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MAGNETOSTRATIGRAPHY OF THE WHITE RIVER GROUP AND ITS IMPLICATIONS FOR OLIGOCENE GEOCHRONOLOGY*

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ABSTRACT

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Magnetostratigraphic studies of the Oligocene White River Group in Wyoming, Colorado, Nebraska, and the Dakotas have yielded a radiometrically-dated polarity stratigraphy. They provided a mid-Tertiary calibration point for the marine magnetic polarity timescale. An unusually long interval of reversed polarity in the Flagstaff Rim section, Natrona Co., Wyoming, is bracketed by K/Ar dates (biotite) of 32.4 Ma slightly above its top and 34.6 Ma at its base (corrected for new decay-constants). It probably corresponds to the long reversed interval between marine magnetic anomalies 12 and 13. Also, the magnetostratigraphies of 17 other fossiliferous sections of Chadronian—Whitneyan (Oligocene) rocks have been correlated with anomalies 9—12. On this basis, the "boundaries" of the Oligocene North American land mammal "ages" are: Chadronian—Orellan — mid-anomaly 11—12 reversal (about 32.4 Ma); Orellan—Whitneyan — mid-anomaly 10—11 reversal (about 30.7 Ma); Whitneyan—Arikareean — base anomaly 9 (about 29.0 Ma). These dates are in good agreement with recent estimates based on mammalian biochronology and with a corrected radiometric date of 28.7 ± 0.7 Ma at the base of the Arikareean.

INTRODUCTION

The Oligocene Epoch has received much attention in recent years as a period of major changes in global climate, sea-level, oceanic circulation, and marine and terrestrial biotas. Major rearrangements of oceanic circulation patterns (Berggren and Hollister, 1974, 1977; Kennett, 1977, 1980; Keigwin, 1980; Schnitker, 1980) appear to be related to large hiatuses in the deep-sea record (Moore et al., 1978), and significant drops in eustatic sea-level (Vail et al., 1977; Pitman, 1978; Olsson et al., 1980), world temperature (Savin et

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al., 1975; Savin, 1977), and the calcite compensation depth (Van Andel, 1975; Van Andel et al., 1977). These climatic and oceanographic changes are reflected by major crises in marine biotas (Cifelli, 1969; Lipps, 1970; Fischer and Arthur, 1977; Haq et al., 1977; Kennett, 1978; Sancetta, 1978), and by significant changes in land floras (Dorf, 1970; Wolfe, 1971, 1978), and faunas (Clark et al., 1967; Lopez and Thaler, 1975; Webb, 1977). Precise correlation and calibration of these land events with the marine record is necessary to unravel their timing and possible causal relationships. Such a correlation between terrestrial and marine stratigraphies is possible only through magnetostratigraphy.

Hampering this effort at paleomagnetic correlation is a growing controversy over the magnetic polarity timescale (MPTS). The MPTS was originally derived by extrapolation of marine magnetic anomaly profiles using land radiometric dates for calibration of the last 5 Ma, and a Cretaceous age for the base of a sediment core near anomaly 31 (Heirtzler et al., 1968). Although there is now radiometric calibration back to 13 Ma (Harrison et al., 1979), older calibration points have been based on indirect methods, chiefly biostratigraphic correlation (Lowrie and Alvarez, 1981). This has resulted in numerous conflicting versions of the Paleogene MPTS, some of which differ by as much as 5 Ma in their placement of polarity features (Ness et al., 1980; Butler and Coney, 1981; Lowrie and Alvarez, 1981). The only published study of a directly-dated Paleogene magnetostratigraphy has been generally ignored (Testarmata and Gose, 1979).

In this paper, we present a radiometrically-dated magnetostratigraphy for the Oligocene White River Group, which constrains the MPTS and allows for direct calibration of changes in land faunas. The work combines two independent studies, whose most important conclusions are derived from strata at Flagstaff Rim, Natrona County, Wyoming (authors C.R.D. and H.G.F.), and at Toadstool Park, Sioux County, Nebraska (author D.R.P.).

METHODS

The picturesque badlands of the White River Group (Fig.1) contain one of the most continuous and fossiliferous Oligocene land records known. The White River Group crops out in numerous thick, well-exposed sections with abundant fossils and marker ashes, making it ideally suited for biostratigraphic and magnetostratigraphic study. The lithology is predominantly ashy siltstone, which is easily sampled by simple hand-tools.

The present work joins two independent studies, as follows. In twelve sections, author D.R.P. and his assistants collected three oriented samples per site at 1.7 m vertical stratigraphic intervals, so that conventional site statistics could be calculated. Authors C.R.D. and H.G.F. collected the Flagstaff Rim section (Fig.3) and all of the Big Badlands sections except Red Shirt Table (Fig.7). In those sections, a single sample was collected at each site, spaced 0.8 m stratigraphically and staggered laterally up to several meters from site

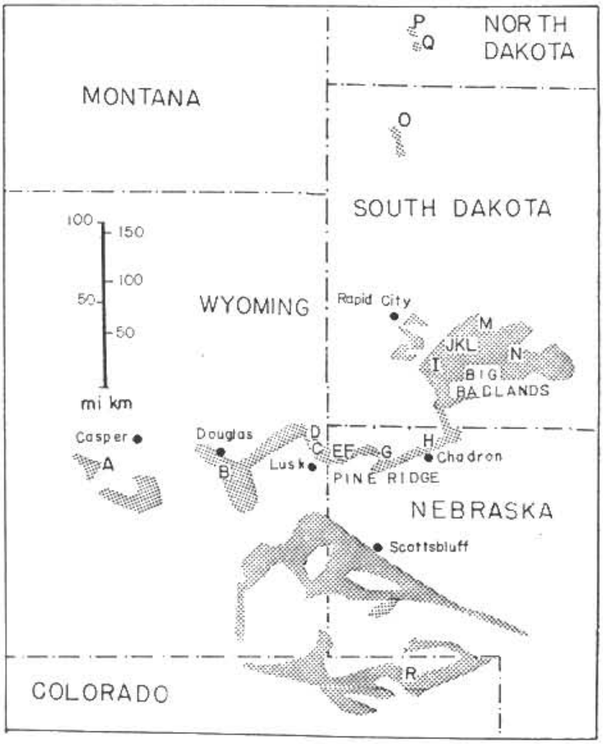

Fig.1. Index map of outcrops of the White River Group (shaded). Localities indicated as follows: *A* = Flagstaff Rim, Natrona Co., Wyoming (Emry, 1973); *B* = Morton Ranch, Converse Co., Wyoming; *C* = Boner Ranch, Niobrara Co., Wyoming; *D* = Thompson Ranch, Niobrara Co., Wyoming; *E* = Geike Ranch, Sioux Co., Nebraska; *F* = Munson Ranch, Sioux Co., Nebraska; *G* = Toadstool Park, Sioux Co., Nebraska (Schultz and Stout, 1955); *H* = North of Chadron, Dawes Co., Nebraska; *I* = Red Shirt Table, Shannon Co., S.D.; *J* = Sheep Mountain Table, Shannon Co., S.D.; *K* = type section of Scenic Member of Brule Formation, Pennington Co., S.D.; *L* = Chamberlain Pass, Pennington Co., S.D.; *M* = Sage Creek Basin, Pennington Co., S.D.; *N* = Cedar Pass, Jackson Co., S.D.; *O* = Slim Buttes, Harding Co., S.D.; *P* = Little Badlands, Stark Co., N.D.; *Q* = Fitterer Ranch, Stark Co., N.D.; *R* = Chimney Canyons, Logan Co., Colorado.

to site. In those sections, the significance of the polarity determination was inferred from the "streaking" behavior observed during a thorough stepwise alternating-field (AF) demagnetization, and from the serial-correlation that is evident from adjacent samples, rather than from discrete levels. Together, the authors have studied a total of 3418 samples from 1813 sites, spanning 2260 m of stratigraphic section at 18 localities.

In the laboratory, the subsamples were made with a carbide-tipped bandsaw and placed in 6.6 cm^3 polystyrene boxes for measurement. The remanent magnetization was measured with the Superconducting Technology C-102 cryogenic magnetometers (Goree and Fuller, 1976) at Woods Hole Oceanographic Institution and Lamont-Doherty Geological Observatory.

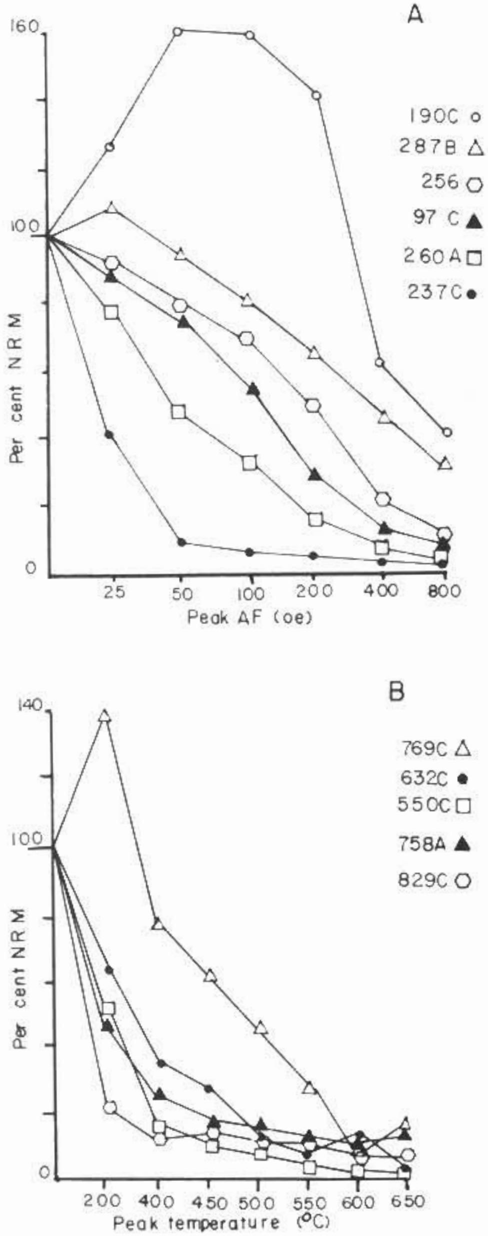

Fig.2. Demagnetization curves of selected samples. A. Alternating field demagnetization. B. Thermal demagnetization.

Alternating-field demagnetization was performed with the Schonstedt GSD-1 device at Woods Hole. Thermal demagnetization was done with the Schonstedt TSD-1 apparatus at Lamont-Doherty.

The original natural remanent magnetization (NRM) intensities ranged from 6 × 10^{-7} to 7 × 10^{-5} G, with a geometric mean of 7 × 10^{-6} G. AF demagnetization testing was done on a suite of 40 pilot samples. Curves for 6 representative samples are shown in Fig.2A. Equal-area stereographic (Fig.3) and vector demagnetization (Zijderveld) diagrams (Fig.4) showed that reversed behavior generally could be recognized at 200 Oe (Oersted) peak AF. However, many samples required stepwise demagnetization above 200 Oe, usually to 800 Oe and often to 1000 Oe, before the polarity preference became evident. The geometric mean intensity dropped to 1.7 × 10^{-6} G at 200 Oe and to 7.6 × 10^{-7} G at 800 Oe.

After completion of AF treatment for all the sites, another suite of 33 pilot samples were thermally demagnetized in stepwise fashion up to 650°C (Fig.2). Remanent magnetization dropped to 8.8 × 10^{-7} G at 500°C. Equal-

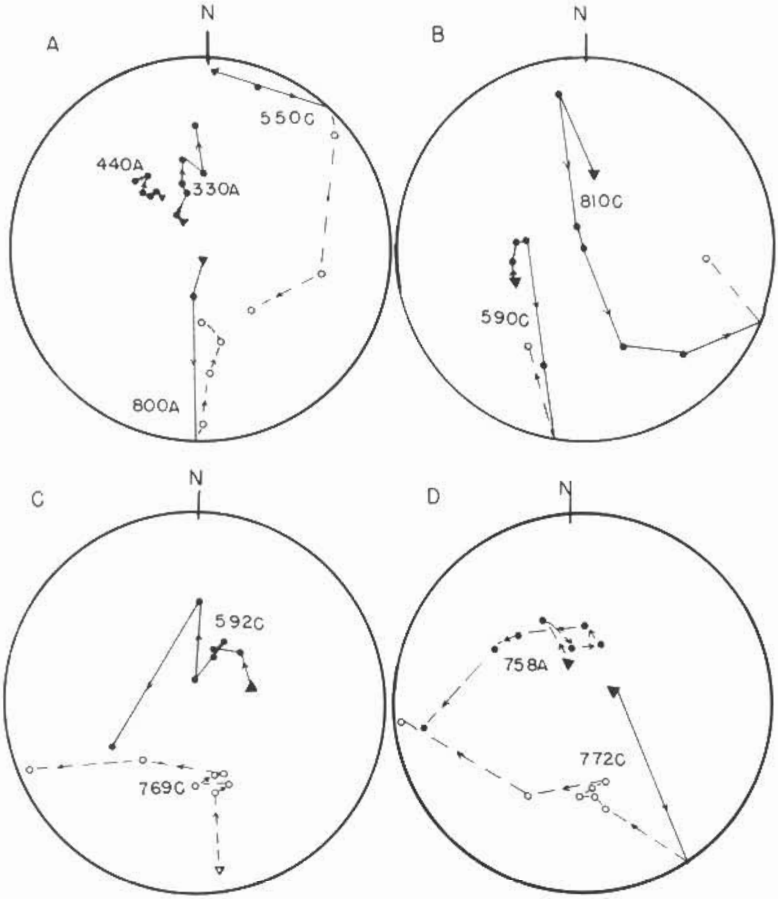

Fig.3. Equal-area stereoplots of demagnetization behavior of selected samples. Open circles are upper hemisphere projections; closed circles are lower hemisphere projections. A. AF demagnetization at 25, 50, 100, 200, 400 and 800 Oe. B. Thermal demagnetization at 200°, 400°, 450°, 500°, 550°, and 600°C.

area stereoplots (Fig.3) showed a stable component that was best isolated at 500°C. Components at 600°C or higher did not show consistent or reasonable directions; they seldom comprised more than 10% of the original NRM. All of D.R.P.'s sites that had not shown clear reversed behavior under AF

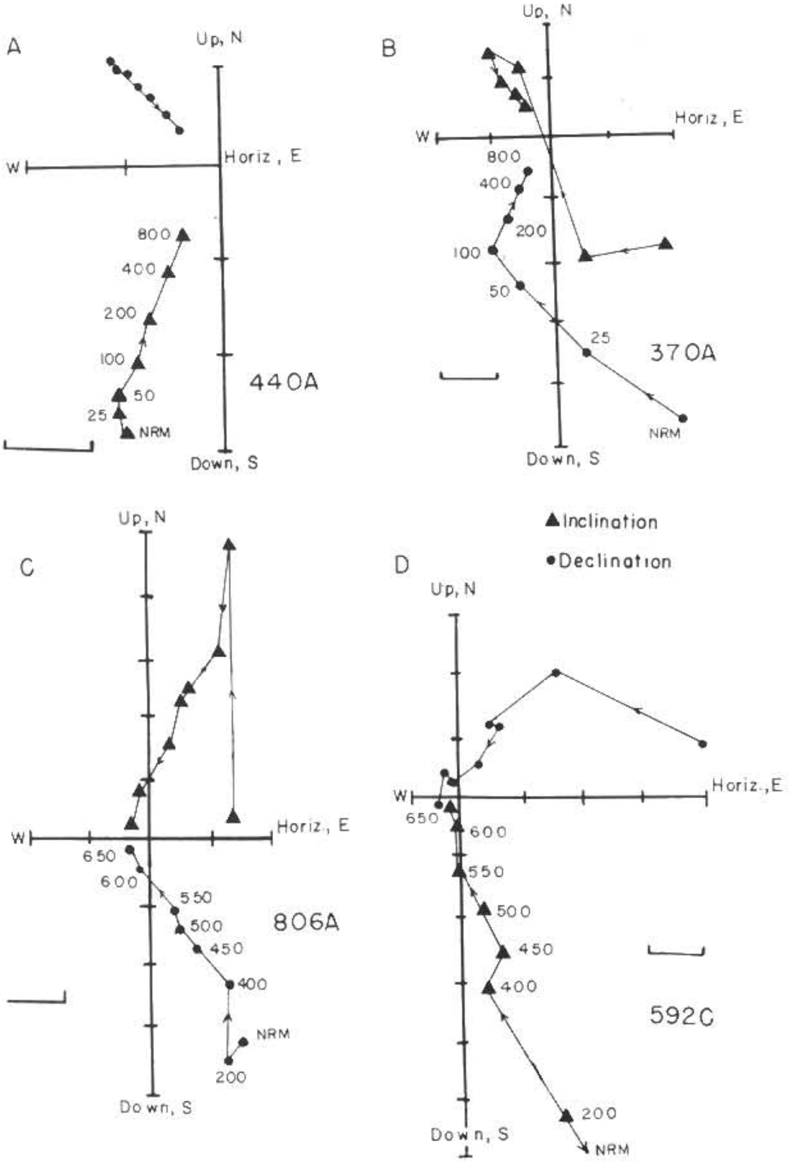

Fig.4. Vector demagnetization diagrams (Zijderveld plots). Circles indicate projection of magnetization vector on horizontal plane. Triangles are used to plot horizontal versus vertical components. A and B. AF demagnetization. Numbers adjacent to data indicate peak AF field. C and D. Thermal demagnetization. Numbers adjacent to data indicate peak temperature in degrees centigrade.

demagnetization were treated at 500°C. A significant number that had remained stably normal under the highest AF cleaning fields showed clear reversed directions after the thermal treatment. Thus, there appears to be some overprinting by a low blocking-temperature, high coercive-force mineral (such as goethite). The AF and thermal behavior generally suggest that most of the remanence is carried by magnetite or titanomagnetite, presumably detrital; no Curie temperature data are available to substantiate this.

In the sections studied by C.R.D. and H.G.F., stepwise thermal testing at about 50 sites had failed to resolve the polarity any more clearly than did the AF treatment. Consequently, thorough stepwise AF treatment was chosen for all the sites. Based on D.R.P.'s thermal experience, this could account for the erratic behavior of adjacent magnetic directions at many of the sites, which could have become evident if more thorough thermal testing had been done, especially at the important Flagstaff Rim section.

In the sections sampled by author D.R.P., site mean directions (Fisher, 1953) and tests for randomness (Watson, 1956) were calculated. The hierarchical classification of sites proposed by Opdyke et al. (1977) was used. "Class I" sites (solid circles in Fig.5) showed a grouping that exceeds the expectation for selection from a random population at the 95% confidence level. "Class II" sites failed the significance test, because only two samples were available or the third was presumed to have been lightning-struck. "Class III" sites had statistically random directions, but two out of three samples showed a clear preference for the same normal or reversed direction. Class II and III sites are indicated by open-circles in Fig.5. "Class IV" sites showed a streaked distribution toward reversed polarity during stepwise demagnetization, but they failed to reach negative inclinations. They are indicated by "*X*" in Fig.5, as are the sites having intermediate or indeterminate polarity. Sites which were stably normal under AF treatment, but showed reversed behavior at 500°C, are shown by open triangles.

In Fig.6, depicting the Flagstaff Rim section of authors C.R.D. and H.G.F., the polarity was inferred from the behavior of the virtual geomagnetic pole latitude as it evolved during the stepwise AF cleaning. "Well-behaved" sites, indicated by closed circles, streaked unmistakeably toward one polarity or the other, or they were stable throughout the AF treatment. Where the behavior would not have placed the VGP destination within 45° of either geographic pole, an "indeterminant" designation was given, marked by "*X*" in Fig.6. No quantitative statistical significance has been assigned, though a qualitative significance can be inferred from the degree of apparent serial correlation in three or more adjacent sites. A quantitative analysis patterned after the multiple-component model of Stupavsky and Symons (1978) is underway and will be reported elsewhere, along with details of the actual data base.

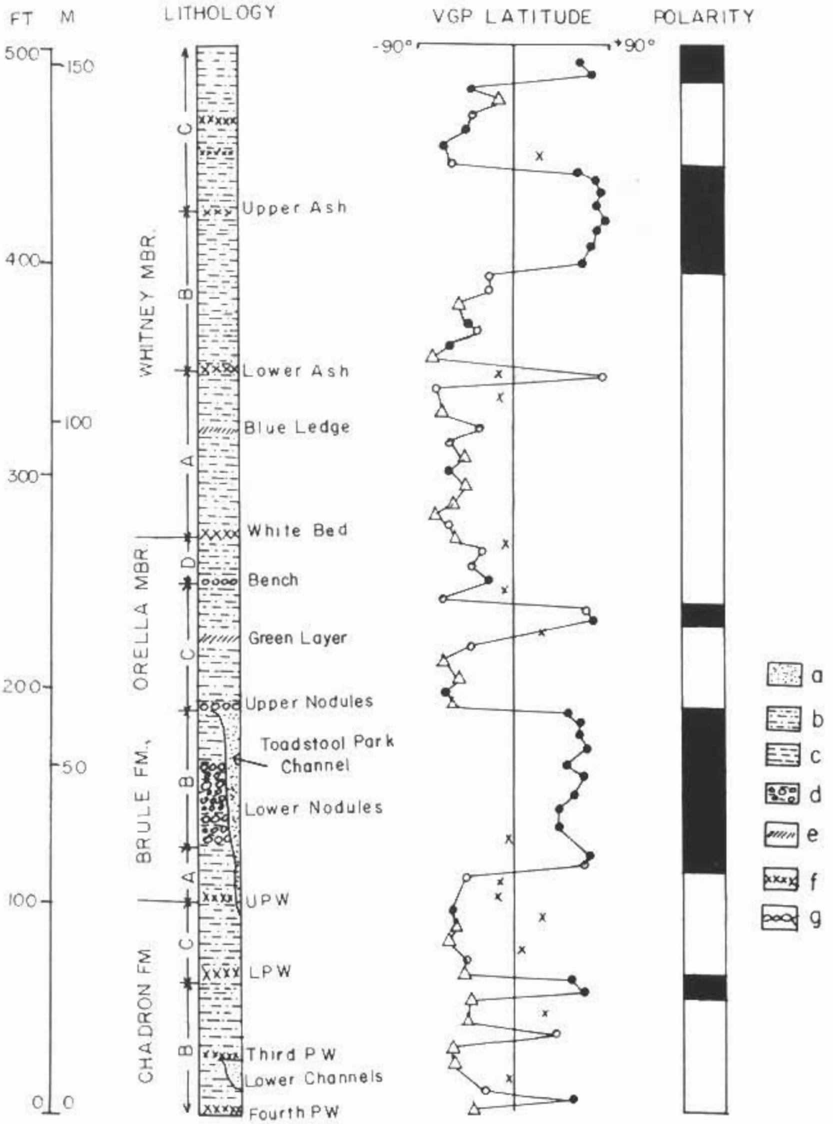

Fig.5. Composite stratigraphy and virtual geomagnetic pole (VGP) latitude plots of the Toadstool Park section, Sioux Co., Nebraska. Lithostratigraphy and terminology after Schultz and Stout (1955). Positive VGP latitudes indicate normal polarity; reversed polarity shown by negative VGP latitudes. Solid circles indicate sites with a grouping of cleaned vectors which is significantly removed from a selection from a random population at the 95% confidence level. These are designated "Class I" sites (Opdyke et al., 1977) in the text. Open circles are "Class II" and "Class III" sites (see text). "Class IV" and indeterminate sites are indicated by an *x*. Sites which were stably normal at highest AF cleaning fields, but reversed after thermal demagnetization, are shown by an open triangle.

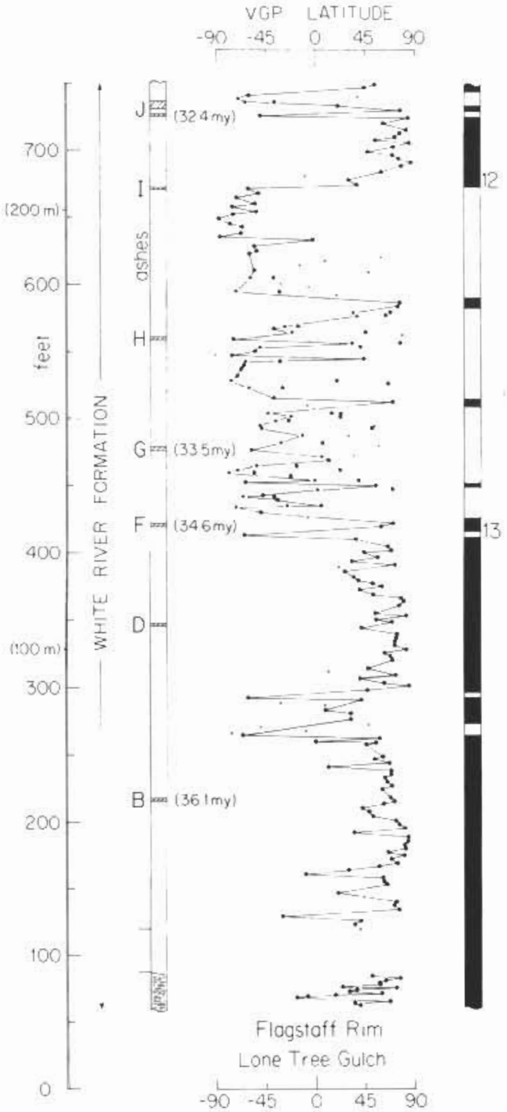

Fig.6. Composite stratigraphic section and representative VGP latitudes for the Lone Tree Gulch section, Flagstaff Rim, Natrona Co., Wyoming. Lithostratigraphy and ash terminology after Emry (1973). Solid circles denote "well-behaved" sites; *X* denotes indeterminate sites.

RESULTS

The two key sections are those at Toadstool Park, Sioux County, Nebraska (Fig.5; Schultz and Stout, 1955) and at Flagstaff Rim, Natrona County, Wyoming (Fig.6; Emry, 1973). Together, these two sections span nearly all of the Chadronian, Orellan, and Whitneyan land mammal "ages", which make up most of the continental Oligocene in North America. Sixteen other section spanning the late Chadronian—Orellan—Whitneyan were also sampled (Fig. 7); their details will be presented elsewhere. The Flagstaff Rim section has four radiometrically dated ashes (Evernden et al., 1964), which are shown in Figs. 6 and 8 (corrected for the new decay constants; Dalrymple, 1979). A two-million year long reversed interval, bracketed by biotite K/Ar dates of 32.4 Ma slightly above its top and 34.6 Ma at its base is found in the upper part of the section. Its base coincides with dated Ash F (34.6 Ma), and its top coincides with undated Ash I (approximately 32.8 Ma), lying just 17 meters below dated Ash J. The whole reversed interval spans 78 meters. It most likely corresponds to the MPTS anomaly 12—13 reversed interval, judging from its age and great length. Beneath this reversed interval is a long normal-polarity zone that may correspond in part to anomaly 13 itself, but which also probably includes remagnetized material, judging from its length, and from the red-clay lithology that prevails at the very base of the section. Only the polarity reversals at Ash F and Ash I, plus the intervening zone of reversed character, are considered to be of importance here at present.

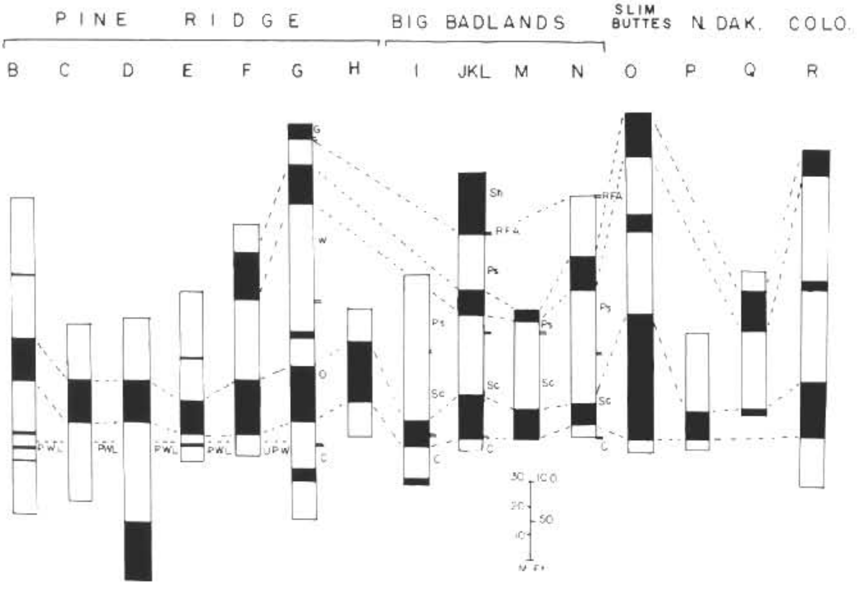

Fig.7. Polarity interpretations of fifteen late Chadronian—Orellan—Whitneyan—Arikareean sections in Wyoming, Nebraska, South and North Dakota. Section locations shown in Fig.1. Solid bars indicate normal polarity; open bars are of reversed polarity; hachured bars are indeterminate. Correlations based on biostratigraphic studies in progress by author D.R.P. Datum is the base of the Brule Formation or its equivalents. Abbreviations are as follows: *C* = Chadron Formation; *G* = Gering Formation, Arikaree Group; *O* = Orella Member, Brule Formation; *P* = Poleslide Member, Brule Formation: *PWL* = Purplish White Layer; *RFA* = Rockyford Ash; *Sc* = Scenic Member, Brule Formation; *Sh* = Sharps Formation, Arikaree Group; *W* = Whitney Member, Brule Formation.

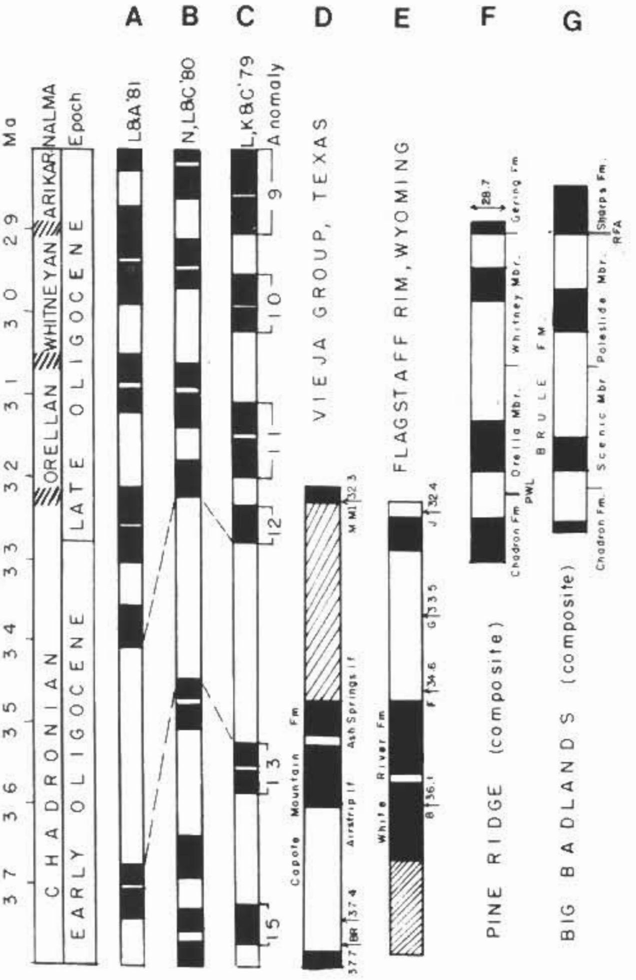

Fig.8. Correlation of Oligocene rocks with the magnetic polarity timescale. A. MPTS after Lowrie and Alvarez (1981). B. MPTS after Ness et al. (1980). C. MPTS after LaBrecque et al. (1977). D. Composite section of the Vieja Group, Trans-Pecos Texas (Testarmata and Gose, 1979). *BR* = Bracks Rhyolite; *MM* = Mitchell Mesa Ignimbrite; *l.f.* = local fauna. E. Composite section at Flagstaff Rim, Wyoming (see Fig.6). Radiometrically-dated ashes shown in geochronologic position. Correlation of Ash Spring and Airstrip local fauna with Wyoming faunas after Emry et al. (in press). F. Composite section of Pine Ridge, Wyoming and Nebraska. Based on sections B—H, Figs. 1 and 7. Chronologic position of date at base of Gering at Wildcat Ridge (Obradovich et al., 1973) shown by arrows. G. Composite of sections from the Big Badlands of South Dakota. Based on sections I—N, Figs. 1 and 7.

The composite polarity picture for the late Chadronian—Orellan—Whitneyan sections at Pine Ridge and the Big Badlands is shown in Fig.8. We suggest that the late Chadronian (basal) part of the Pine Ridge section can be correlated with the top of Flagstaff Rim on two lines of evidence:

(1) Late Chadronian faunas from the base of the Pine Ridge section include numerous taxa which are identical to, or only slightly more advanced than, taxa from the uppermost fossiliferous levels (about Ash G) at Flagstaff Rim. Titanotheres are known above Ash J at Flagstaff Rim, and they also occur above and below the Purplish White Layer (PWL) at Pine Ridge.

(2) There is a radiometric date of 28.7 ± 0.7 Ma at the base of the Arikareean (Obradovich et al., 1973), that is in a zone of normal polarity in Toadstool Park and the Big Badlands. Beneath this zone are at least three more zones of normal polarity, and no long reversed interval. If the identification of the anomaly 12—13 reversed interval at Flagstaff Rim is correct, then this Arikareean date constrains the age of the Orellan—Whitneyan sections. We suggest that the late Chadronian normal zone seen at the base of the Pine Ridge section represents anomaly 12. The early Orellan normal zone would then be anomaly 11, and the medial Whitneyan normal zone would be anomaly 10. The base of the Arikareean thus correlates with anomaly 9.

A section from the Vieja Group of Trans-Pecos Texas (Testarmata and Gose, 1979) further corroborates our correlations. It is bracketed by corrected dates of 32.3 Ma and 37.4 Ma (Fig.8). It contains two mammal assemblages, the Airstrip and the Ash Springs local faunas, which are correlative with the Flagstaff Rim faunas between Ashes B and G (Emry et al., in press). The Vieja section has a long zone of reversed polarity above the Bracks Rhyolite that we interpret to be the anomaly 13—15 reversed interval. Above anomaly 13 and beneath the Mitchell Mesa Ignimbrite is a long interval of indeterminate polarity. We suggest that the anomaly 12—13 reversed interval lies unseen within this zone. Testarmata and Gose (1979) assigned the long reversed interval to the anomaly 12—13 reversed interval. Their identification is contradicted by the radiometric dates, and by the faunal correlations with Flagstaff Rim; hence, we think that their correlation is incorrect.

DISCUSSION

The composite polarity picture (Fig.8) for the Flagstaff Rim, Vieja Group, and the Orellan—Whitneyan sections fits the MPTS in only one way. The pattern of two long reversed intervals (anomalies 13—15 and 12—13), followed by several shorter periods of normal polarity is unique in the Oligocene part of the MPTS. We therefore suggest that the top of the anomaly 12—13 reversed interval is dated as 32.8 Ma by linear interpolation, and that the base is dated at 34.6 Ma. Of the various conflicting versions of the MPTS, the timescales of LaBrecque et al. (1977) and Ness et al. (1980) are indistinguishable during this time, given the uncertainty of the radiometric dating. We prefer the LaBrecque et al. version here, because it places anomaly 12 older than 32.4 Ma and anomaly 13 older than 34.6 Ma. The recently proposed timescale of Lowrie and Alvarez (1981) places the anomaly 12—13 reversed interval some two million years too old (Fig. 8), well beyond the errors to the radiometric dates. The Lowrie and Alvarez timescale was not directly dated by radiometric means in the Paleogene, but rather indirectly through biostratigraphy. It appears that the absolute ages of the biostratigraphic correlations on which their timescale is based need some adjustment. If, too, the LaBrecque et al. (1977) and Ness et al. (1980) scales need adjustment in the Paleocene and Eocene, as Butler and Coney (1981) and Butler et al. (1981) suggest, then no currently published version of the MPTS is adequate for the Eocene and Oligocene.

Paleomagnetic dating of the White River Group makes possible the absolute calibration of the Oligocene North American land mammal "ages" for the first time. Chadronian faunas are known from rocks correlated with the base of anomaly 15 (our reinterpretation of Testarmata and Gose, 1979) to the reversal above anomaly 12. Using the LaBrecque et al. (1977) timescale, the Chadronian thus ranges from about 32.4 Ma to 38.0 Ma. Orellan faunas occur in rocks correlated with the reversal above anomaly 12 to the middle of the reversed interval above anomaly 11, or about 30.7—32.4 Ma. This is in agreement with previous estimates based on other evidence that suggests that the Orellan was only about 1—2 Ma long (Emry et al., in press). Whitneyan faunas occur in rocks correlated with the middle of the reversal above anomaly 11 to the base of anomaly 9, or about 29.0—30.7 Ma. Further work on Whitneyan—Arikareean sections is needed to refine the magnetostratigraphy of that interval.

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