, p. 463-582.
- , 1940, Paleocene faunas of the Polecat Bench Formation, Park County, Wyoming: Amer. Phil. Soc. Proc., v. 83, p. 217-341.
- , and Woodburne, M. O., 1969, Paleocene hyracothere from Polecat Bench Formation, Wyoming: Science, v. 164, p. 543-547.
- Johnson, N. M.; Opdyke, N. D.; and Lindsay, E. H., 1975, Magnetic polarity stratigraphy of Pliocene-Pleistocene terrestrial deposits and vertebrate faunas, San Pedro Valley, Arizona: Geol. Soc. America Bull., v. 86, p. 5-12.
- Kraus, M. J., 1980, Genesis of a fluvial sheet sandstone, Willwood Formation, Northwest Wyoming, in Gingerich, P. D., ed., Early Cenozoic paleontology and stratigraphy of the Bighorn Basin, Wyoming: University of Michigan Papers in Paleontology 24, p. 87-94.
- LaBrecque, J. L.; Kent, D. V.; and Cande, S. C., 1977, Revised magnetic polarity time scale for late Cretaceous and Cenozoic time: Geology, v. 5, p. 330-335.
- Lerbekmo, J. F.; Evans, M. E.; and Baadsgaard, H.: 1979, Magnetostratigraphy, biostratigraphy, and geochronology of Cretaceous-Tertiary boundary sediments, Red Deer Valley: Nature, v. 279, p. 26-30.
- Lindsay, E. H.; Butler, R. F.; and Johnson, N. M., 1980, Magnetic Polarity Zonation and biostratigraphy of late Cretaceous and Paleocene continental deposits, San Juan Basin, New Mexico: Am. Jour. Sci., in press.
- ; ——; ——; and Jacobs, L. L., 1979a, Reply to comment by Alvarez and Vann: Geology, v. 7, p. 68-69.
- ; ——; ——; ——; 1979b, Reply to comment by Fassett: Geology, v. 7, p. 69-71.
- ; Jacobs, L. L.; and Butler, R. F., 1978, Biostratigraphy and magnetostratigraphy of Paleocene terrestrial deposits, San Juan Basin, New Mexico: Geology, v. 6, p. 426-429.
- Ness, G.; Levi, S.; and Couch, R., 1980, Marine magnetic anomaly time scales for the Cenozoic and Late Cretaceous: A precis, critique and synthesis: Rev. Geophys. Space Phys., in press.
- Pomerol, C., 1969, Rapport sur la limite Paléocène-Eocène, in Colloque sur l'Eocène: Paris, Bur. Recherches Géol. Minières Mém., v. 69, p. 447-449.
- Rose, K. D., 1980, Clarkforkian land-mammal age: revised definition, zonation, and tentative intercontinental correlations: Science, v. 208, p. 744-746.
- Russell, D. E., 1968, Succession, en Europe, des faunes mammaliennes au début du Tertiaire: Mém. Bur. Rech. Géol. Minièr., v. 58, p. 291-296.
- Schimper, W. P., 1874, Traité de paléontologie végétale. (Baillièrre, Paris), v. 3, p. 1-896.
- Schorn, H. E., 1971, What is type Paleocene?: Am. Jour. Sci., v. 271, p. 402-409.
- Sclater, J. G.; Jarrard, R. D.; and Gartner, S., 1974, Comparison of the magnetic and biostratigraphic time scales since the Late Cretaceous: Initial Rept. Deep Sea Drilling Project., v. 22, p. 381-386.
- Simpson, G. G., 1935, The Tiffany fauna, upper Paleocene: Amer. Mus. Novitates, v. 795, p. 1-19; v. 816, p. 1-30; v. 817, p. 1-28.
- Sinclair, W. J., and Granger, W., 1912, Notes on the Tertiary deposits of the Bighorn Basin: Amer. Mus. Nat. Hist. Bull., v. 31, p. 57-67.
- Taylor, L. H., and Butler, R. F., 1980, Magnetic-polarity stratigraphy of Torrejonian sediments, Nacimiento Formation, San Juan Basin, New Mexico: Am. Jour. Sci., v. 280, p. 97-115.
- Tomida, Y., and Butler, R. F., 1980, Dragonian mammals and Paleocene magnetic-polarity stratigraphy, North Horn Formation, Central Utah: Am. Jour. Sci., in press.
- Van Houten, F. B., 1944, Stratigraphy of the Willwood and Tatman Formations in northwestern Wyoming: Geol. Soc. America Bull., v. 55, p. 165-210.
- Van Valen, L., 1966, Deltatheridia, a new order of mammals: Amer. Mus. Nat. Hist. Bull., v. 132, p. 1-126.
- Watson, G. S., 1956, A test for randomness of directions: Mon. Nat. Roy. Astron. Soc. Geophys. Suppl., v. 7, p. 160-161.
- Wood, H. E.; Chaney, R. W.; Clark, J.; Colbert, E. H.; Jepsen, G. L.; Reeside, J. B.; and Stock, C., 1941, Nomenclature and correlation of the North American continental Tertiary: Geol. Soc. America Bull., v. 52, p. 1-48.