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

MURRAY N. PROTHERO
Department of Geology, Occidental College, Los Angeles, CA 90041

ABSTRACT

New magnetostratigraphic studies have been conducted on Early Oligocene sections at Flaggstaff Rim and Lodge Creek, Natrona County, Wyoming, and the Dith Road, Converse County, Wyoming. Thermal demagnetization has considerably improved the polarity interpretation of Flaggstaff 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 C2r to Chron C15 of the magnetic polarity timescale (23 to 37 m.y. based on K-Ar dates from Flaggstaff Rim). This additional, more complete magnetostratigraphic evidence shows clearly that the Eocene-Oligocene boundary must be 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 flora (Wolfe 1972), marine faunas and floras (Fischler and Arctow 1977; Cavinelli et al. 1981) which were associated with a major global cooling of 1-3°C (Spavon 1977), a major regression (Vail et al. 1977), a drop in the carbonate compensation depth (Cavinelli et al. 1981), and the brining of modern oceanic circulation with the development of the circum-Antarctic current and deep bottom waters (Kennett 1979). The "Terminal Eocene Event" (Cavinelli 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 synopses (e.g., the symposium edited by Cavinelli et al. 1981) and organizations (KCGP Project 174: Les Evénements Geologiques de la limite Eocene-Oligocene). Evidence of catastrophic extraterrestrial events (Glass and Covillie 1982; Alvarez et al. 1982; Alvarez et al. 1987; Gasparczyk 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. 1942; Palmer 1983) age estimate of 36-38 m.y. (Bergeron 1972; Nard- enholb and Bergren 1978) has recently been challenged by a number of authors who place the Eocene-Oligocene boundary between 32 and 34 m.y. (Glass and Covillie 1982; Arment trous 1981; Wolfe 1978, 1981; Odlin 1978; Harris and Zullo 1980). Studies on marine sections with both planktonic microfossils and magnetic stratigraphy (Lowe et al. 1982; Poore et al. 1982) have established that the Eocene-Oligocene boundary falls between Chron C13 and C15 of the magnetic polarity timescale, or within reversed Chron C13r. However, the uncertainty over the calibration of the magnetic polarity timescale (Lowe and Alvarez 1981; Hess et al. 1980; Lalonde et al. 1977) has been considerable and possible local paleomagnetic sections with high-temperature K-Ar ages (Prothero et al. 1982, 1983a) have recently been described (Bergeron et al. 1984) and have allowed direct calibration of three diagnostically long reversed polarity events which have been called Chron C13r, C13s, and C20r (Bergeron et al. 1984, fig. 1). This calibration remains controversial (Ness 1983; Prothero et al. 1983b), although new evidence from marine Oligocene sections in the Olympic Peninsula of Washington (Prothero and Armstrong 1985; Armentrou and Prothero pers. comm.) support the calibration of Bergeron et al. (1984).

Prothero et al. (1982, 1983a) described the
magnetostratigraphy of a critical stratigraphic section at Flagstaff, Wyoming. In the summer of 1973 I resampled Flagstaff Rim to solve some questions about the magnetostratigraphy. A more thorough sampling and demagnetization program described below has improved the magnetostratigraphy considerably. Sections of similar age at Lodge Creek and Dils Ranch, Wyoming, were also sampled to test the eastern extent of Flagstaff Rim. This paper describes these new data, which cast considerable light on age estimates of the Eocene-Oligocene boundary.

MAGNETIC STRATIGRAPHY

The tuffaceous sediments of the White River Group in Wyoming (fig. 11) are particularly well suited to magnetostratigraphic analysis. They are well exposed, full-lying, and highly fossiliferous. Many of these rocks contain volcanic ash layers which have been, or could be, dated by overtone archaeometry. The Flagstaff Rim area (geology described by Kem 1973) contains the thickest and most complete bioturbational record of the Chattian. Entry (1973: pers. comm.) is presently preparing a published bioturbational section for this region. The Lodge Creek area has been described briefly by Skinner and Coors (1966). It produces a fauna similar to that of Flagstaff Rim, but the section is thinner and less fossiliferous. The deposits and fauna of the Dils Ranch area an ancription to the Chattian of Komin (1973).

Using the published and unpublished stratigraphic sections in these areas, three field samples and two paleomagnetic samples of these sections in the summer of 1973. The Lodge Creek section was measured along the north face of Lone Tree Gulch from the NE, SW, SE, SE, Section 23, T13N, R38W, to the tip of the hill of 673 ft (88.2 m) elevation in the center of Section 23. The section begins at the Carboniferous-Oligocene contact immediately south of an abandoned well going into Lone Tree Gulch and continues 23 m above Ash B (the top of R37S, 3-7). The upper part of the section bears just above Ash B in Lone Tree Gulch (SW, NW, SE, SW, Section 23) and runs down into R37S, 4-7. Full documentation of each site as seen in the site as seen in the text and other sections discussed here is available from the author on request.

The Lodge Creek section was taken along the northwestern face of the canyon labeled "Ledge Creek Number 2" by Skinner and Coors (1966). This section begins at beds at the mouth of the canyon (SW, NE, NE, Section 22: T29N, R38W, Bear

The data show a number of sites that were difficult to interpret, although the long reversed interval between Ash B and the interpreted normal of C3 was clearly visible. The remaining section below Ash B (interpreted as C3N) was almost entirely of normal polarity, yet the magnetic polarity of the section shows a very short C3N interval to the length of a single C1R. For this reason, I suspected that normal overprinting had not been adequately removed. Pilot thermal demagnetization studies (figs. 3, 4, and 5) showed that the primary carrier of the remanence was a low coercivity, low Curie point mineral such as a form of titanomagnete. 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 500°C, although some samples required further heating at 500 to 700°C. After demagnetization, stand Site statistics (Fisher and Kram 1953; Irving 1954) were calculated on the cleaned directions. The tachildiatical classification scheme of Opdyke (1957) was used to look at the White River rocks, which does not employ thermal demagnetization, but must be viewed with caution.

All of the published sections have been reviewed except the original Flagstaff Rim section. Section 23 was treated with limited thermal demagnetization and was based on a single sample per site, so that no statistics could be calculated. As a result.
of Flagstaff Rim consistently show there are at least two explanations for this:
1. the real 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 unable to use the technique of Chown et al. 1977 sites, which have one of the three directions divergent. A single divergent direction at a given site in very common in thermal demagnetization and anisotropy of elastic constants. This may improve the chemical overprinting to variability of the characteristic remanence in some samples, or to a number of other possible choices. Whatever the reason, the sample per site in order to be anisotropy in establish site polarity, let alone calculate the statistics. There are too many ways that a single sample can lead one to errors.

The results of interpretation of Flagstaff Rim sites shown that the entire sequence from about 10 m above Ash B to Ash F is reversely

FIG. 5. A. Original polarity interpretation of Demuth et al. 1982 for Flagstaff Rim. B. Revised interpretation of lower half of sequence after thermal demagnetization and multiple samples per site.

C. Powers stratigraphy of the Lead Creek No. 2 section. P. Red and yellow shades indicate reversed polarity, green and blue are normal. Ash sample horizons along with the depth in feet below the base of the member. D. Red and yellow shades indicate reversed polarity, green and blue are normal. Ash sample horizons along with the depth in feet below the base of the member. E. Red and yellow shades indicate reversed polarity, green and blue are normal. Ash sample horizons along with the depth in feet below the base of the member.
Above this marker zone is a long reversed interval (zone 6), or China C19; a short normal zone (5), or China C18; and a long reversed interval that continues beyond the top of the section (4), or China C17. The relative durations of these zones can be compared with the Flagstaff Rim and with the magnetic polarity timescale (fig. 7). The Dils Ranch section (fig. 6) is the key to correlating the Chadronian sections with the Flagstaff Rim and the Dils Ranch section with the lower Dilmunia sections described by Partridge et al. (1970a, 1970b). The basal portion of the Dils Ranch section contains early-middle Chadronian faunas (zone 5), primarily two smaller localities, informally known as "The Splits" and "Thryomacs." These fossils, especially the toothed rodents, Pteronotus, and longnosed condylarthrs, resemble forms from the Ash B to Ash D level at Flagstaff Rim (Koon, 1957, 1962). The upper portion of the section above the "grey layer" contains late Chadronian and middle Uinta mammal faunas, which correlate with faunas from similar deposits north of Dils Ranch and the North Platte River, near Douglas, Wyoming (Koon, 1960). The composite Dils Ranch section is therefore a critical tie between the Chadronian sections at Flagstaff Rim and the latest Chadronian-Orellan White River sections found elsewhere in the White River Group.

The Dils Ranch section shows three episodes of normal polarity in a predominantly reversed section. The uppermost normal magnetic zone (zone 6), 94.9 to 113.1 in the megasequence section), is associated with early Uinta mammal faunas, which closely resemble deposits in association with China C11. The middle normal magnetic zone (zone 4), 73 to 94 in the composite section, above the "grey layer" is associated with late Chadronian faunas. This fauna also occurs in the uppermost fossiliferous beds of the Flagstaff Rim and at Near Ranch, Sweetwater County, Wyoming (Partridge 1982) which are correlated with China C12. The lower normal magnetic zone (zone 2) is a long block of reversed polarity, interrupted by a normal magnetic zone of 12 to 25 m in the composite section (zone N2). Based on its association with early-middle Chadronian faunas, this normal magnetic zone appears to correlate with a relatively thin sequence representing China C12 at Flagstaff Rim, but the biostratigraphic evidence allows no certain identification of the "grey layer" or evidence sections which produced early-middle Chadronian faunas (Koon, 1978). A show a normal magnetic zone that probably represents China C3, although not a section in long enough to produce a diurnal pattern of polarity events.

Discussion

The correlation diagram above is summarized in figure 8. Five areas now produce Chadronian magnetostratigraphic results which can be correlated to the magnetic polarity timescale. The Vajcia Gorge in Texas (Tantouman and Good 1979; reinterpreted by Partridge et al. 1984) appears to span the interval between China C1 and China C3. Two important radiometrically dated volcanic layers known as zones a help constrain the age limits of the section. The revised Flagstaff Rim section now matches the segment of the magnetic polarity timescale for China C1 and C2 very well. The Vajcia data also constrain the diurnal age of this section. Together, these three sections provide the primary evidence for the radiation of the magnetic polarity timescale of Partridge et al. (1982, 1984).

The Dils Ranch section provides further correlation of the polarity pattern seen at Flagstaff Rim. It is correlated to Flagstaff Rim by its magnetic zone 1 at mammalian faunas, although dittdigable in this zone is not available. The Dils Ranch section ties the most significant part of the magnetic polarity timescale of Partridge et al. (1982, 1984) to the Orellan-White River section. It is preserved near Chadron and China C19. The magnetic stratigraphy and biostratigraphic evidence from the Dils Ranch section correlates with the interpretation of Partridge et al. (1982, 1984) that the Chadron and White River sections in the magnetic polarity timescale. The Dils Ranch section, the White river segment of magnetostratigraphy is now completely based on an overlapping, mammal-bearing section, with no significant gaps. Two other sections deserve mention. The classic early-middle Chadronian locality at Prentice Springs, Montana (Koon and
which appear to correlate with Chrom C12 and the base of Chrom C12r (Prothero 1970). Samples were also taken in the thickest portion of the Chadrion record in the Big Badlands of South Dakota, where the "Ahrn," "Gayle Johnson," and "Plains Peak" members of the Chadron Formation were described by Clark (1937, 1954; Clark et al. 1967). These rocks proved to have a stubborn normal overprint due to chemical remanence from biotite and did not respond to either thermal or AF demagnetization. Unless they were tipped by chemical means to remove the overprint, they will not yield an irreversible magnetostrophic equilibrated.

Some workers (Glass 1972, comm.; Wotzki pers. comm.) have suggested other interpretations of Flagstaff Rim that are consistent with their interpretation that the Eocene-Oligocene boundary is about 32 to 34 m.y. in age. They interpreted the reversed interval between Adr. 4 and 1 at Flagstaff Rim (based on the original magnetostrophic interpretation in Prothero et al. 1982) to be Chrom C13r and suggest that Chrom C12r lies in the Orellan. This is clearly not consistent with the evidence now available (Fig. 8). The revised magnetostrophic interpretation of Flagstaff Rim, reflected by the record at Lodge Creek, gives a reversed interval bracketed by K-Ar dates which is clearly too long for any other magnetic excursion except Chrom C12r. Biostatigraphic correlations in this section to the Dils Ranch section, and thus to the rest of the Orellan-Whitean-Omaha magnetic stratigraphy, nowhere are in the Orellan or Whitean because there is a reversed magnetostrophic of sufficient length to be Chrom C12r. None of the known reversed zones in the Orellan or Whitean could be this long, or they would make the Orellan-Whitean-much younger and conflict with the K-Ar date at the base of the remaining Gering Formation of 28.7 ± 0.7 m.y. (Dobrovolsky et al. 1975). The composite White River-Yegua magnetostrophic is not tightly bracketed by mammalian biostatigraphy and by numerous high-temperature K-Ar dates that any alternative interpretation would seriously conflict with the biostatigraphy or with the radiometric dates.

These K-Ar dates have also been questioned by some workers, since they conflict with the glacialite dates of Odin (1978). As Berggren et al. (1986) have thoroughly documented, high-temperature K-Ar dates on biotite are much more reliable than those based on glaebrite (Thompson and Flower, 1973). At Flagstaff Rim, the original K-Ar dates reported by Evensen et al. (1964) were done in the 1960's of K-Ar dating, so there are no published error estimates. These dates have been retot with both K-Ar and fission track methods (D. V. Kent pers. comm.) and have proven reliable. Only the dates on Adr B (160 ± 40 m.y. on radiometric; 34.2 m.y. on biotite, corrected for the saw decay constant of Dalrymple 1979) have proven problematic. The biotite date on Adr B may seem inconsistent with the stratigraphic position of the sample, so most authors (Emery 1969, Emery et al. 1982; Prothero et al. 1982, 1983) have tried the sodium date. Normal error estimates on dates of this age range should be in the order of 0.7 to 0.8 m.y.

The biotite date on Adr B may be fact consistent if allowance is made for three possible error estimates. Even if Adr B is not used (e.g., Berggren et al. 1984), the other dates at Flagstaff Rim and on the Yegua Group are sufficient to support the great chronologic span of the reversed magnetostrophic between Adr B and J which we interpreted as Chrom C12r. With these constraints on the magnetic polarity timescale, there can be no longer any doubt that Chrom C12r occurs between 33 and 35 m.y. Thus, Chrom C12r and the Eocene-Oligocene boundary must lie between 36 and 31 m.y.

ACKNOWLEDGMENTS—I thank Rob Lamont, Allison Katzik, and Annie Walton for assistance in the field and the laboratory, and W. K. Reigemma for permission to use the paleomagnetics lab at the South Dakota School of Mines. R. J. Entry (Flagstaff Rim, Lodge Creek) and D. G. Aronson (Dills Ranch) graciously guided me through the stratigraphy of their respective areas. I thank W. A. Berggren, R. J. Entry, J. J. Flynn, B. F. Glass, D. V. Kent, G. G. Kruse, M. D. Opdyke, and J. A. Wolfe for helpful comments and criticisms. Acknowledgment is made to the Donors of the Petroleum Research Fund administered by the American Chemical Society for partial support of this research.