CHADRONIAN (EARLY OLIGOCENE) MAGNETOSTRATIGRAPHY OF EASTERN WYOMING: IMPLICATIONS FOR THE AGE OF THE EOCENE-OLIGOCENE BOUNDARY[1]

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ABSTRACT

New magnetostratigraphic studies have been conducted on Early Oligocene sections at Flagstaff Rim and Ledge Creek, Natrona County, Wyoming and the Dilts Ranch, Converse County, Wyoming. Thermal demagnetization has considerably improved the polarity interpretation of Flagstaff Rim, since AF demagnetization had failed to remove a diagenetic normal overprint. The polarity pattern in these sections appears to span the interval from Chron C10r to Chron C15 of the magnetic polarity timescale (31 to 37.5 m.y. based on K-Ar dates from Flagstaff Rim). This additional, more complete magnetostratigraphic evidence shows clearly that the Eocene-Oligocene boundary must lie between 36 and 37 m.y. in age.

INTRODUCTION

The Eocene-Oligocene transition was one of the most important episodes in the Tertiary. There were major worldwide changes in land faunas (Prothero in press), land floras (Wolfe 1978), marine faunas and floras (Fischer and Arthur 1977; Cavelier et al. 1981) which were associated with a major global cooling of 3–5°C (Savin 1977), a major regression (Vail et al. 1977), a drop in the carbonate compensation depth (Cavelier et al. 1981), and the beginning of modern oceanic circulation with the development of the circum-Antarctic current and deep bottom waters (Kennett 1977). The "Terminal Eocene Event" (Cavelier et al. 1981) set the stage for modern world climates and ended the subtropical, more equable climates of the Cretaceous and early Tertiary. The Eocene-Oligocene transition has generated much recent attention, as shown by several recent symposia (e.g., the symposium edited by Cavelier et al. 1981) and organizations (IGCP Project 174: Les Evenements Geologiques a la limite Eocene-Oligocene). Evidence of catastrophic extraterrestrial events (Glass and Crosbie 1982; Alvarez et al. 1982; Asaro et al. 1982; Ganapathy 1982) has also been inferred at this transition, but this is controversial (Corliss et al. 1984).

Our understanding of the Eocene-Oligocene transition is complicated by a controversy over the age of the Eocene-Oligocene boundary itself. The widely accepted (Harland et al. 1982; Palmer 1983) age estimate of 36–38 m.y. (Berggren 1972; Hardenbol and Berggren 1978) has recently been challenged by a number of authors who place the Eocene-Oligocene boundary between 32 and 34 m.y. (Glass and Crosbie 1982; Armentrout 1981; Wolfe 1978, 1981; Odin 1978; Harris and Zullo 1980). Studies on marine sections with both planktonic microfossils and good magnetostratigraphy (Lowrie et al. 1982; Poore et al. 1982) have established that the Eocene-Oligocene boundary falls between Chrons C13 and C15 of the magnetic polarity timescale, or within reversed Chron C13R. However, the uncertainty over the calibration of the magnetic polarity timescale (Lowrie and Alvarez 1981; Ness et al. 1980; LaBrecque et al. 1977) has been a considerable problem until land paleomagnetic sections with high-temperature K-Ar dates (Prothero et al. 1982, 1983*a*; Berggren et al. 1984) have allowed direct calibration of three diagnostically long reversed polarity events, which have been called Chrons C12R, C13R, and C20R (Berggren et al. 1984, fig. 1). This calibration remains controversial (Ness 1983; Prothero et al. 1983*b*), although new evidence from marine Oligocene sections in the Olympic peninsula of Washington (Prothero and Armentrout 1985; Armentrout and Prothero pers. comm.) support the calibration of Berggren et al. (1984).

Prothero et al. (1982, 1983*a*) described the

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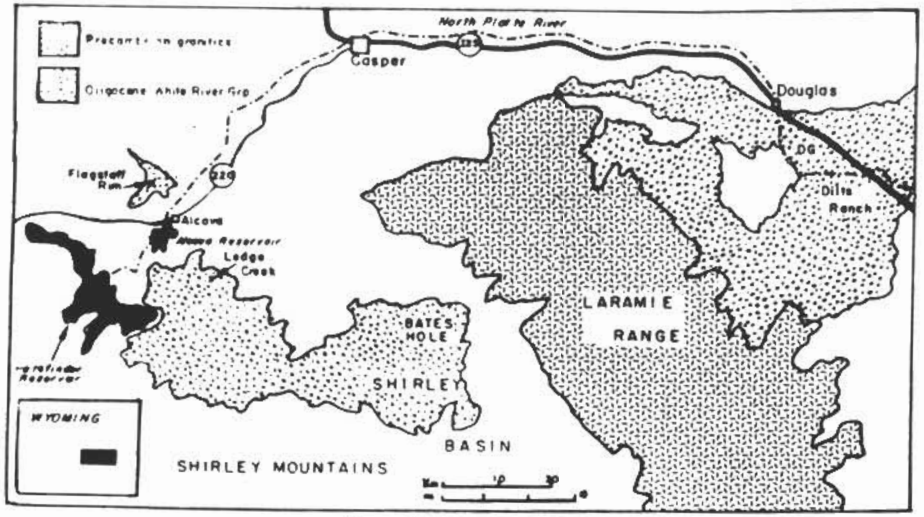


FIG. 1.—Location map, showing position of localities mentioned in text. DG = localities north of the North Platte River near Douglas (Prothero 1982).

magnetostratigraphy of a critical stratigraphic section at Flagstaff Rim, Wyoming. In the summer of 1983 I resampled Flagstaff Rim to resolve some questions about the magnetostratigraphy. A more thorough sampling and demagnetization program (described below) has improved the magnetostratigraphy considerably. Sections of similar age at Ledge Creek and Dilts Ranch, Wyoming were also sampled to test the pattern seen at Flagstaff Rim. This paper describes these new data, which cast considerable light on age estimates of the Eocene-Oligocene boundary.

MAGNETIC STRATIGRAPHY

The tuffaceous siltstones of the White River Group in Wyoming (fig. 1) are particularly well suited to magnetostratigraphic analysis. They are well exposed, flat-lying, and highly fossiliferous. Many of these rocks contain volcanic ash layers which have been, or could be, dated by potassium-argon methods. The Flagstaff Rim area (geology described by Emry 1973) contains the thickest and most complete biostratigraphic record of the Chadronian. Emry (1973; pers. comm.) is presently preparing a complete biostratigraphic zonation for this section. The Ledge Creek area has only been described briefly by Skinner and Gooris (1966). It produces a fauna similar to that of Flagstaff Rim, but the section is thinner and less fossiliferous. The deposits and faunas of the Dilts Ranch area are described by Kron (1978).

Using the published and unpublished stratigraphic sections in these areas, three field assistants and I collected paleomagnetic samples of these sections in the summer of 1983. The Flagstaff Rim section was measured along the north face of Lone Tree Gulch from the SE¼, SW¼, SE¼, Section 23; T31N, R83W, to the top of the hill of 6175 ft (1882 m) elevation in the center of Section 23. The section began at the Cretaceous-Oligocene contact immediately north of an abandoned well casing in Lone Tree Gulch and continued to 22 m above Ash B (the top of Hill 6175). The upper part of the section began just above Ash B in Lone Tree Gulch (NW ¼, NW ¼, SW ¼, Section 23) and ran due west up the ravine until it reached the level of Ash F at the base of Flagstaff Rim (NE ¼, NW ¼, SW ¼, Section 22). Full documentation of each site level in this and other sections discussed here is available from the author on request.

The Ledge Creek section was taken along the northwest face of the canyon labeled "Ledge Creek Number 2" by Skinner and Gooris (1966). This section began in the red beds at the mouth of the canyon (NW¼, NE ¼, NE¼, Section 22; T29N, R82W, Bear Springs 7.5-minute quadrangle, Natrona County, Wyoming) and continued to the level or the "Saddle Ash" or "6610 ft ash" of Skinner and Gooris (1966, fig. 3), which is located in the NE¼, SW¼, NE¼ of Section 22. The Dilts Ranch section is a composite of a number of subsections described by Kron (1978). The detailed location of each of these sections is given in the caption of figure 6.

Each section was measured using a telescoping hand level, with sites spaced every 1.67 m (5.5 ft). At each site, three oriented block samples were collected with simple hand tools. Oriented surfaces were all planed to horizontal and marked with a series of north arrows to minimize potential for orientation error and to simplify sampling. Samples were then removed, wrapped individually by site, and transported back to the laboratory. There they were trimmed on a band saw equipped with a tungsten carbide blade. The samples were measured on a CTF Systems, Inc., cryogenic magnetometer at the South Dakota School of Mines and Technology. Mean natural remanent magnetization (NRM) intensity was 2.9×10^{-6} Gauss.

A suite of 39 pilot samples was treated with progressive thermal demagnetization to determine optimum cleaning temperature (fig. 2). Previous work with White River rocks was done almost entirely with alternating field (AF) demagnetization (Prothero 1982; Prothero et al. 1982, 1983*a*). In that research I found that some samples with normal overprinting did not respond to AF treatment but showed clear reversed directions with thermal demagnetization of 200–300°C. This is probably due to a chemical remanence from iron hydroxides (such as goethite) or from low blocking temperature hematite, which was acquired during weathering. The coercivity of this mineral is too high to be treated by AF demagnetization, even at 1000 oersteds, but it readily responds to thermal demagnetization. Thus, most earlier work on White River rocks, which does not employ some thermal demagnetization, must be viewed with caution.

All of our published sections have been so treated except the original Flagstaff Rim section (fig. 5*a*). This section was treated with limited thermal demagnetization and was based on only one sample per site, so that no site statistics could be calculated. As a result, the data showed a number of sites that were difficult to interpret, although the long reversed interval between Ashes F and I (interpreted as representing Chron C12R) was clearly visible. The remaining section below Ash F (interpreted as Chron C13) was almost entirely of normal polarity, yet the magnetic polarity timescale shows a very short Chron C13 relative to the length of Chron C12R. For this reason, I suspected that normal overprinting had not been adequately removed.

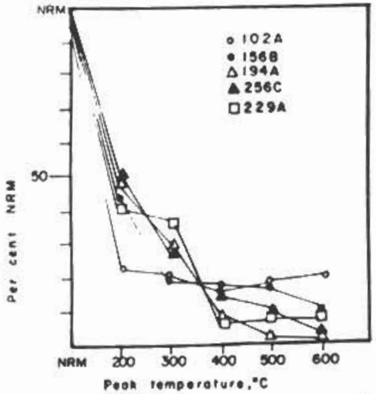


FIG. 2.—Thermal demagnetization curves of representative samples.

Pilot thermal demagnetization studies (figs. 2, 3, and 4) showed that the primary carrier of the remanence was a low coercivity, low Curie point mineral such as a form of titanomagnetite. Above the Curie point of titanomagnetite (550°C), less than 10% of the remanence was left in most specimens (fig. 2). Thermal demagnetization produced reversed directions that usually were stable by 300°C, although some samples required further cleaning at 400–500°C to reach stable directions (figs. 3, 4). After demagnetization, standard site statistics (Fisher 1953; Irving 1964) were calculated on the cleaned directions. The hierarchical classification scheme of Opdyke et al. (1977) was used to rank the sites, since many sites failed the significance test at the 95% confidence interval but still yielded valuable polarity information.

RESULTS

As predicted, the larger sample base and more thorough thermal demagnetization procedure improved the polarity interpretation

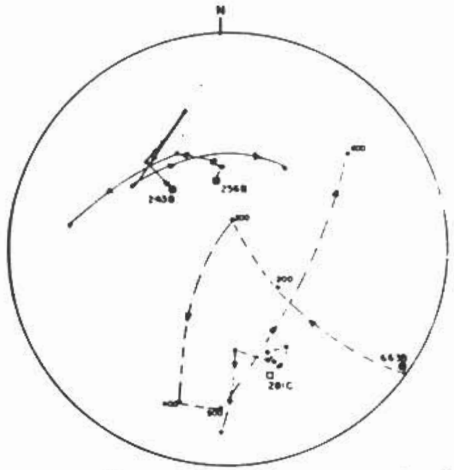
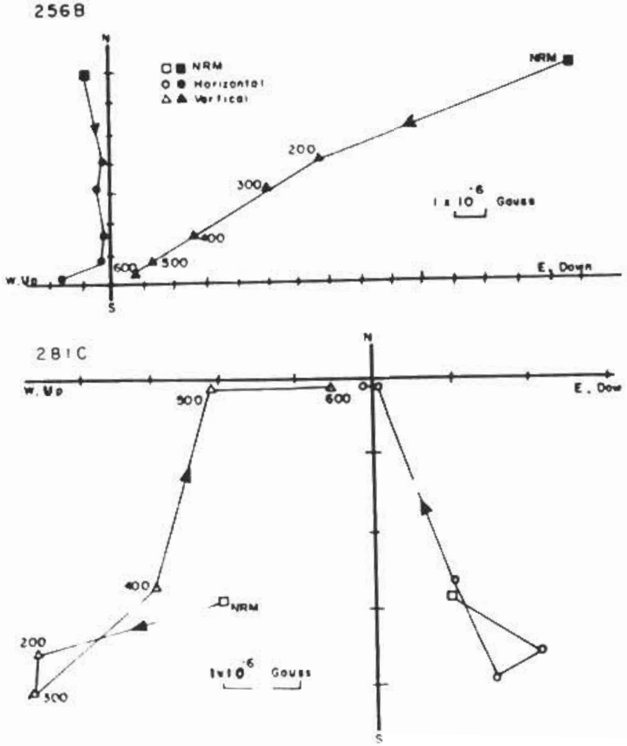


FIG. 3.—Stereoplots of directional behavior of four representative samples. Square = NRM direction. Solid circles and lines are lower hemisphere projections; open circles and dashed lines are upper hemisphere projections. Demagnetization steps are: NRM, 200°, 300°, 400°, 500°, and 600°C.

of Flagstaff Rim considerably (fig. 5*a*). There are at least two explanations for this:

1) Thermal demagnetization removes normal overprinting due to goethite, or low blocking temperature hematite, while AF demagnetization does not.

2) With only one sample per site, we were misled by the numerous Class III (Opdyke et al. 1977) sites, which have one of the three directions divergent. A single divergent direction at a given site is very common in these weakly magnetized, highly overprinted volcaniclastic siltstones. This may be due to chemical overprinting, to instability of the characteristic remanence in some samples, or to a number of other possible causes. Whatever the reason, one sample per site is inadequate to establish site polarity, let alone calculate site statistics. There are too many ways that a single sample can lead one astray.



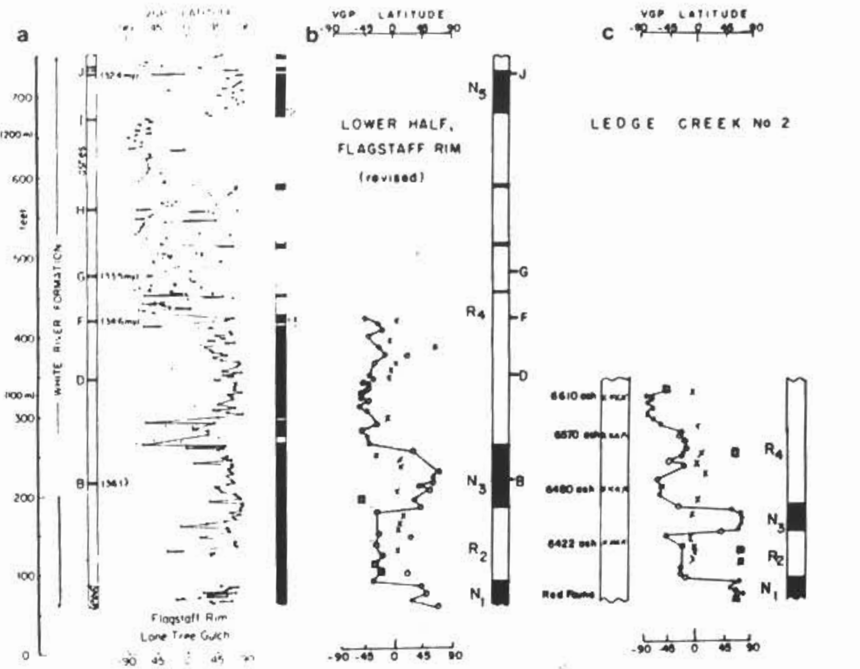


FIG. 5.—A. Original polarity interpretation of Denham (in Prothero et al. 1982) for Flagstaff Rim. *B*. Revised interpretation of lower half of section after thermal demagnetization and multiple samples per site. *C*. Polarity stratigraphy of the Ledge Creek No. 2 section. Positive VGP (virtual geomagnetic pole) latitudes and solid bars are normal; negative VGP latitudes and open bars are reversed. Ash terminology and dates after Emry (1973). Site classification after Opdyke et al. (1977): Class I (significant) = solid circles; Class II (one sample lost) = open squares; Class III (one sample divergent) = open circles; "X" = indeterminate. Isolated sites which differ from sites above and below are not connected to the polarity log.

The revised interpretation of Flagstaff Rim (fig. 5*b*) shows that the entire sequence from about 10 m above Ash B to Ash F is reversely magnetized (reversed zone R4), although it was originally reported as normally magnetized. This extends the length of Chron C12R from the level of Ash I down to just above Ash B. The increased length of Chron C12R is in much better agreement with the magnetic polarity timescale. Chron C13 is now restricted to the interval from about 10 m above Ash B to 11 m below it (zone N3), which agrees with the relatively short duration of Chron C13 on the magnetic polarity timescale. Thermal demagnetization also revealed another zone of reversed polarity extending from 11 m below Ash B to 7 m above the base of the section (R2). This seems to correspond to Chron C13R, which is shorter than Chron C12R but longer than Chron C13. Finally, the lowest four sites in the "lower banded zone" (Emry 1973) at the base of the section are of normal polarity (N1), and prob-

a Duchesnean or earliest Chadronian age (Emry 1981, pers. comm.). The revised polarity interpretation is thus in much better accord with the magnetic polarity timescale (figs. 7, 8) and also more consistent with the K-Ar dates.

Corroboration of this interpretation comes from the Ledge Creek section, about 15 air miles to the southeast of Flagstaff Rim (fig. 1). Although the Ledge Creek section is thinner than Flagstaff Rim, it contains a similar sequence of late Duchesnean to early and medial Chadronian mammals. It also contains a number of marker ashes, although no attempt has been made yet to correlate these ashes with those at Flagstaff Rim.

The Ledge Creek section (fig. 5*c*) shows the same polarity pattern seen at Flagstaff Rim, only thinner. The Duchesnean "Red Fauna" (Skinner and Gooris 1966) at the base

Above this magnetozone is a long reversed interval (zone R2, or Chron C13R), a short normal zone (N3, or Chron C13), and a long reversed interval that continues beyond the top of the section (R4, or Chron C12r). The relative thickness of these zones is comparable with Flagstaff Rim and with the magnetic polarity timescale (figs. 7, 8).

The Dilts Ranch section (fig. 6) is the key to correlating the Chadronian sections at Flagstaff Rim and Ledge Creek with the later Oligocene sections described by Prothero et al. (1983*a*; Prothero 1982). The basal portion of the Dilts Ranch section contains early-medial Chadronian fossils (Kron 1978), primarily in two smaller localities, informally known as "The Sphinx" and "Tripyramid." These fossils (especially the sciuravid rodents, *Parvitragulus*, and limnocyonine carnivores) compare favorably with fossils from the Ash B to Ash D level at Flagstaff Rim (Kron pers. comm.). The upper part of the section above the "Glory Hole" Ash contains latest Chadronian and earliest Orellan mammals, which correlate with faunas from similar deposits north of Dilts Ranch and the North Platte River, near Douglas, Wyoming (Prothero 1982). The composite Dilts Ranch section is therefore a critical tie between the Chadronian sections at Flagstaff Rim and the latest Chadronian-Orellan-Whitneyan sections found elsewhere in the White River Group.

The Dilts Ranch section shows three episodes of normal polarity in a predominantly reversed section. The uppermost normal magnetozone (zone N6, 90 m to 113 m on the measured section) is associated with an early Orellan fauna, which elsewhere is found in association with Chron C11. The middle normal magnetozone (zone N4, 53 to 61 m on the zonation section, above the "Third Ash") is associated with a late Chadronian fauna. This fauna also occurs in the uppermost fossiliferous parts of Flagstaff Rim and at Boner Ranch, Niobrara County, Wyoming (Prothero 1982) which are correlated with Chron C12. Beneath the Third Ash is a long zone of reversed polarity, interrupted by a normal magnetozone at 12 to 21 m on the composite section (zone N2). Based on its association with early-medial Chadronian faunas, this rmal magnetozone appears to correlate there is a relatively thin sequence representing Chron C12R at Dilts Ranch, but the biostratigraphic evidence allows no other interpretation. The Tripyramid and Sphinx sections, which produce early-medial Chadronian faunas (Kron 1978), show a short normal magnetozone that probably represents Chron C13, although neither section is long enough to produce a diagnostic pattern of polarity events.

DISCUSSION

The correlations discussed above are summarized in figure 8. Five areas now produce Chadronian magnetostratigraphic records which can be correlated to the magnetic polarity timescale. The Vieja Group in Texas (Testarmata and Gose 1979; reinterpreted by Prothero et al. 1983*a*) appears to span the interval between Chron C12 and Chron C15. Two important radiometrically-dated volcanic layers (shown by arrows in fig. 8) help constrain the age limits of this section. The revised Flagstaff Rim section now matches the segment of the magnetic polarity timescale between Chrons C12 and C15 very well. The K-Ar dates also constrain the geologic age of this section. Together, these two sections provide the primary evidence for the calibration of the magnetic polarity timescale of Prothero et al. (1982, 1983*a*).

The Ledge Creek section provides further corroboration of the polarity pattern seen at Flagstaff Rim. It is correlated to Flagstaff Rim by its mammalian faunas, although datable ashes are also available. The Dilts Ranch section ties the Flagstaff Rim-Ledge Creek-Vieja composite to the overlying Orellan-Whitneyan record exposed along the Pine Ridge in Nebraska and the Big Badlands of South Dakota. The magnetostratigraphic and biostratigraphic evidence from the Dilts Ranch section corroborates the interpretation of Prothero et al. (1982, 1983*a*) that the Orellan and Whitneyan span Chrons C9 to C11 of the magnetic polarity timescale. With the Dilts Ranch section, the White River composite magnetostratigraphy is now completely based on overlapping, mammal-bearing sections, with no significant gaps.

Two other sections deserve mention. The classic early-medial Chadronian locality at Pipestone Springs, Montana (Kuenzi and

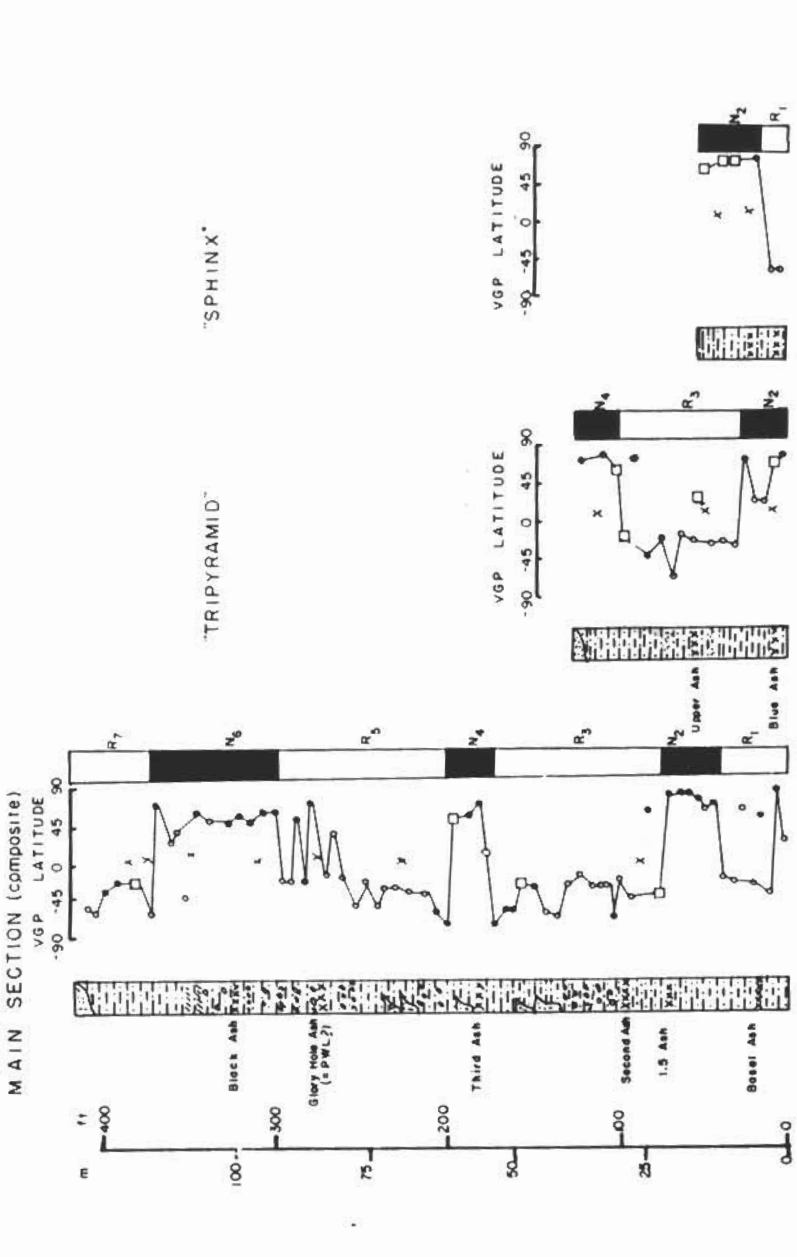


FIG. 6.—Magnetic polarity stratigraphy of Dilts Ranch area. Site classification and symbols as in figure 5. Sections located as follows: "Sphinx"—SW¼ SW¼ NE¼ Sec. 24, T31N R71W, Irvine Bridge 7½-minute quadrangle; "Tripyramid"—SW¼ NW¼ NW¼ Sec. 30, T31N R70W, Irvine Bridge 7½-minute quadrangle; "Composite" base of section to "Second Ash"—SW¼ NE¼ SE¼ Sec. 29, T31N R70W, Irvine Bridge quadrangle; "Second Ash" to "Third Ash"—NE¼ SW¼ SE¼ Sec. 29, T31N R70W, Dilts Ranch 7½-minute quadrangle; "Third Ash" to "Glory Hole Ash"—SW¼ NW¼ NE¼ Sec. 32, T31N R70W, Dilts Ranch quadrangle; "Glory Hole Ash" to top—NE¼ SW¼ NE¼ and SE¼ NW¼ SE¼ Sec. 33, T31N R70W, Dilts Ranch quadrangle. PWL = "Persistent White Layer" (Prothero 1982).

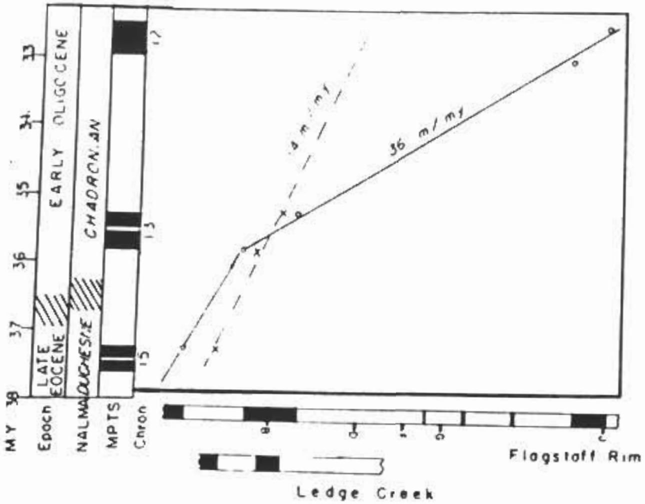


FIG. 7.—Regression plot of magnetic polarity timescale of Berggren et al. (1984) against polarity records of Flagstaff Rim and Ledge Creek. Approximate rate of sedimentation (slope of line) indicated in italics. Abbreviations as in figure 8.

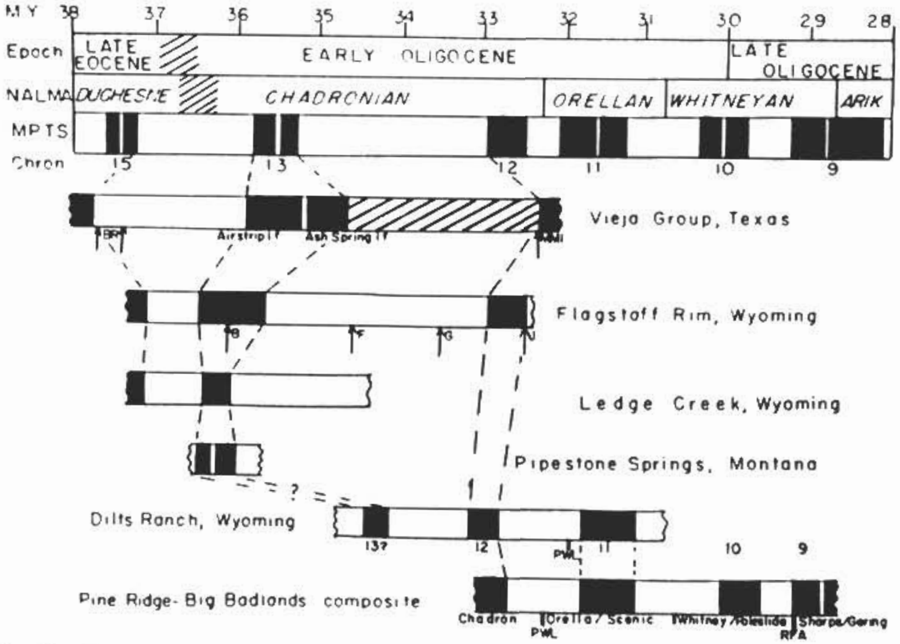


FIG. 8.—Magnetostratigraphic correlation of Oligocene rocks with the polarity timescale of Berggren et al. (1984). Abbreviations: NALMA = North American land mammal ages; DUCHESNE. = Duchesnean; ARIK. = Arikareean; MPTS = magnetic polarity timescale; BR = Bracks Rhyolite; MMI = Mitchell Mesa Ignimbrite (dates on these layers indicated by arrows); l.f. = local fauna; B,F,G,J = chronologic position of lettered Flagstaff Rim ashes (shown by arrows); PWL = Persistent White Layer (Prothero 1982); RFA = Rockyford Ash. Vieja Group magnetostratigraphy after Prothero et al. (1982); Pine Ridge-Big dlands composite after Prothero et al. (1983).

which appears to correlate with Chron C13 and the base of Chron C12r (Prothero 1984). Samples were also taken in the thickest portion of the Chadronian record in the Big Badlands of South Dakota, where the "Ahearn," "Crazy Johnson," and "Peanut Peak" members of the Chadron Formation were described by Clark (1937, 1954; Clark et al. 1967). These rocks proved to have a stubborn normal overprinting due to chemical remanence from hematite and did not respond to either thermal or AF demagnetization. Unless they can be treated by chemical means to remove this overprint, they will not yield an interpretable magnetostratigraphic record.

Some workers (Glass pers. comm.; Wolfe pers. comm.) have suggested other interpretations of Flagstaff Rim that are consistent with their contention that the Eocene-Oligocene boundary is about 32 to 34 m.y. in age. They interpreted the reversed interval between Ashes F and I at Flagstaff Rim (based on the original magnetostratigraphy in Prothero et al. 1982) to be Chron C13R, and implied that Chron C12R lies in the Orellan. This is clearly not consistent with the evidence now available (fig. 8). The revised magnetostratigraphy of Flagstaff Rim, reinforced by the record at Ledge Creek, gives a reversed interval bracketed by K-Ar dates which is clearly too long for any other magnetochron except Chron C12R. Biostratigraphic correlations tie this section to the Dilts Ranch section, and thus to the rest of the Orellan-Whitneyan magnetostratigraphy. Nowhere in the Orellan or Whitneyan is there a reversed magnetozone of sufficient length to be Chron C12R. None of the known reversed zones in the Orellan or Whitneyan could be this long, or they would make the Orellan-Whitneyan much younger and conflict with the K-Ar date at the base of the overlying Gering Formation of 28.7 ± 0.7 m.y. (Obradovich et al. 1973). The composite White River-Vieja magnetostratigraphy is now so tightly corroborated by mammalian biostratigraphy and by numerous high-temperature K-Ar dates that any alternative interpretation would seriously conflict with the biostratigraphy or with the radiometric dates.

These K-Ar dates have also been questioned by some workers, since they conflict with the glauconite dates of Odin (1978). As Berggren et al. (1984) have thoroughly documented, high-temperature K-Ar dates on biotite are much more reliable than those based on glauconite (Thompson and Hower 1973). At Flagstaff Rim, the original K-Ar dates reported by Evernden et al. (1964) were done in the early days of K-Ar dating, so there are no published error estimates. These dates have been rerun with both K-Ar and fission track methods (D. V. Kent pers. comm.) and have proven reliable. Only the dates on Ash B (36.1 m.y. on sanidine; 34.2 m.y. on biotite, corrected for the new decay constants of Dalrymple 1979) have proven problematical. The biotite date on Ash B seems inconsistent with the stratigraphic position of the sample, so most authors (Emry 1973; Emry et al. in press; Prothero et al. 1982, 1983*a*) have used the sanidine date. Normal error estimates on dates of this age range should be in the order of 0.7 to 1.0 m.y. The biotite date on Ash B may in fact be consistent if allowance is made for these possible error estimates. Even if Ash B is not used (e.g., Berggren et al. 1984), the other dates at Flagstaff Rim and on the Vieja Group are sufficient to support the great chronological span of the reversed magnetozone between Ashes B and J, which we have interpreted as Chron C12r. With these constraints on the magnetic polarity timescale, there can be no longer any doubt that Chron C12r occurs between 33 and 35 m.y. Thus, Chron C13r and the Eocene-Oligocene boundary must lie between 36 and 37 m.y.

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