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13. Magnetic Stratigraphy of the White River Group in the High Plains

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ABSTRACT

Magnetostratigraphic sampling was conducted on key fossiliferous exposures of the upper Eocene-lower Oligocene (Chadronian-Whitneyan) White River Group in North Dakota, the Pine Ridge area of Nebraska, the North Platte River-Wildcat Ridge area of Nebraska and Wyoming, and the Cedar Creek area of northeastern Colorado. Together with results from other White River outcrops reported elsewhere, a general magnetostratigraphic pattern can be seen. Most sections are of predominantly reversed polarity, but there are two short zones of normal polarity in the middle and late Chadronian, another in the early Orellan, and another in the late Whitneyan. Based on $^{40}Ar/^{39}Ar$ dates and correlation to the Berggren et al. (1995) time scale, the middle Chadronian normal magnetozone correlates with Chron C16n (35.4-35.6 Ma), the late Chadronian normal magnetozone with Chron C15n (35.7-35.9 Ma), the early Orellan normal magnetozone with Chron C13n (33.0-33.5 Ma), and the late Whitneyan with Chron C12n (30.5-30.9 Ma). The Chadronian spans the interval from about 37 Ma to about 33.8 Ma; the Orellan from 33.8-32 Ma; the Whitneyan from 32 to about 30 Ma.

INTRODUCTION

The richly fossiliferous and spectacularly scenic badlands of the White River Group in the High Plains (Fig. 1) have been a magnet to fossil collectors and paleontologists ever since the first fossils were collected and described in 1846. In the century and a half since then, tens of thousands of fossils of extraordinary quality have been recovered from White River rocks, making them the most productive mammal-bearing sequence in North America. When the Wood Committee (Wood et al., 1941) set up a provincial time scale for North America, they based the Chadronian through Whitneyan land mammal "ages" (then thought to be early-late Oligocene, but now considered to be late Eocene-early Oligocene) on the White River Group and its mammals. Many detailed lithostratigraphic studies have been published over the years (Sinclair, 1921; Wanless, 1923; Schultz and Stout, 1955; Clark et al., 1967; Singler and Picard, 1980; Retallack, 1983; Seeland, 1985, among others; reviewed by Emry et al., 1987). Despite the amazing quality and quantity of fossils, biostratigraphic studies have been much less detailed (see Emry et al., 1987), but the updated systematic reviews of the critical fossil mammal groups in this volume finally allow us to construct a detailed range-zone biostratigraphy (see Prothero and Whittlesey, in press, and the summary chapter for this volume).

Since 1976, magnetic stratigraphy has also figured prominently in improving correlation within the White River Group, and with the global magnetic time scale. The initial studies in 1976-1977 by Charles Denham and Harlow Farmer (then of the Woods Hole Oceanographic Institute) were a first attempt to determine if a stable magnetic polarity stratigraphy could be obtained from White River outcrops. In 1979-1980 I conducted my initial sampling program as part of my doctoral dissertation (Prothero, 1982). Further sampling was conducted in the summers of 1983, 1986, and 1987. Brief summaries of this research have been published over the years (Prothero et al., 1982, 1983; Prothero, 1985a, b; Swisher and Prothero, 1990; Evanoff et al., 1992; Prothero and Swisher, 1992), but space limitations prevented a detailed discussion of the polarity stratigraphy of each section. This chapter, and another paper now in press (Prothero and Whittlesey, in press), finally present the details of the past 20 years of magnetostratigraphic research in the White River Group.

METHODS

As previously described in Prothero et al. (1983) and Prothero (1985a), all samples were collected with simple hand tools as horizontally oriented blocks of rock. Three samples were collected per site, and most sites were spaced 5.5 feet (1.7 m) stratigraphically. In the laboratory, the samples were trimmed into oriented cubes approximately 2.5 cm in length.

Different laboratories were used for the samples as they were collected over the years, and my procedures have evolved as well. For the sections that were done in the field summers of 1979-1980, most samples were run on the ScT cryogenic magnetometer at Woods Hole Oceanographic Institute. Most samples were treated primarily with AF demagnetization; thermal demagnetization was undertaken later at Lamont-Doherty Geological Observatory when it became apparent that AF demagnetization could not remove overprints due to iron hydroxides. These 1979-1980 sections include most of the Pine Ridge sequences: Geike and Munson Ranches, and Toadstool Park in Sioux County, Nebraska, and Trunk Butte and Bartlett-Morris Ranches in Dawes County, Nebraska. In addition, the 1980 sampling included the White River strata in Logan County, Colorado; Slim Buttes, Harding County, South Dakota; and the Little Badlands and Fitterer Ranch, Stark County, North Dakota. I also sampled the Red Shirt Table section in the Big Badlands of South Dakota to supplement Denham's sections elsewhere in the Big Badlands (Denham, 1984). A more detailed discussion of the geology and stratigraphy of most of these regions follows; for further details, see Prothero (1982). Of

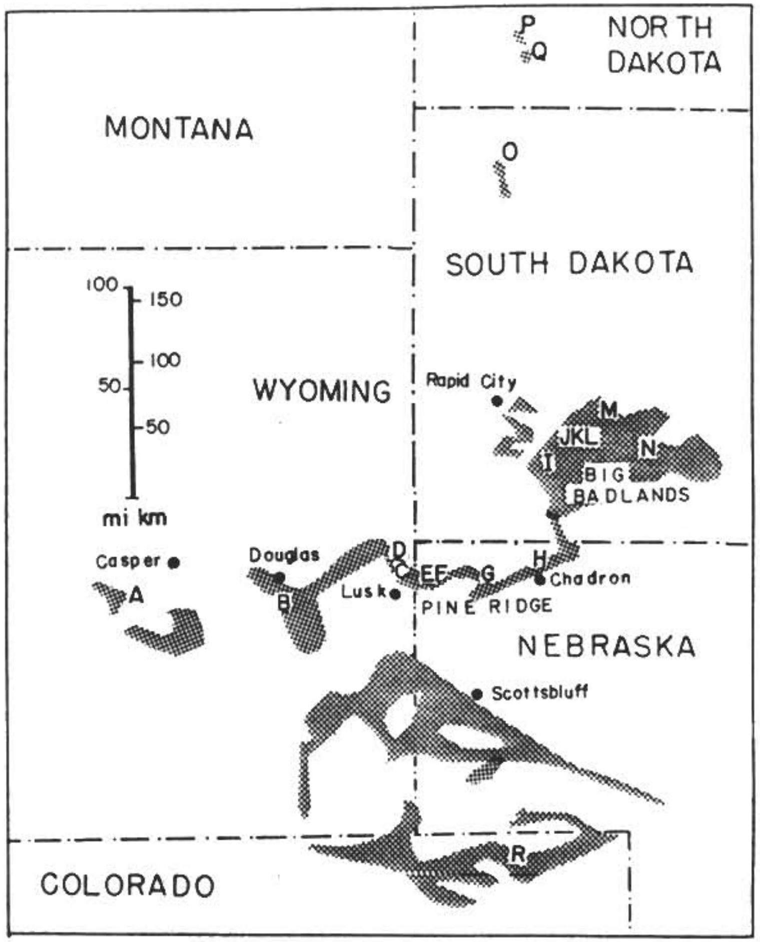

Figure 1. Index map showing localities mentioned in text. Outcrop of White River Group indicated by stipple. A, Flagstaff Rim, Natrona County, Wyoming (see Emry, 1992; Prothero and Swisher, 1992); B, Douglas-Dilts Ranch area, Converse County, Wyoming (see Evanoff et al., 1992); C, Sherrill Hills and Thompson Ranch, and D, Boner Ranch, in the Seaman Hills, Niobrara County, Wyoming (see Prothero and Whittlesey, in press); E, Geike Ranch; F, Munson Ranch; G, Toadstool Park and Raben Ranch area (E-G in Sioux County, Nebraska); H, Trunk Butte and Morris-Bartlett Ranches, Dawes County, Nebraska; I-N, sections in Big Badlands of South Dakota (see Prothero and Swisher, 1992, and Prothero and Whittlesey, in press); O, Slim Buttes, Harding County, South Dakota (see Prothero, 1985b); P, Little Badlands, and Q, Fitterer Ranch, Stark County, North Dakota; R, Flat Top and Chimney Canyons, Logan County, Colorado.

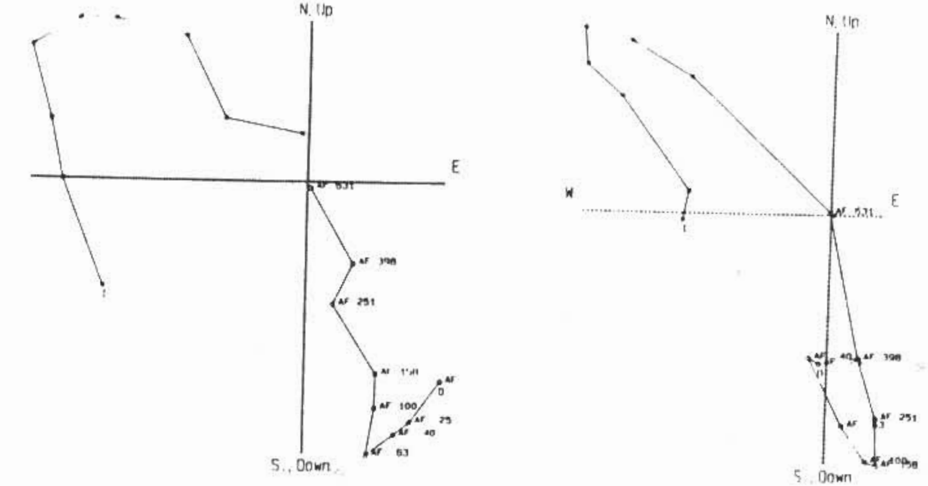

Figure 2. Typical orthogonal demagnetization plots ("Zijderveld" plots) of alternating field (AF) demagnetization of representative samples. Declination is shown by open boxes (with the AF field in Gauss indicated); inclination by asterisks. I = NRM direction of inclination. Each division = 10^{-6} emu. The intensity drops rapidly through AF demagnetization, suggesting that magnetite is the primary carrier of the remanence.

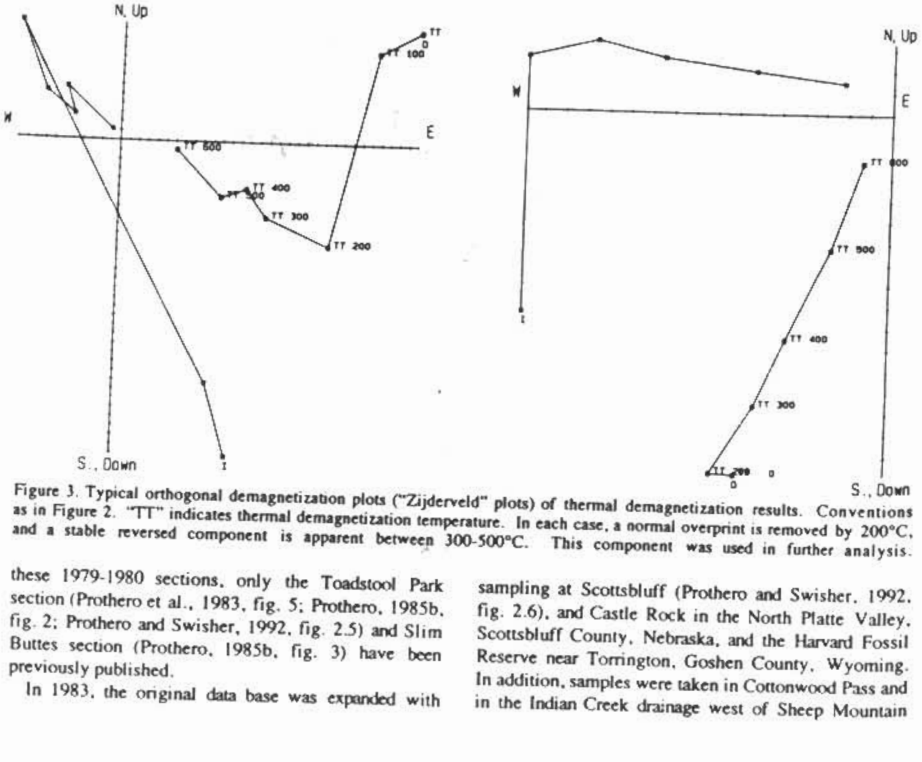

Figure 3. Typical orthogonal demagnetization plots ("Zijderveld" plots) of thermal demagnetization results. Conventions as in Figure 2. "TT" indicates thermal demagnetization temperature. In each case, a normal overprint is removed by 200°C, and a stable reversed component is apparent between 300-500°C. This component was used in further analysis.

these 1979-1980 sections, only the Toadstool Park section (Prothero et al., 1983, fig. 5; Prothero, 1985b, fig. 2; Prothero and Swisher, 1992, fig. 2.5) and Slim Buttes section (Prothero, 1985b, fig. 3) have been previously published.

In 1983, the original data base was expanded with sampling at Scottsbluff (Prothero and Swisher, 1992, fig. 2.6), and Castle Rock in the North Platte Valley, Scottsbluff County, Nebraska, and the Harvard Fossil Reserve near Torrington, Goshen County, Wyoming. In addition, samples were taken in Cottonwood Pass and in the Indian Creek drainage west of Sheep Mountain Table in the Big Badlands, site of Clark's (1937) Ahearn, Crazy Johnson, and Peanut Peak members of the Chadron Formation. Sections were taken at Ledge Creek and Flagstaff Rim, Natrona County, Wyoming (Prothero, 1985a); except for these and the Scottsbluff section, the rest of these sections have not yet been published. These samples were run on the ScT cryogenic magnetometer at the laboratory of the South Dakota School of Mines in Rapid City, using mostly thermal demagnetization, with AF demagnetization of pilot samples undertaken to determine coercivity behavior.

In the early 1980s, it became apparent that the original magnetic analysis by Denham and Farmer was inadequate, because they used only one sample per site (preventing calculation of site statistics), and used almost no thermal demagnetization to remove overprinting that might be due to high-coercivity iron hydroxides. The resampling and thermal demagnetization analysis of samples from the Flagstaff Rim section (Prothero, 1985a; Prothero and Swisher, 1992, fig. 2.4) radically changed the pattern originally obtained by Denham (in Prothero et al., 1982, fig. 1; Prothero et al., 1983, fig. 6). In addition, the Big Badlands sections had to be resampled, since none of the results reported by Denham (1984) used thermal demagnetization. In 1986, several areas were sampled: Raben Ranch, Sioux County Nebraska; the upper part of the Roundtop-Toadstool section (Prothero and Swisher, 1992, fig. 2.5), and a dense resampling program in the Big Badlands, following the measured sections and field notes of the Frick Laboratory (particularly those of Morris Skinner). The Cedar Pass, Pinnacles, and Wolf Table-Wanblee sections were sampled that summer. In 1987, we continued the Big Badlands sampling with a section at Sheep Mountain Table. These Badlands magnetic sections were summarized by Prothero and Swisher (1992, fig. 2.7). In 1994, Karen Whittlesey supplemented the Badlands coverage with sections at Sage Creek and the type Scenic area; these are described elsewhere (Prothero and Whittlesey, in press).

The samples taken in 1979-1980 and 1983 were treated with thermal demagnetization at 300-500°C, based on detailed stepwise thermal and AF demagnetization of a pilot suite (e.g., Prothero et al., 1983, fig. 4). All of the samples run since 1986 have been analyzed on a 2G cryogenic magnetometer using extensive thermal and AF demagnetization at the paleomagnetics laboratory at the California Institute of Technology. AF demagnetization (Fig. 2) showed that most samples declined in intensity rapidly, showing that the primary carrier of remanence was a low-coercivity mineral such as magnetite. Thermal demagnetization (Fig. 3) showed that overprints were removed between 200-300°C, and results obtained between 300-400°C were used in the analysis.

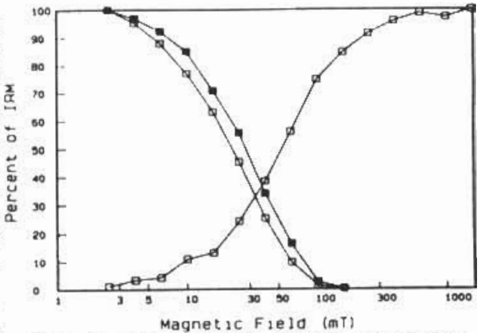

Figure 4. IRM (isothermal remanent magnetization) acquisition (ascending curve on the right) and Lowrie-Fuller test (two descending curves on left) of a typical sample. Open boxes indicate IRM; solid boxes indicate ARM (anhysteretic remanent magnetization). The IRM saturates by 300 mT (millitesla), showing that magnetite is the dominant magnetic mineral phase. In the Lowrie-Fuller test, the ARM (black squares) is more resistant to AF demagnetization than the IRM (open squares) suggesting that single-domain or pseudo-single-domain grains predominate (see Pluhar et al., 1991, for details of the methods).

IRM (isothermal remanent magnetization) acquisition studies (Fig. 4) clearly showed saturation between 300 and 1000 mT (millitesla), indicating that the carrier of remanence is mostly magnetite. A modified Lowrie-Fuller ARM (anhysteretic remanent magnetization) test (e.g., Johnson et al., 1975) was also conducted during the IRM analysis (see Pluhar et al., 1991, for details). This test compares the resistance of AF demagnetization of both an IRM acquired in a 100 mT peak field, and an ARM gained in a 100 mT oscillating field. In almost all samples, the ARM (black squares) demagnetizes at higher peak fields than does the IRM (open squares), indicating that the remanence is carried by single-domain or pseudo-single-domain grains.

Based on these results, the vectors obtained between 300-500°C were averaged using the methods of Fisher (1953; see Butler, 1992). Class I sites of Opdyke et al. (1977) showed a clustering that differed significantly from random at the 95% confidence level. In Class II sites, one sample was lost or crumbled, but the remaining samples gave a clear polarity indication. In Class III sites of Opdyke et al. (1977), two samples showed a clear polarity preference, but the third sample was divergent because of insufficient removal of overprinting. A few samples were considered indeterminate if their magnetic signature was unstable, or their direction uninterpretable.

The means for the normal and reversed sites at each locality were also averaged using the methods of Fisher (1953). The mean of all 143 Class I reversed sites (D = 155.8, I = -40.8, k = 7.8, α_{95} = 4.5) is antipodal to the mean of all 272 Class I normal sites (D = 351.2, I =

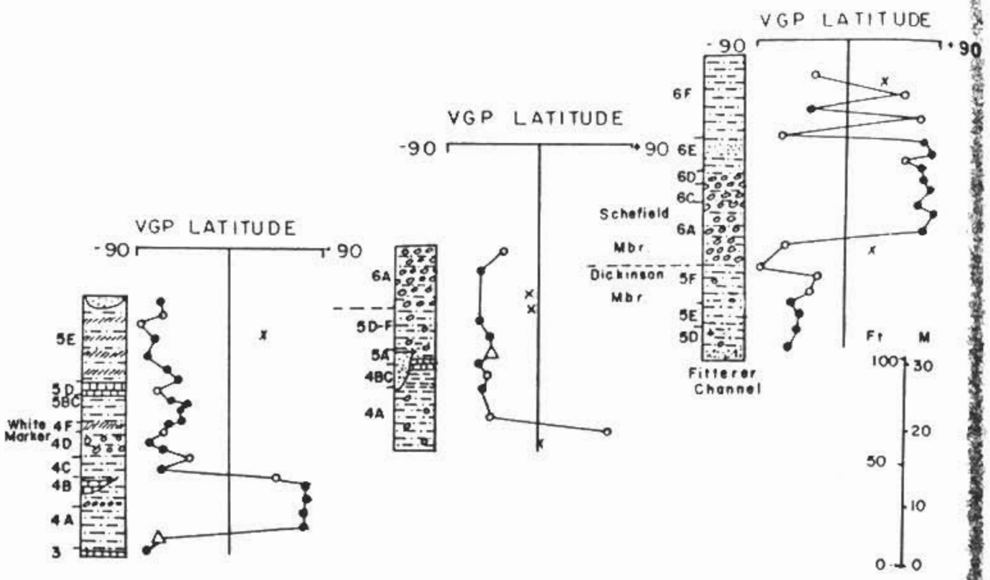

Figure 5. Magnetic stratigraphy of of the "Little Badlands" (left) and "Fitterer Ranch" (center and right) sections in Stark County, North Dakota. Exact location of sections given in text. Stratigraphic terminology follows Skinner (1951) and Stone (1972). Solid circles are Class I sites of Opdyke et al. (1977), which are statistically separated from a random distribution at the 95% confidence level. Triangles are Class II sites, which could not be statistically analyzed because only two samples remained; the third was lost or crumbled. Open circles are Class III sites, in which two samples showed a clear polarity preference, but the third sample was divergent. "x" indicates site of indeterminate polarity.

67.4, k = 25.7, α_{95} = 1.7) within the α_{95} error estimate. This positive reversal test suggests that the magnetization is primary and not due to secondary overprinting. Most of the strata are horizontal, so no fold test could be conducted.

In some sections, it was not possible to completely remove the overprinting on every site, so that there are isolated single-site "polarity events." In most cases (such as single normal sites within a long reversed interval), these are most likely due to unremoved normal overprinting. Consequently, the correlations discussed below are based only on magnetozones that are at least two or more sites thick; single-site "polarity events" are not correlated between regions, since they are not consistently found in every section. However, the possibility that these short "polarity events" are real cannot be ruled out, since detailed analysis of Oligocene deep-sea cores (Hartl et al., 1993) demonstrates that there were a number of brief polarity events during the Eocene and Oligocene.

RESULTS

The magnetic polarity patterns of each of these regions are discussed below. Details of the Douglas area sections have already been published elsewhere (Evanoff et al., 1992). The Big Badlands sections, and the sections in the Lusk area, Niobrara County, Wyoming, are described by Prothero and Whittlesey (in press). The Slim Buttes section was described by Prothero (1985b, fig. 3), and the Scottsbluff section was detailed in Prothero and Swisher (1992, fig. 2.6). From north to south, the rest of the sections are described below.

Southwestern North Dakota

Isolated remnants of the White River "blanket" (Trimble, 1980) occur as scattered buttes and badlands in several places in southwestern North Dakota, eastern Montana, and northwest South Dakota (Denson and Gill, 1965; Murphy et al., 1993). The most important of these are the "Little Badlands" and related exposures in Stark County, North Dakota. First described by Cope (1883), Douglass (1909), and Leonard (1922), these outcrops and their fossils have been collected and studied by a number of field parties and institutions over the years. In addition, exploration for uranium led to much detailed geological research (summarized by Murphy et al., 1993).

The first detailed report on the stratigraphy of the mammal-bearing beds was by Skinner (1951), based on Frick Laboratory collecting in the area starting in 1944. Skinner presented a detailed lithostratigraphy for the classic collecting areas in the Little Badlands, and for the newly discovered Frick localities at Fitterer Ranch. Stone (1972) presented a more detailed lithostratigraphy of the White River outcrops, coining several new names for the members he recognized. However, those names have proven to be of limited utility (Hoganson, 1986; Murphy et al., 1993). Since the 1980s, the White River outcrops of North Dakota have been extensively studied and published by personnel of the North Dakota Geological Survey (Hoganson, 1986; Hoganson and Lammers, 1985, 1992). The White River Group in the region was monographed in detail by Murphy et al. (1993).

In 1980 I had only Skinner (1951) and Skinner's unpublished field notes on which to base a magnetostratigraphy of the important Frick collections from the area. A magnetic section was taken in the main area of the Little Badlands ("7 miles south of South Heart" in the Frick Laboratory terminology; "Privratsky Ranch" of Murphy et al., 1993, p. 35). The section (Fig. 5) began in SE NW NW Sec. 23, and then concluded in SW SW NE Sec. 23, T138N R98W, Belfield SE 7.5' quadrangle, Stark County, North Dakota. It spans about 120 feet of Orellan strata (units 3-5E of Skinner, 1951, p. 57) and produces an early Orellan fauna. Units 4A-4B of Skinner (1951) are of normal polarity, and probably correlate with the early Orellan normal magnetozone found throughout the White River Group. The rest of the section is of reversed polarity.

Important collections were also made by the Frick Laboratory at Fitterer Ranch. The measured section began in NW SW Sec. 7, T137N R98W, New England NW 7.5' quadrangle, Stark County, North Dakota (Fig. 5); the upper part of the section above Fitterer Ranch channel was taken in NW SW NW Sec. 17. The sections and stratigraphic terminology shown in Figure 5 follow Skinner (1951); the section is also described by Murphy et al. (1993, p. 37). In these sections, unit 4A of Skinner (1951) is of normal polarity, as it is in the Little Badlands. However, unit 4B is of reversed polarity, unlike the Little Badlands section. The rest of the lower half of the Fitterer Ranch section is of reversed polarity. The upper half of the section began at the top of the highly fossiliferous Fitterer Ranch channel sandstone, and units 5D through lower unit 6A of Skinner (1951) are of reversed polarity. The rest of units 6A through 6E of Skinner (1951) are of normal polarity. In the Frick Laboratory notes, these strata are thought to be Whitneyan, which if true would make this normal magnetozone correlative with the upper Whitneyan normal magnetozone (Prothero and Swisher, 1992). Murphy et al. (1993, p. 106) questioned the age assignment of these strata, since few diagnostic Whitneyan mammals have been described from them so far. However, the majority of the Frick collections from these beds have not yet been studied. They may eventually substantiate the suggestions of Morris Skinner and the others in the Frick collecting parties.

Pine Ridge area, Sioux County, Nebraska

Outside the Big Badlands and the Lusk-Douglas sections along the Pine Ridge in Wyoming, the most fossiliferous collecting areas occur along the Pine Ridge in Nebraska. The thickest and most complete of these sections is the Toadstool Park-Roundtop section, described by Schultz and Stout (1955, fig. 3, sections 8-9; also shown in Schultz and Stout, 1961), Harvey (1960), and Singler and Picard (1979; 1980, Section 1). It has been used as the basis for zonation of the University of Nebraska State Museum fossil collections (e.g., Schultz and Falkenbach, 1968; Korth, 1989). The revised magnetostratigraphy of the Toadstool Park-Roundtop section is shown by Prothero and Swisher (1992, fig. 2.5).

Within the Toadstool Park area (Fig. 6), however, a thick fluvial channel-fill sequence cuts down from a level near the top of Orella B (Schultz and Stout, 1955, fig. 3, Section 4; also shown in Schultz and Stout, 1961). In the main Toadstool Park section, this channeled disconformity at the Orella B/C boundary also occurs at a transition from normal to reversed polarity. In 1980 a magnetostratigraphic section was taken through the main part of the channel sequence (S 1/2 Sec. 5, T33N, R53W, Roundtop 7.5' quadrangle, Sioux County, Nebraska). From the base of the channel to about 100 feet upsection (near the top of Orella C), the channel fill is of normal polarity (Fig. 6A). In the channel sequence, the normal-reversed transition occurs just above the upper nodules in Orella C, slightly higher than it appears in the main Toadstool-Roundtop section. The remaining parts of Orella C and D are reversed in polarity.

Further west along the Pine Ridge are numerous important collecting localities of both the University of Nebraska State Museum and the Frick Laboratory. Most of these are discussed in the unpublished dissertation of Harvey (1960) and in the field notebooks of Morris Skinner in the Archives of the Department of Vertebrate Paleontology of the American Museum of Natural History. For example, the Albert Meng ranch (SE Sec. 2 T33N R54W, Sioux County, Nebraska) is described in the Skinner notebooks (1944, Vol. 5, pp. 20-23) and is also known as University of Nebraska locality Sx-14. In this area, Skinner measured 60 feet of Chadron below the PWL ("Purplish-White Layer" of Schultz and Stout, 1955, 1961; known as the "Persistent White Layer" in the Frick Laboratory), and over 115 feet of the Orella Member (through Orella C). The stratigraphy is so similar to that of the Toadstool Park area (just 2 miles to the east) that no magnetostratigraphic section was taken.

The next important collecting area along the Pine

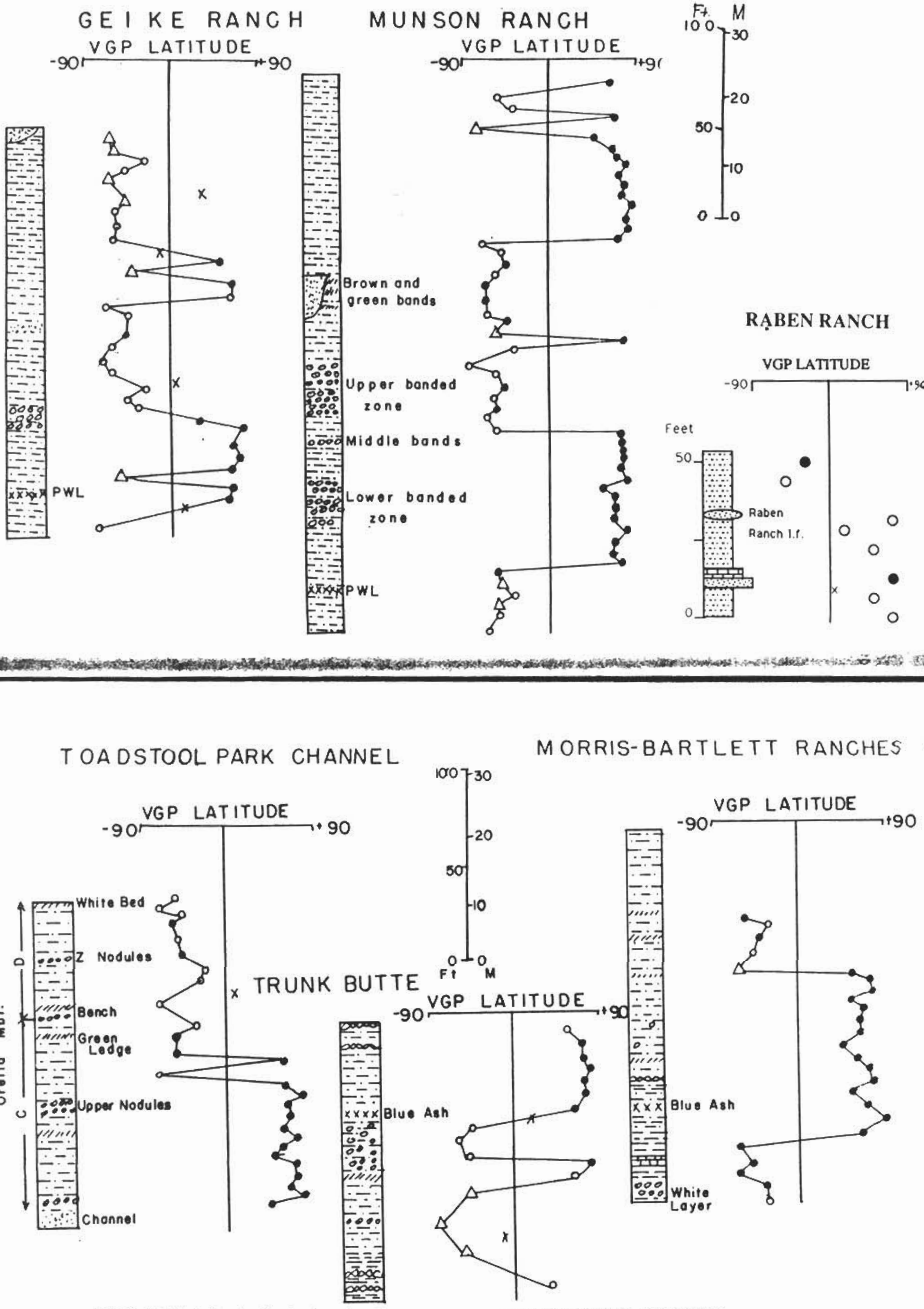

Figure 6. Magnetic stratigraphy of sections in northern Sioux and Dawes counties, northwestern Nebraska. Exact locations of sections described in text. Lithostratigraphy of most sections follows Skinner (unpublished field notes, on file in the Archives of the Department of Vertebrate Paleontology, American Museum of Natural History). Toadstool Park channel section after Schultz and Stout (1951). Raben Ranch section after Ostrander (1985). All other symbols as in Figure 5.

Ridge occurs in the Prairie Dog Creek drainage, just east of the road north from Harrison as it descends through Monroe Creek Canyon. Known in the Frick Collection as "Plunkett-Parsons Ranch" (after the ranch owners in the 1960s when Morris Skinner and Bob Emry measured these sections; Skinner section books, Vol. 6, pp. 88-89), it has also been called "Munson Ranch" (after the landowners in the 1970s), "10 miles north of Harrison," "Hall Ranch," and "Warbonnet Creek" in the Frick Collection; localities Sx 1-6 and Sx 37-38 of the University of Nebraska State Museum cover the same area. The 1980 edition of the Warbonnet Ranch 7.5' quadrangle calls it "Shalimar Ranch." The main part of the measured section occurs in NW NW NW Sec. 31 (lower part) and then continues up the southeast-trending ravine from center to SW SE Sec. 36, T33N R56W, Bodarc 7.5' quadrangle, Sioux County. A nearby section is shown by Singler and Picard (1980, fig. 4, section 4). This collecting area is about 15 miles west of Toadstool Park, and the detailed stratigraphy differs considerably from the units recognized by Schultz and Stout (1955, 1961) and Harvey (1960). Although the PWL is clearly present (Fig. 6B), it is not at all clear whether the Orella A-D units can be recognized (*contra* Harvey, 1960, and Singler and Picard, 1980, fig. 4, section 4). In the Frick Laboratory notes, the section was zoned by "lower," "middle," and "upper banded zones" which were extraordinarily rich in fossils (especially small mammals). Based on the magnetostratigraphic pattern (Fig. 6), the early Orellan normal magnetozone occurs only 15 feet above the PWL (so Orella "A" is extremely short), and the top of the early Orellan normal zone occurs in the "middle bands" (corresponding to the "Upper Nodules" at Toadstool Park, which mark the division between Orella B and C). Another long normal zone occurs between 190 and 240 feet in the section, and appears to correspond to the middle Whitneyan normal zone, which brackets the Upper Whitney Ash (upper Whitney B and lower Whitney C) at Toadstool Park. However, neither Whitneyan mammals nor the Lower or Upper Whitney Ashes have been recognized at Munson Ranch.

On the west side of the road north out of Harrison is another, smaller collecting area known to the Frick Laboratory as Geike Ranch. The main section, as measured by Morris Skinner in October, 1955 (Skinner section books, Vol. 5, pp. 24-25), begins in NE SW SW Sec. 17 and moves up the ravine to the top of the butte (BM 4384) in SE SE SW Sec. 17, T33N R56W, Warbonnet Ranch 7.5' quadrangle, Sioux County. In the University of Nebraska catalogues, it corresponds to locality Sx-36. The section differs so much from the Munson Ranch section (just a mile to the east) that Skinner used a completely different stratigraphic terminology (Fig. 6). Based on the magnetic polarity pattern, the early Orellan normal magnetozone is much shorter (from 15-50 feet on the measured section), and a short normal magnetozone, between 110 and 130 feet in the section, may correspond the late Whitneyan normal magnetozone (unfortunately, no Whitneyan fossils have yet been reported from Geike Ranch). The bulk of the collections, however, is from the lower (Orellan) part of the section.

North of the Pine Ridge proper in the low flatlands of Chadron Formation is the Raben Ranch locality, described by Ostrander (1985). It contains an important middle Chadronian mammalian fauna, the most diverse Chadronian fauna reported from Sioux County. The exposures occur in a small eroded ravine running from NE SE SW Sec. 30 to SW NW NE Sec. 31, T34N R53W, Orella 7.5' quadrangle, Sioux County, Nebraska. Although Ostrander (1985, pp. 226-227) measured 65.6 feet of section, in 1986 we could measure and sample only the top 50 feet in one continuous exposure (Fig. 6). All but the top two sites (the upper 15 feet) of the section is of normal polarity.

Chadron area, Dawes County, Nebraska

East of the Toadstool Park area are additional exposures that have proven to be important for White River stratigraphy and faunas. Clustered around the town of Chadron, in Dawes County, Nebraska, these areas have been collected and studied by the Frick Laboratory, the University of Nebraska State Museum, and many others, but the only published stratigraphic descriptions were by Vondra (1960) and Gustafson (1986). The latter paper summarizes the stratigraphy and faunas as currently known.

One of the most important sections was measured and sampled in 1980 on a prominent landmark known as Trunk Butte (northeast face, in NW SW NW Sec. 31, T33N R49W, Trunk Butte 7.5' quadrangle, Dawes County, Nebraska). First studied by Morris Skinner in 1951 (Skinner section books, Vol. 4, pp. 14-15), it was also measured and described by Gustafson (1986, section 1). The Trunk Butte section includes 45 feet of typical bentonitic Chadron clays at the base, overlain by 50 feet of white ashy Chadronian (based on brontothere tooth fragments) deposits below the PWL (Fig. 6). Skinner (field notes, dated August 2, 1953) planned to name these volcaniclastic-rich strata the "Trunk Butte Member" of the Chadron Formation. They closely resembled the white, ashy Chadronian deposits he had studied in the Lusk and Douglas areas of Wyoming, as well as other exposures around Chadron, Nebraska, and the Chadronian exposures at Slim Buttes, Harding County, South Dakota (Lillegraven, 1970). Over 40 years later, the same concept is now being resurrected, but Terry et al. (1995) call this volcaniclastic-rich Chadronian unit the "Big Cottonwood Creek Member" of the Chadron Formation.

Above this Chadronian sequence at Trunk Butte is the PWL (called the "white clay with brown spots" by Skinner, but referred to the PWL or "UPW" by Gustafson, 1986), overlain by 60 feet of typical Orella Member (including the "Blue Ash" marker bed of Skinner). The upper 50 feet of section (starting just below the Blue Ash) produces an early Orellan fauna (Gustafson, 1986) and is of normal polarity, so it probably correlates with the early Orellan normal magnetozone found throughout the White River Group. The lower 85 feet of section is of reversed polarity, except for two sites near the PWL (Fig. 6).

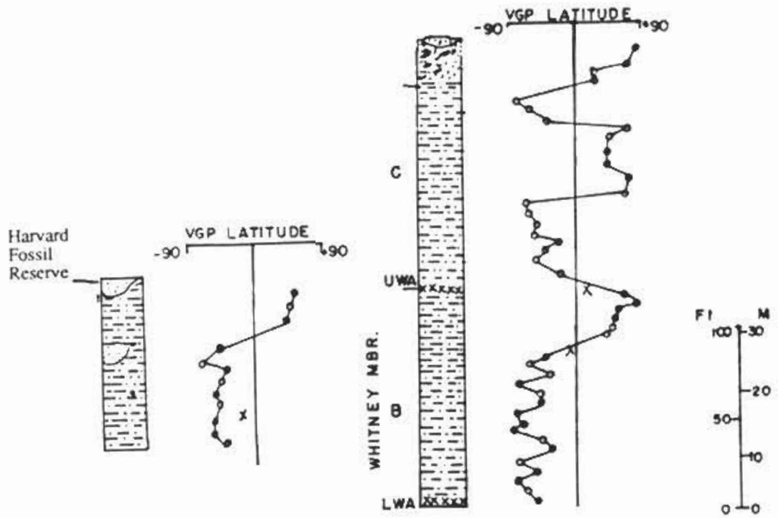

Figure 7. Magnetic stratigraphy of the Torrington (left) and Castle Rock (right) sections along the North Platte River Valley, Scottsbluff County, Nebraska, and Goshen County, Wyoming. Exact location of sections described in text. Castle Rock section after Schultz and Stout (1955); Torrington section after Schlaikjer (1935). All symbols as in Fig. 5.

Another important collecting area for the Frick Laboratory is about 2.5 miles north of Chadron, in low exposures known as the Morris and Bartlett ranches (NW Sec. 5 and W1/2 NE Sec. 6, T33N R48W, Chadron West 7.5' quadrangle, Dawes County, Nebraska). The 1980 sampling and sections were based on Skinner's notes (Vol. 4, pp. 10-12; Vol. 5, pp. 104-105); this section also corresponds to Gustafson's (1986, p. 11) section 4. The very base of the exposures appears to include the PWL; above this layer are about 190 feet of Orella Member with an early Orellan fauna (Fig. 6). The section above the Blue Ash was sampled at Bartlett Ranch (NW Sec. 5) and the section below this marker was sampled at Morris Ranch (W1/2 NE Sec. 6). As in the Trunk Butte section, the early Orellan normal magnetozone begins just below the Blue Ash and extends upward for about 90 feet (as indicated by Gustafson, 1986, fig. 3, column 5). The sections below and above this zone were of reversed polarity, although the upper 40 feet of section could not be sampled due to poor exposures.

North Platte River Valley, Wyoming and Nebraska

In addition to the Pine Ridge escarpment, important White River outcrops occur along the North Platte River Valley in the Wildcat Ridge area, Scottsbluff County, Nebraska, and on into Goshen County, Wyoming (Schlaikjer, 1935; Schultz and Stout, 1955, fig. 10; Schultz and Stout, 1961; Swinehart et al., 1985). The thickest and most complete section is found at Scottsbluff National Monument (published in Prothero and Swisher, 1992, fig. 2.6). About eight miles to the east, near the town of McGrew, Nebraska, is an isolated butte known as Castle Rock (SW NW Sec. 6, T20N R53W, McGrew 7.5' quadrangle, Scottsbluff County, Nebraska). This section was first described by Schultz and Stout (1955, fig. 10, section 6). In 1983, we sampled on the southwest face of the bluff from the Lower Whitney Ash (Fig. 7) through Whitney C and the brown siltstone beds (Swinehart et al., 1985). As in the section at Scottsbluff and elsewhere, a normal magnetozone occurs below and above the Upper Whitney Ash. Based on the $^{40}Ar/^{39}Ar$ date of 30.58 ± 0.18 Ma on the UWA at Scottsbluff (Swisher and Prothero, 1992), this magnetozone correlates with Chron C12n. Above this level are two other normal magnetozones which may correlate with Chrons C11n and C10n (see Tedford et al., this volume, Chapter 15).

Schlaikjer (1935) and Schultz and Stout (1955, fig. 10, section 15-18) described a short section at Harvard Fossil Reserve, just south of Torrington, Wyoming

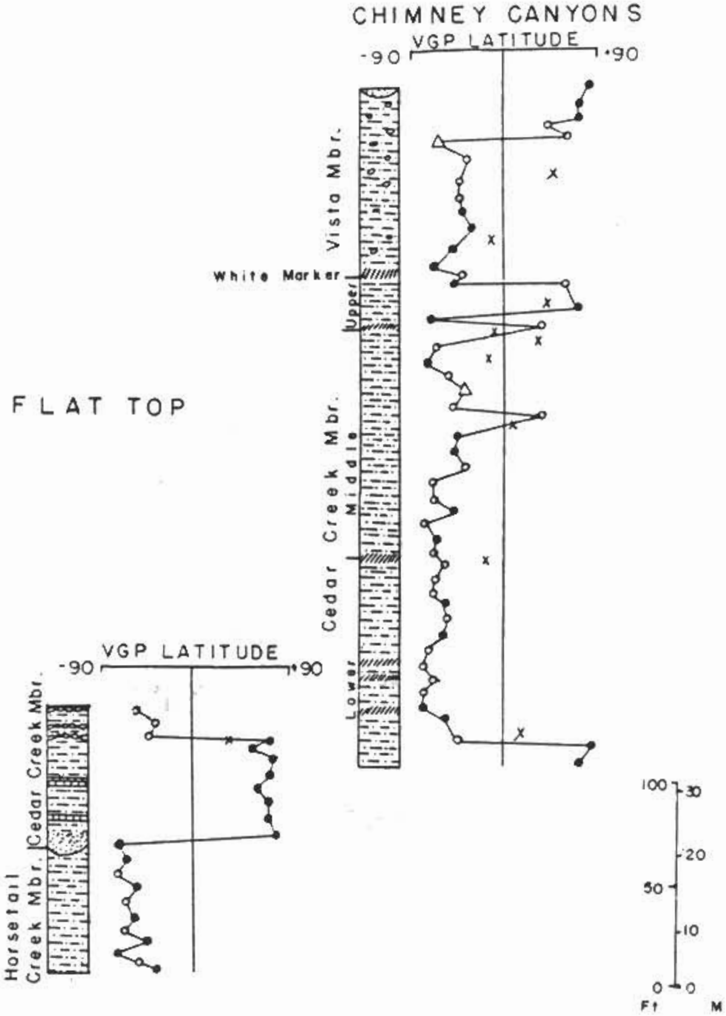

Figure 8. Magnetic stratigraphy of sections in northern Logan County, Colorado. Exact location of sections described in text. Lithostratigraphy after Galbreath (1953). All symbols as in Fig. 5.

(NW NW Sec. 32, T24N R61W, Torrington 7.5' quadrangle, Goshen County, Wyoming). Approximately 80 feet of Orella Member were sampled in 1983, starting at the lowest exposures in the ravine and ending with the limestone that caps the escarpment. The lower 60 feet of the section (Fig. 7) are of reversed polarity, and the upper 20 feet (containing the "Harvard Fossil Reserve Quarry" of Schlaikjer, 1935, or "Torrington Quarry" of Schultz and Stout, 1955) is of normal polarity. Based on the late early Orellan nature of the fossil assemblage (based on taxa such as *Mesohippus barbouri*), this normal magnetozone probably correlates with the early Orellan normal magnetozone found elsewhere in the Brule Formation.

Northeastern Colorado

Galbreath (1953) described a thick sequence of White River exposures along the southern rim of the High Plains in Logan and Weld counties, northeastern Colorado (Fig. 1). These areas had been important for fossil mammals since Marsh first collected there in 1870, and Cope (1874) first described Colorado fossil mammals; the first detailed study was published by Matthew (1901). Since that time, large collections have been made by the American Museum of Natural History, the Frick Laboratory, the Denver Museum of Natural History, the University of California, the University of Kansas Museum of Natural History, and Southern Illinois University. However, only the last two collections (made largely by Galbreath) have adequately detailed biostratigraphic data.

Although the stratigraphic units are similar to other White River deposits, they are different enough (with a much higher ash content, and few nodular beds or river channel sandstones) that they have their own stratigraphic terminology. Galbreath (1953) called the Chadronian beds at the base of the section the Horsetail Creek Member, the Orellan exposures the Cedar Creek Member, and the high Whitneyan cliffs the Vista Member of the White River Formation. The mammalian faunas allow some biostratigraphic correlation with other areas, but none of the marker beds found in Nebraska or Wyoming (such as the PWL or the Lower or Upper Whitney Ashes) was thought to occur in these sections. However, Evanoff (personal communication) has sampled the White Marker bed at the base of the Vista Member, and believes it can be geochemically correlated with the Lower Whitney Ash.

At Galbreath's suggestion, two main sections were sampled. The Chadronian Horsetail Creek Member was sampled along a low hill known as "Flat Top Butte" (Galbreath, 1953, plate 1C, figs. 6-7, section IX). The section (Fig. 8) was located in S1/2 Sec. 1, T10N R54W, North Sterling Reservoir 7.5' quadrangle, Logan County, Colorado. The lower 60 feet of the section include the maximum thickness of Horsetail Creek Member, and are entirely of reversed polarity. Disconformably incised into this sequence is the late early Orellan lower Cedar Creek Member; the lower 50 feet of this section at Flat Top are of normal polarity, and the top 15 feet are of reversed polarity. Based on the presence of late early Orellan fossils, this Cedar Creek normal magnetozone probably correlates with the early Orellan normal magnetozone found elsewhere in the White River group.

The second section (Fig. 8) spans about 250 feet of the Cedar Creek Member and about 90 feet of the Vista Member in Chimney Canyons (Galbreath, 1953, plate 1A-B, figures 6-7, section VII). The lower part of the section was taken in the ravine in NW NE Sec. 10, and continued up the canyon between "West Chimney" and "East Chimney" in SW SE Sec. 3, T11N R54W, Chimney Canyons 7.5' quadrangle, Logan County, Colorado. The upper part of the section went up the south face of "East Chimney" (SE SE SE Sec. 3) and then the top of the section was taken in the canyon behind "West Chimney" (SE NW Sec. 3). At the base of the lower Cedar Creek Member is the early Orellan normal magnetozone, but the rest of the lower and middle parts of the Cedar Creek Member is of reversed polarity. A short normal magnetozone occurs in the thin upper part of the Cedar Creek Member. The lower 60 feet of the Vista Member are again of reversed polarity, but the upper 30 feet are of normal polarity.

CALIBRATION AND CORRELATION

As discussed by Swisher and Prothero (1990) and Prothero and Swisher (1992), the White River magnetic stratigraphy can be correlated to the magnetic polarity time scale of Berggren et al. (1995) by numerous $^{40}Ar/^{39}Ar$ dates (Fig. 9). The oldest exposures sampled in this study produce the middle Chadronian Raben Ranch fauna. Based on Ostrander's correlation of these mammals with those found between Ashes B and F at Flagstaff Rim, Wyoming (Emry, 1992; Prothero and Swisher, 1992, fig. 2.4), the Raben Ranch section probably correlates with the normal and reversed magnetozones just above Ash B (but below Ash D), which would correlate with Chrons C16n.1 and C15r (Prothero and Swisher, 1992, fig. 2.3).

The widespread early Orellan normal magnetozone consistently lies above the PWL. This layer has long been correlated with the "5 tuff" of Evanoff et al. (1992) near Douglas, Wyoming, which has been $^{40}Ar/^{39}Ar$ dated at 33.91 ± 0.06 Ma (Prothero and Swisher, 1992). Obradovich et al. (1995) report a $^{40}Ar/^{39}Ar$ date of 33.59 ± 0.14 Ma for the same tuff. However, Larson and Evanoff (in press) have shown that the Douglas 5 tuff is geochemically distinct from the PWL in Lusk or to the east in Nebraska. Instead, the PWL seems to geochemically match Ash J at Flagstaff Rim, Wyoming, which has been $^{40}Ar/^{39}Ar$ dated at 34.7 ± 0.04 Ma (Swisher and Prothero, 1992) or 34.36 ± 0.11 Ma (Obradovich et al., 1995). According to Larson and Evanoff (in press), the PWL and Ash J also appear to correlate with the "4 tuff" at Douglas (Evanoff et al., 1992), rather than the 5 tuff. Ash J at Flagstaff Rimand the 4 and 5 tuffs at Douglas all occur in Chron C13r (Prothero and Swisher, 1992; Evanoff et al., 1992). Despite the changes in ash correlations, these dates would place the early Orellan normal magnetozone in Chron C13n (33.0-33.4 Ma in the time scale of Berggren et al., 1995).

The long reversed interval that spans most of the later Orellan and early Whitneyan thus correlates with Chron C12r (30.9-33.0 Ma). This is corroborated by the $^{40}Ar/^{39}Ar$ date of 31.8 ± 0.007 on the Lower Whitney Ash (Swisher and Prothero, 1990; Prothero and Swisher, 1992). The late Whitneyan normal magneto

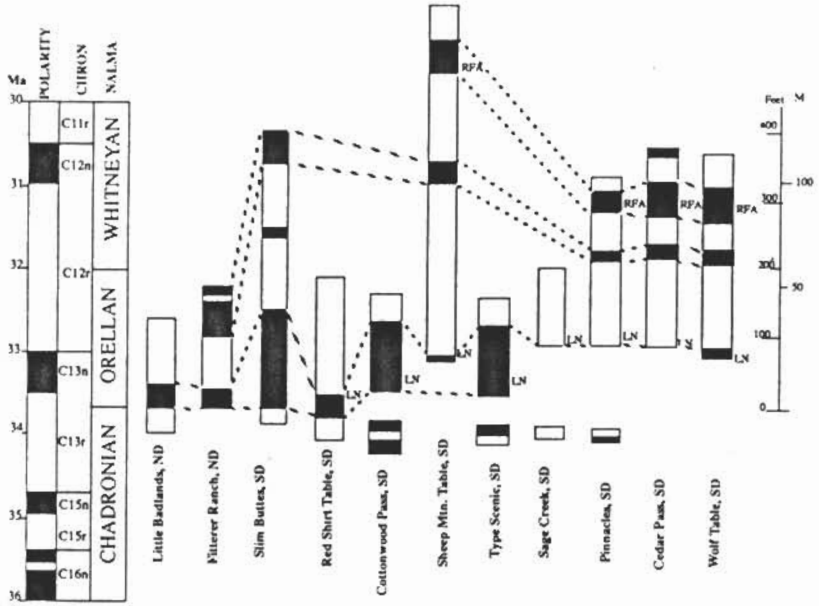

Figure 9. Magnetic correlation of sections within the White River Group, based on sections presented in this paper, Prothero and Whittlesey (in press), Swisher and Prothero (1992), and Prothero (1985b). Datum for sections is the Chadron-Brule contact or the PWL. Correlation to the time scale of Berggren et al. (1995) based on dates presented in Prothero and Swisher (1992).

zone correlates with Chron C12n (30.5-30.9 Ma), which is calibrated by the Upper Whitney Ash within this zone, $^{40}Ar/^{39}Ar$ dated at 30.58 ± 0.18 Ma (Swisher and Prothero, 1990; Prothero and Swisher, 1992). The Whitneyan/Arikareean boundary is a bit more difficult to define, but based on the criteria discussed by Tedford et al. (this volume, Chapter 15), it occurs in Chron C11n, about 30 Ma. The contact between the Whitney Member and "brown siltstone" beds of the Brule Formation appears to lie within Chron C11r (about 30.0 Ma), and the oldest rocks of the Arikaree Group occur in Chron C9r (about 28.3 Ma).

Based on the information presented above and in Prothero and Swisher (1992), the Chadronian appears to span the interval from about 37 Ma to about 33.8 Ma. The Orellan runs from 33.8-32 Ma, and the Whitneyan from 32 Ma to about 30 Ma. This is slightly different from the calibrations reported by Prothero and Swisher (1992), mostly due to the changes in the Berggren et al. (1995) time scale and the new dates reported by Obradovich et al. (1995).

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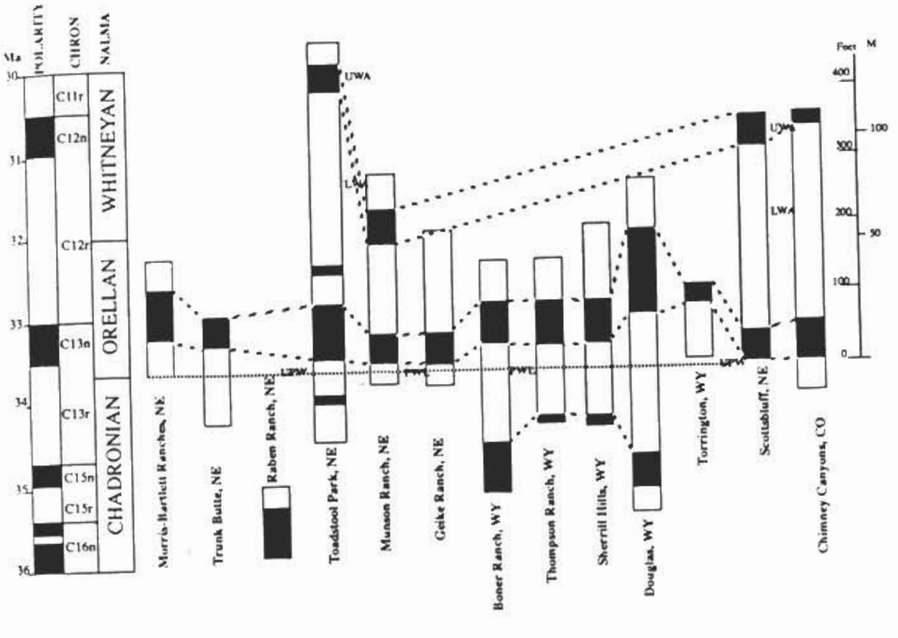

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