

# MAGNETIC STRATIGRAPHY OF THE HEMINGFORDIAN-BARSTOVIAN (LOWER TO MIDDLE MIOCENE) MARTIN CANYON AND PAWNEE CREEK FORMATIONS, NORTHEASTERN COLORADO, AND THE AGE OF THE "PROBOSCIDEAN DATUM" IN THE HIGH PLAINS

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**Abstract**—The Pawnee Creek Formation consists of about 50 m of siltstone and sandstone incised into the White River Group at Pawnee Buttes and along Chalk Bluffs in northeastern Colorado. The Pawnee Creek area has produced many important fossil mammal assemblages, including some of the first well-documented Miocene assemblages of the High Plains (Matthew, 1901), and large collections for the Frick Laboratory at Horse and Mastodon Quarry, Dark Cap Quarry, and Clay Quarry. The first locality also marks the oldest proboscidean fossils known from the Great Plains, and is an important calibration point for the "Proboscidean Datum" of late Barstovian age of Tedford et al. (1987). Paleomagnetic samples were taken spanning the Pawnee Creek Formation at Davis Ranch (Dark Cap and Horse and Mastodon Quarries), and the type section near Eubanks. Most samples showed a single component of remanence held in magnetite with minor overprinting, although some samples were unstable and could not be interpreted. The normal and reversed means of stable samples passed a reversal test, so the directions are primary. Most of the section is reversed in polarity, except for a short normal magnetozone at the top of the lower Pawnee Creek Formation. Based on  $^{40}\text{Ar}/^{39}\text{Ar}$  dates of  $14.5 \pm 0.09$  Ma below the base of the section, and  $14.3 \pm 0.02$  Ma on the lower part of the section, we correlate the Pawnee Creek Formation with Chrons C5ACr-C5ADr (14.0–14.7 Ma). This places the Proboscidean Datum in the High Plains in Chron C5ACr (between 14.0 and 14.2 Ma), much younger than it appears in many other places in North America. The oldest occurrences of proboscideans are now late Hemingfordian in northwest Nevada, and early Barstovian in Oregon, California, Nevada, Montana, Texas, Florida, and Mexico.

Unconformably beneath the Pawnee Creek Formation lies the Martin Canyon Formation, which yields an important early Hemingfordian (early Miocene) fauna. A magnetostratigraphic section was collected through Frick Clay Quarry to the top of the formation. These samples also had a remanence held in magnetite that passed a reversal test, so the remanence is primary. The base of the formation (including Clay Quarry) was reversed in polarity, but the upper 30 m of the formation was normal. Based on the early Hemingfordian fauna, we correlate the Martin Canyon Formation with Chrons C5En-C5Er (18.3–19.1 Ma).

## INTRODUCTION

The area around Pawnee Buttes and Chalk Bluffs, in Weld and Logan counties, northeastern Colorado (Figs. 1–2), has long been important for its vertebrate fossils (see review by Galbreath, 1953, and Tedford, 1999, 2004). The area was first explored by Marsh and his Yale crews in 1870 and 1872, followed by Cope in 1873. Most of these collections focused on the White River beds near the base of the bluffs, but both Marsh and Cope made important collections from the Miocene beds above the White River deposits (then called the "Loup Fork beds"). In 1898, 1901, and 1902, W.D. Matthew led parties from the American Museum of Natural History that made important collections over the entire area, some of which were documented in Matthew (1901). Matthew clarified the confused stratigraphy of Marsh and Cope, and recognized several faunal units in the "Loup Fork beds." These were some of the first significant middle Miocene collections from the High Plains (preceding many of the important discoveries in Nebraska, Kansas, and elsewhere), and thus many of the holotypes of Great Plains Miocene mammals come from Pawnee Creek. Galbreath (1953) noted that some 61% of the 59 species recorded from the Pawnee Creek are types of species or higher taxa. Other large collections were made for the University of Kansas, the University of California, the Denver Museum, and the Frick Laboratory during the early part of the twentieth century, although only some of these collections have been adequately described (mainly by Galbreath, 1953). Tedford (1999, 2004) has provided an updated review of the stratigraphy of the Pawnee Creek area, but major parts of the Frick Collections from these beds have still not been for-

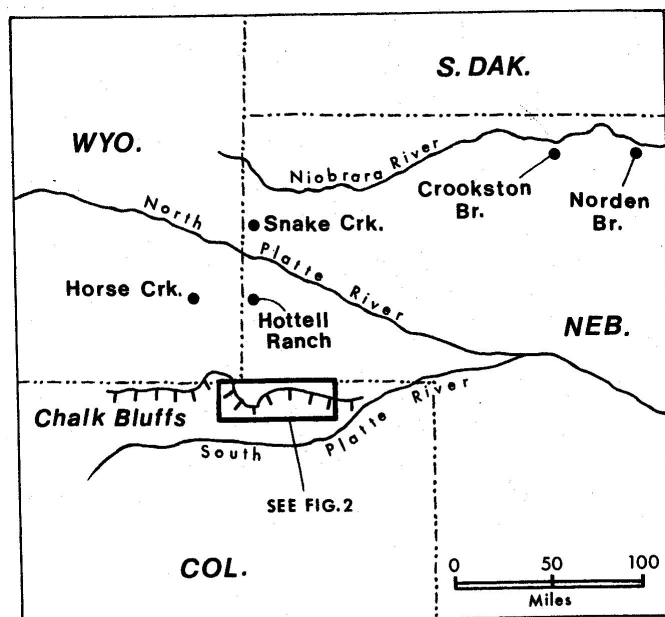


FIGURE 1. Location map of the Chalk Bluffs and Pawnee Buttes area, along with other important Miocene localities in adjacent states (after Tedford, 1999, fig. 15).

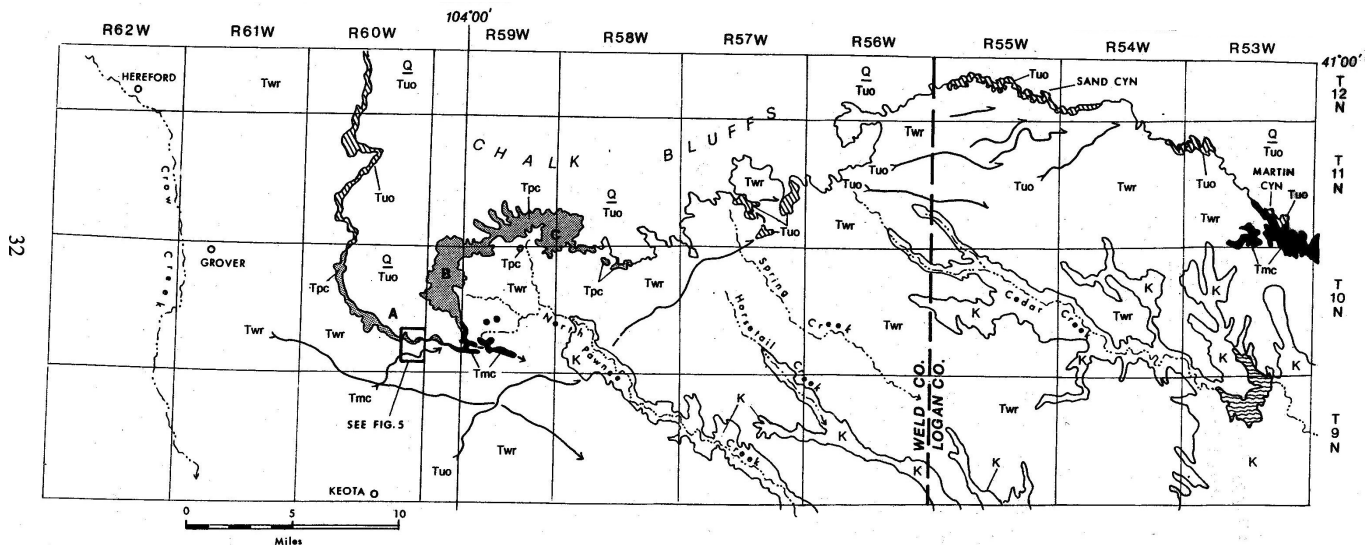


FIGURE 2. Simplified geologic map of the Pawnee Buttes and Chalk Bluffs area. A: Davis Ranch/Clay Quarry area; B, Frick's Dinner Pit/East Valley Pit area; C, Eubanks area. The location of the type Martin Canyon Formation in Logan County is also shown. Lithologic abbreviations: K, undivided Cretaceous marine sediments; Twr, White River Group; Tmc, Martin Canyon Formation (black); Tpc, Pawnee Creek Formation (obliquely ruled); Tuo, upper Ogallala Group (dots); Q/Tuo, upper Ogallala Group where concealed by younger alluvium eolian deposits, or soil. Sinuous lines terminating in arrowheads show axial channel trends and transport directions (after Tedford, 1999, fig. 16).

mally documented.

In addition to their historical importance, and the large number of holotypes from the area, the Pawnee Creek beds are important for another reason. The upper part of the Pawnee Creek Formation at Frick Horse and Mastodon Quarry yields the first appearance of immigrant proboscideans (*Gomphotherium* and *Zygodon*) in the Great Plains. Tedford et al. (1987) noted that proboscideans were absent from the rich early Barstovian deposits of the Great Plains (especially the Olcott Formation in Nebraska, and the lower Pawnee Creek Formation in Colorado), as well as important Barstovian faunas elsewhere (such as the early Barstovian in the type Barstow Formation in California, the Skull Ridge Member of the Tesuque Formation in New Mexico, and the Trinity River local fauna in the Texas Gulf Coastal Plain). On this basis, they used the first appearance of Proboscidea at Horse and Mastodon Quarry in the upper Pawnee Creek Formation as an important calibration point for their "Proboscidean Datum," which supposedly marked the beginning of the late Barstovian.

### STRATIGRAPHY

As noted above, the Miocene stratigraphy of the Pawnee Creek area was initially quite confused, since all the formations were lumped into the "Loup Fork beds" by early collectors, and the exact stratigraphic provenience of many important specimens is still impossible to establish. Matthew (1901) made the first attempt to separate the faunas, recognizing a "Pawnee Creek fauna" as distinct from the others collected in the area. But it was not until the detailed work of Galbreath (1953) that the formations and local faunas were adequately separated. Galbreath (1953) formally defined the Pawnee Creek Formation, and designated the area just east of the old Eubanks ranch house (NE sec. 1, T10N R59W) as the type section ("Eubanks section" in this report) (Figs. 2C, 3A). The Pawnee Creek Formation consists largely of well-bedded fine to medium sands with abundant pedogenic nodules (rhizonodules) and minor gravels. These deposits fill a series of at least six incised paleovalleys (Tedford, 1999, 2004), which reach a maximum thickness of 47 m (155 feet) in some paleovalleys. The Eubanks section produces the early Bartovian Eubanks l.f. of Galbreath (1953). The upper parts of the Pawnee Creek Formation produced the late Barstovian Vim-Peetz l.f., Kennesaw l.f., and Sand Canyon l.f. of Galbreath, and the Keota l.f. of Tedford (1999).

Disconformably beneath the Pawnee Creek Formation is a paleovalley fill sequence that had been called the "Martin Canyon beds" or "Horizon D" by Matthew (1901), although the confused stratigraphy used by his field crews did not allow Matthew (1901) to recognize the distinctiveness of the Martin Canyon fossils. Galbreath (1953, p. 20) recognized that these beds were distinct from the underlying White River deposits, but he did not formalize its distinction from the Pawnee Creek Formation. He did, however, show that the Martin Canyon beds yield an early Hemingfordian fauna (especially from University of Kansas "Quarry A") that was distinct from the classic Barstovian mammals of the Pawnee Creek Formation. Galbreath was reluctant to name a new formation for the Martin Canyon beds because it was difficult to distinguish lithologically from the Pawnee Creek Formation, and he did not think that it occurred widely outside of Martin Canyon (Fig. 2). However, the Frick Laboratory collected from a number of important localities to the west of Martin Canyon, and the faunal and lithologic distinctiveness of the formation is now well established. Tedford (1999, p. 37) formally raised this unit to formational rank as the "Martin Canyon Formation" and indicated that its type section would be Matthew's (1901) Martin Canyon section (Fig. 2), also shown as Galbreath's (1953, section XVI, p. 26) section in Martin Canyon (NE sec. 27, T11N R53W, Logan County, Colorado). The Martin Canyon Formation can be distinguished from the underlying White River beds by its coarser grain size (mainly fine sands) and gray color in weathered outcrop, and it is generally finer-grained and grayer than the tan-colored Pawnee Creek sandstones. It is also contains a distinctive lithic conglomerate at the base composed of rolled calcareous siltstone and sandstone nodules reworked from the surrounding beds, with minor crystalline granitic and andesitic pebbles from the Rocky Mountains. In the Pawnee Buttes area, the Martin Canyon paleovalley fill reaches a maximum thickness of 55 m (180 feet), but in most places it is much thinner (Tedford, 1999).

Besides the biostratigraphy, there was little chronostratigraphic control on the Pawnee Creek and Martin Canyon formations until recently. Tedford (1999) cites two  $^{40}\text{Ar}/^{39}\text{Ar}$  dates of  $14.5 \pm 0.09$  Ma and  $14.3 \pm 0.02$  Ma, analyzed by Carl Swisher, and also indicated that Steve Barghoorn had done some paleomagnetic sampling. Although the results were never published, Tedford (1999) suggested that the Davis Ranch section correlated with Chron C5Br1-C5ACr.

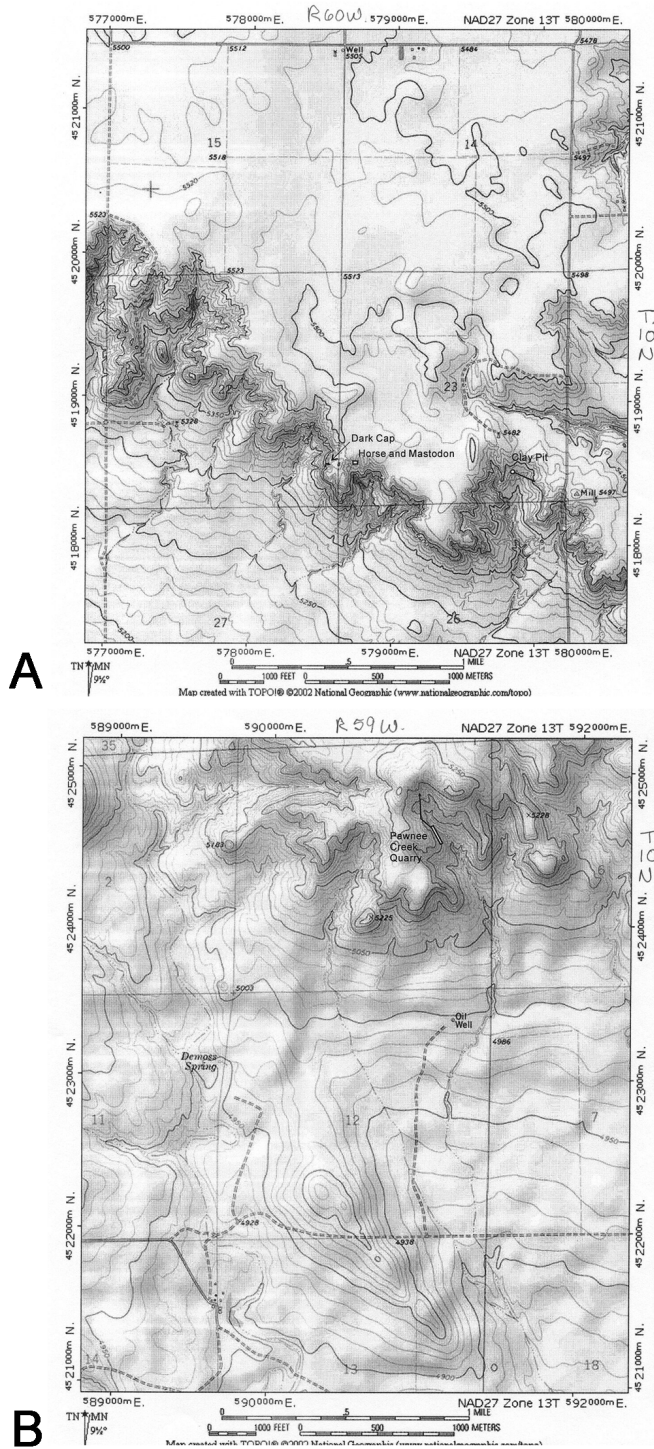


FIGURE 3. Detail of topographic maps showing locations of sections. **A**, Location of sections through Davis Ranch (Dark Cap and Horse and Mastodon quarries), and Clay Pit. **B**, Location of the Eubanks section.

## METHODS

Following the field notes of R. Tedford (pers. commun.) and the described sections in Tedford (1999, 2004), we sampled three principal sections in the spring of 2003. The first section was the Davis Ranch section of Tedford (1999, fig. 18), which spanned about 20 m of the upper and lower Pawnee Creek Formation (Figs. 2A, 3A). The Davis Ranch section ran up the west side of the bluffs through the Frick "Dark Cap Quarry" (NE 1/4 SE 1/4 SE 1/4 section 22, T10N R60W, Grover SE

7.5' quadrangle, Weld County, Colorado; latitude 40°48'57"N longitude 104°04'08"W); a separate site was taken just to the east of this section in the abandoned excavation of Frick Horse and Mastodon Quarry (NW 1/4 SW 1/4 SW 1/4 section 23, T10N R60W; latitude 40°48'57"N longitude 104°03'56"W).

A second section was taken through the thickest part of the Martin Canyon Formation at the Frick Clay Quarry (Fig. 3A), located in the SW 1/4 SE 1/4 SE 1/4 section 23, T10N R60W; latitude 40°48'54"N longitude 104°03'06"W). This section spanned about 10 m of the Martin Canyon Formation (with Clay Quarry near the base) and about 6 m of the overlying Pawnee Creek Formation.

The third and final traverse, the Eubanks section, was taken much further to the east (Figs. 2C, 3B) along the west side of the amphitheater that most closely approximates Galbreath's (1953) type section of the Pawnee Creek Formation. It started in the Frick Pawnee Quarry exposures (SW 1/4 NE 1/4 NE 1/4 section 1, T10N R59W, Pawnee Buttes 7.5' quadrangle, Weld County, Colorado) and ran up the western side of the ravine to the top of the bench and the highest exposures, spanning about 45 m (150 feet) of section.

Section was measured with a Brunton using the Hewett method. A total of 33 magnetic sites (3 samples per site) were collected every few meters of section wherever suitable exposures could be found. Samples were taken as oriented blocks of rock with simple hand tools, and then wrapped and carried back to the laboratory. There they were subsampled into cores using a drill press, or if the sample was too crumbly, casts into disks of Zircar aluminum ceramic. The samples were then analyzed on a 2G cryogenic magnetometer with an automatic sample changer at the California Institute of Technology. After measurement of NRM (natural remanent magnetization), they were demagnetized in alternating fields (AF) of 25, 50, and 100 Gauss to prevent the remanence of multi-domain grains from being baked in, and to examine the coercivity behavior of each specimen. AF demagnetization was followed by thermal demagnetization of every sample in 50°C steps from 200° to 630°C to get rid of high-coercivity chemical overprints due to iron hydroxides such as goethite, and to determine how much remanence was left after the Curie temperature of magnetite (580°C) was exceeded.

Results were plotted on orthogonal demagnetization ("Zijderveld") plots, and average directions of each sample were determined by the least-squares method of Kirschvink (1980). Mean directions for each sample were then analyzed using Fisher (1953) statistics, and classified according to the scheme of Opdyke et al. (1977).

## RESULTS

Although a majority of the samples retained a stable remanence that could be interpreted, a significant number (especially in the Davis Ranch section) showed no stable directions and could not be used. Fortunately, with three samples per site, a single unstable sample did not always hamper our interpretation, but a few sites had no usable samples.

Orthogonal demagnetization ("Zijderveld") plots of representative stable samples are shown in Figure 4. The rapid drop in intensity in most samples shows that the remanence is largely carried in a low-coercivity mineral such as magnetite; this is corroborated by the fact that all remanence was lost by the Curie point of magnetite (580°C). Most samples had a single component of remanence that decayed smoothly to the origin with little or no overprinting. Many reversed samples (e.g., Figs. 4C, E) had a slight overprint that was removed during the AF demagnetization, and stabilized in a reversed (south and down) direction by the low-temperature thermal steps. This component then decayed steadily to the origin, and was the component used in further analysis.

The site statistics are given in Table 1. The mean for normal samples for the Pawnee Creek Formation was  $D = 15.9$ ,  $I = 42.6$ ,  $k = 11.9$ ,  $\alpha_{95} = 12.5$ ,  $n = 14$ , and the mean for the reversed samples was  $D = 175.8$ ,  $I = -55.1$ ,  $k = 7.3$ ,  $\alpha_{95} = 12.3$ ,  $n = 22$ . The mean directions are antipodal within error estimates (Fig. 5), so the remanence is primary, and the overprinting has been removed. The mean for normal samples for

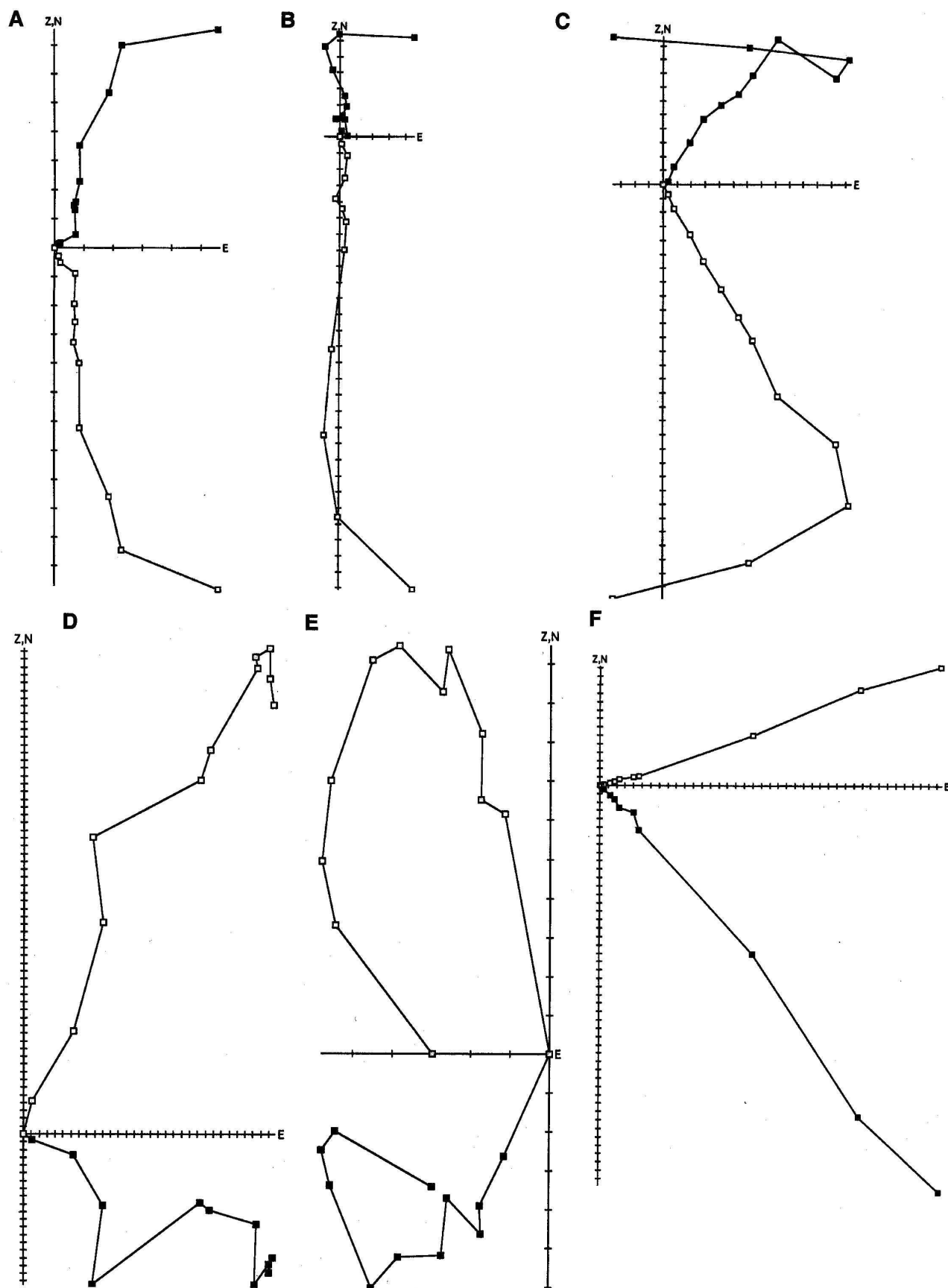


FIGURE 4. Orthogonal demagnetization ("Zijderveld") plots of representative samples. Solid squares indicate declination (horizontal component); open squares indicate inclination (vertical component). First step is NRM, followed by AF steps of 25, 50, and 100 Gauss, then thermal steps from 200° to 630°C in 50°C increments. Each division equals  $10^{-5}$  emu.

TABLE 1. Paleomagnetic data. N = number of samples; D = declination; I = inclination; K = precision parameter;  $\alpha_{95}$  = ellipse of 95% confidence around mean.

SITE	N	D	I	K	$\alpha_{95}$
<b>Davis Ranch (lower and upper Pawnee Creek Formation)</b>					
1	3	171.3	-54.3	5.5	58.5
3	3	115.5	-37.6	14.3	33.8
4	3	18.0	37.8	8.8	44.4
5	2	44.2	46.9	14.0	72.9
6	3	186.4	-64.6	29.5	23.1
7	3	18.4	50.2	74.0	14.4
8	3	189.8	-71.3	10.9	39.2
9	2	172.6	-52.7	14.2	72.3
10	3	180.1	-58.5	6.0	55.5
11	3	111.5	-62.8	12.2	36.9
<b>Clay Quarry section (Martin Canyon Formation/Pawnee Creek Formation)</b>					
14	3	183.6	-63.5	18.8	29.3
15	3	180.6	-42.6	2.3	114.3
16	3	31.2	62.2	2.8	94.5
17	3	18.8	41.4	10.5	40.1
18	3	10.1	56.6	283.9	7.3
19	2	354.2	63.5	33.3	44.7
20	3	359.8	55.7	72.8	14.5
21	2	359.4	59.4	14.1	72.4
22	3	155.8	-1.8	5.1	61.2
23	3	4.8	21.6	18.9	29.2
<b>Eubanks type section (lower Pawnee Creek Formation)</b>					
24	3	195.6	-30.7	8.6	45.0
25	3	188.7	-39.9	7.8	47.7
26	3	171.6	-45.5	33.1	21.8
27	3	184.9	-66.6	15.0	33.0
28	3	176.8	-60.5	15.4	32.6
29	2	233.4	-45.1	311.7	14.2
30	3	176.0	-37.1	11.8	37.7
31	3	221.6	-42.2	2.1	130.3
32	3	208.9	-51.4	17.5	30.4
33	3	188.7	-33.6	20.2	28.2

the Martin Canyon Formation was  $D = 11.4$ ,  $I = 55.7$ ,  $k = 11.1$ ,  $\alpha_{95} = 12.5$ ,  $n = 14$ , and the mean for the reversed samples was  $D = 182.0$ ,  $I = -54.7$ ,  $k = 4.7$ ,  $\alpha_{95} = 34.4$ ,  $n = 6$ . These means are also antipodal within error limits (and statistically indistinguishable from the Pawnee Creek means), so they also pass a reversal test and their directions are primary (Fig. 5).

The magnetic stratigraphy of the main Davis Ranch section is shown in Figure 6. Three sites (numbers 2, 12, and 13) yielded no stable results and could not be interpreted. Eight sites were statistically significant, i.e., separated from a random distribution at the 95% confidence level (Class I sites of Opdyke et al., 1977). Two sites had only two interpretable directions, so they were Class II sites of Opdyke et al. (1977), and significance could not be calculated. The basal site (site 3) just above Dark Cap Quarry was reversed in polarity, but the remaining 7 m of section (covering the rest of the lower member and the 14.3 Ma date of Swisher) was normal in polarity. The sites (8-11) in the lower part of the upper member, plus site 1 in Horse and Mastodon Quarry, were all reversed in polarity. The upper part of the upper member yielded sites (such as 12 and 13) with no stable directions.

The magnetic stratigraphy of the Eubanks type section of the Pawnee Creek Formation is shown in Figure 7. All 10 sites were reversed in polarity, covering 45 m of section. Of these, eight sites were Class I, one site was Class II, and one site had two directions which clearly indicated polarity, but a third vector which was divergent (Class III site of Opdyke et al., 1977).

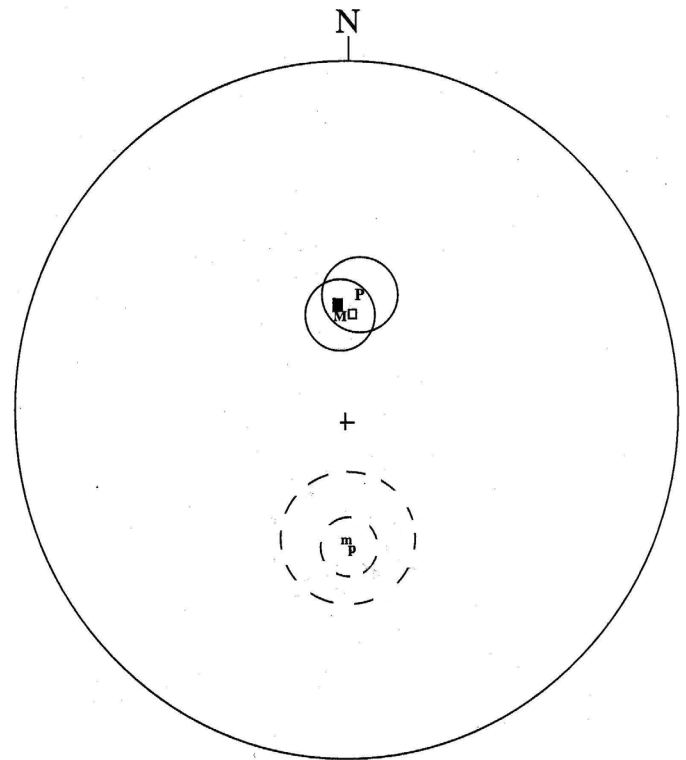


FIGURE 5. Stereonet of means of normal and reversed sites. Upper case bold letter ("M" for Martin Canyon; "P" for Pawnee Creek") and solid circle indicate mean for normal sites (lower hemisphere projection). Lower case bold letter ("m" and "p") and dashed line indicate mean of reversed samples (upper hemisphere projection). Solid square indicates projection of reversed Pawnee Creek mean to the lower hemisphere of the stereonet; open square shows projection of reversed Martin Canyon mean to the lower hemisphere. This shows the directions are antipodal, and that the primary remanence has been obtained and overprinting removed.

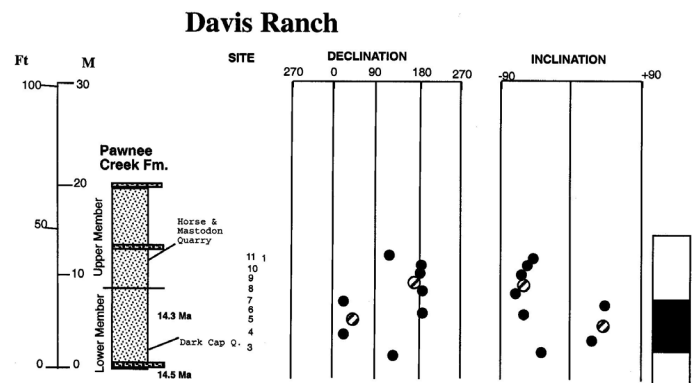


FIGURE 6. Lithostratigraphy and magnetic stratigraphy of the Pawnee Creek Formation at Davis Ranch. Radiometric date after Swisher (in Tedford et al., 2004). Declination and inclination of magnetic sites are shown. Solid circles are sites that are statistically removed from a random distribution at the 95% confidence level (Class I sites of Opdyke et al., 1977). Hatched circles are Class II sites of Opdyke et al. (1977), which had only two usable directions because one sample crumbled or was magnetically unstable.

The magnetic stratigraphy of the Clay Quarry section is shown in Figure 8. The basal two sites in the Martin Canyon Formation (just above and below Clay Quarry) were reversed in polarity, but the remaining upper 8 m of the Martin Canyon Formation was normal in polarity. Three sites spanning 5 m from the overlying Pawnee Creek Formation were also normal in polarity.

### Eubanks (type section)

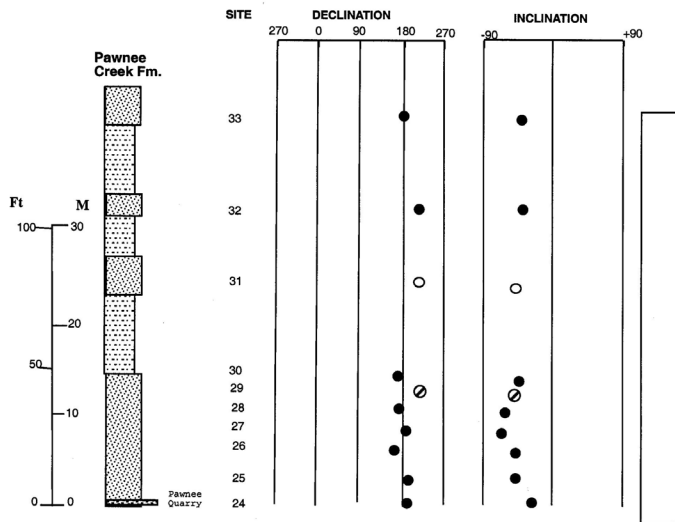


FIGURE 7. Lithostratigraphy and magnetic stratigraphy of the type Pawnee Creek Formation near Eubanks. Conventions as in Figure 6. Open circles are Class III sites of Opdyke et al. (1977), in which two samples showed a clear polarity, but one vector was divergent.

### Clay Quarry

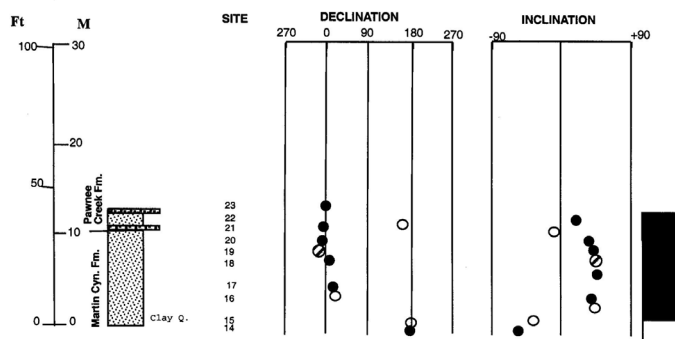


FIGURE 8. Lithostratigraphy and magnetic stratigraphy of the Martin Canyon and Pawnee Creek formations at Clay Quarry. Conventions as in Figures 6 and 7.

## DISCUSSION

Correlation of the Pawnee Creek sections is shown in Figure 9. The presence of the  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $14.3 \pm 0.02$  Ma in the middle of the normal magnetozone in the upper part of the lower member of the Pawnee Creek Formation establishes its correlation with Chron C5ADn (14.2–14.4 Ma). The overlying reversed magnetozone (including Horse and Mastodon Quarry) in the lower part of the upper member would correlate with Chron C5ACr (14.0–14.2 Ma), as originally suggested by Tedford (1999), and thus the first appearance of Proboscidea in the High Plains occurred between 14.0 and 14.2 Ma. The basal reversed magnetozone (containing Dark Cap Quarry) is probably Chron C5ADr (14.4–14.5 Ma), consistent with the  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $14.5 \pm 0.09$  Ma just beneath the sampled part of the section.

There are no  $^{40}\text{Ar}/^{39}\text{Ar}$  dates to constrain the long reversed magnetozone in the Eubanks section. Tedford (1999, fig. 18) suggested that this section fills the lowest paleovalley in the Pawnee Creek Formation, and thus is older than the majority of the Davis Ranch section. This is corroborated by the early Barstovian mammals from the Frick Pawnee Quarry (the “Eubanks Fauna” or “Eubanks local fauna” of Galbreath, 1953, and Tedford, 1999, 2004), which occurs at the very base of this section. Given these constraints, two possible correlations can be sug-

gested (Fig. 8). If this sequence is equivalent to the lower Davis Ranch paleovalley fills (as indicated by Tedford, 1999), then it probably also correlates with Chron C5ADr (14.4–14.5 Ma). This is consistent with the late early Barstovian nature of the fauna from Pawnee Quarry. However, if the great thickness of this reversed magnetozone it taken at face value, it is conceivable that it correlates with Chron C5Br (15.1–16 Ma), as suggested by Tedford (1999). This correlation, however, would require that the fauna be earliest Barstovian in aspect, which it is not (Tedford, 1999).

There are no radiometric dates to constrain the age of the Martin Canyon Formation, so correlation must be based on biostratigraphy. Galbreath (1953), Tedford et al. (1987, 2004), and Tedford (1999, 2004) have shown that the fauna is very similar to that of the Runningwater Formation of Nebraska. According to MacFadden and Hunt (1998), the Runningwater Fauna occurs in Chron C5En (18.3–18.7 Ma). Thus, we correlate the reversed-normal sequence in the Martin Canyon Formation with Chrons C5En–C5Er (18.3–19.1 Ma).

### IMPLICATIONS FOR THE “PROBOSCIDEAN DATUM”

Although this research now places tight age constraints on the “Proboscidean Datum” in the High Plains between 14.0–14.2 Ma, use of the “Proboscidean Datum” as a marker for the beginning of the late Barstovian (as advocated by Tedford et al., 1987) has been diminished by recent discoveries. Woodburne and Swisher (1995) and Tedford et al. (2004, p. 214–215) list a number of pre-late Barstovian occurrences in Proboscidea in regions outside the High Plains. The oldest known is the latest Hemingfordian Massacre Lake l.f. of northwestern Nevada (Morea, 1981) which lies just beneath a volcanic unit  $^{40}\text{Ar}/^{39}\text{Ar}$  dated at  $16.47 \pm 0.04$  Ma (Woodburne and Swisher, 1995; Prothero et al., this volume a). Thus, Proboscidea arrived in North America at least 2.2 million years before their fossils appear in the Great Plains. This is the oldest known occurrence, but there are now numerous early Barstovian records. The absence of proboscidean body fossils from the early Barstovian of the type Barstow Formation is still true, but there are proboscidean trackways in the early Barstovian at 16.2 Ma (Reynolds, 1999; Reynolds and Woodburne, 2001), so the creatures were present, even if they left no bones behind in that area until 14.8 Ma. Other early Barstovian occurrences in California include the North Coalinga l.f. in the Coast Ranges, and the Sharktooth Hill bone bed near Bakersfield (in Chron C5Br, about 15.7 Ma, according to Prothero et al., this volume b). There are numerous early Barstovian proboscidean occurrences in northwestern Nevada and eastern Oregon. These include Virgin Valley ( $^{40}\text{Ar}/^{39}\text{Ar}$  dated between  $15.18 \pm 0.76$  and  $15.84 \pm 0.13$  Ma, according to Tedford et al., 2004) and High Rock Lake in Nevada, and Sucker Creek (below a basalt date of 14.7 Ma) and Skull Springs ( $^{40}\text{Ar}/^{39}\text{Ar}$  dated at  $15.9 \pm 0.07$  Ma) in Oregon, as well as the Mascall fauna in the John Day region of Oregon (also in Chron C5Br, between dates of 15.8 and 16.2 Ma, *vide* Prothero et al., 2006). In addition, proboscideans occur in the early Barstovian of Montana (Deep River and Madison Valley faunas), and in the Gulf Coast of Texas (Burkeville l.f.) and Florida (Willacoochee Creek fauna). Finally, there are gomphotheres collected from strata below a tuff dated 15–16 Ma in Ixtapa, Chiapas, Mexico. Indeed, the only well-documented regions that do not have early Barstovian proboscideans are the Great Plains and the Española Basin of New Mexico.

Proboscidean fossils are so large and conspicuous that they are impossible to miss while collecting, so paleontologists have long treated the lack of proboscidean fossils as evidence of absence, not absence of evidence. This creates a puzzle as to why they appeared on the continent about 16.5 Ma but took 2.2 million years to reach the plains. Living proboscideans can travel so rapidly and widely that it seems odd that they have such a diachronous occurrence across North America. Tedford et al. (2004, p. 214) noted that most of the late Hemingfordian-early Barstovian occurrences based on diagnostic fossils are of the mammutid *Zygolophodon*, and this has led some authors to speculate that the High Plains and New Mexico might have been inhospitable for the forest-

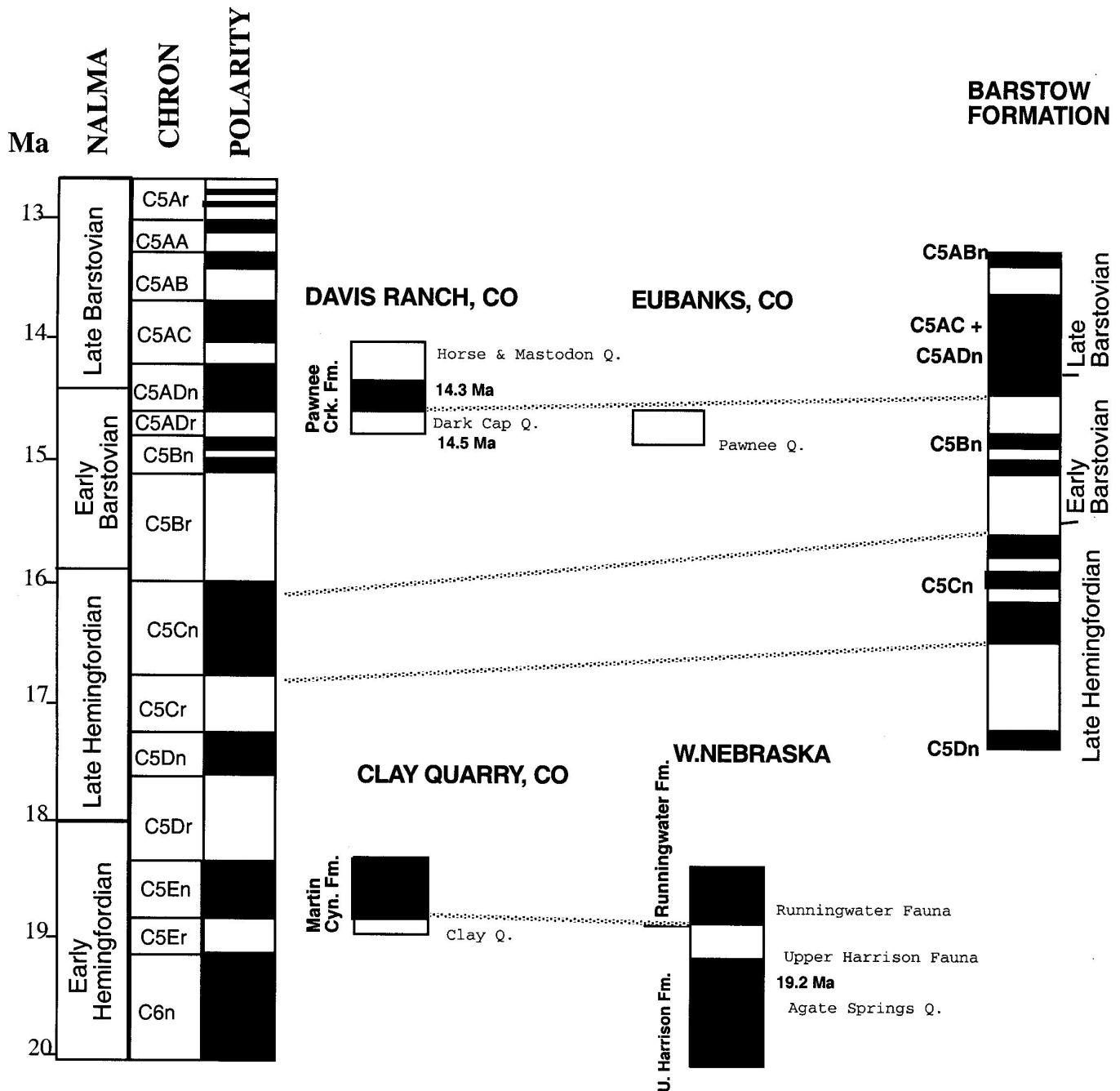


FIGURE 9. Correlation of the Pawnee Creek and Martin Canyon formations, based on the dates and age constraints discussed in the text. Magnetic stratigraphy of the Barstow Formation after MacFadden et al. (1990) and Woodburne (1996), and of the western Nebraska section after MacFadden and Hunt (1998). Time scale after Berggren et al. (1995), Woodburne and Swisher (1995), and Tedford et al. (2004).

adapted mammutids. According to this model, only the later arrival of gomphotheres allowed proboscideans to spread out onto the plains. Unfortunately for this hypothesis, Tedford et al. (2004) point out that *Gomphotherium* is present before 14.8 Ma in both Mexico and the North Coalinga l.f. in California, and possibly in some of the other localities listed above. As noted by Prothero et al. (this volume a), this hypothesis is insufficient to explain the peculiar distribution of first occurrences of proboscideans, and a detailed faunal analysis revealed no common causes that might explain the pattern (other than lack of adequate sampling).

Perhaps we have overestimated the preservation potential and collection probability of proboscidean fossils. After all, a century of collecting in the Barstow Formation has failed to turn up any probos-

cidean body fossils in the early Barstovian (despite the abundance of other large mammals, such as rhinos, horses, and camels), and only recently has the discovery of undoubted proboscidean trackways (Reynolds, 1999; Reynolds and Woodburne, 2001) proven that they were indeed present about 1.4 million years before they left body fossils. Paleontologists are traditionally cautious about overinterpreting the biostratigraphic occurrences of rare or small fossils, but perhaps we need to be more cautious about even the large, conspicuous and abundant fossils as well.

### CONCLUSIONS

The Pawnee Buttes-Chalk Bluffs region of northeast Colorado yields important mammalian fossils from two formations. The early Hemingfordian fauna correlates the Martin Canyon Formation

magnetozones with Chrons C5En-C5Er (18.3-19.1 Ma). The Pawnee Creek Formation correlates with Chrons C5ACr-C5ADr (14.0-14.7 Ma), based on  $^{40}\text{Ar}/^{39}\text{Ar}$  dates of  $14.5 \pm 0.09$  Ma below the base of the section, and  $14.3 \pm 0.02$  Ma on the lower part of the section, although the long reversed magnetozones in the lower part of the formation in the Eubanks section could correlate with Chron C5Br (15.2-16.1 Ma). The "Proboscidean Datum" in the High Plains is calibrated between 14.0-14.2 Ma, but this is at least 2.2 million years later than Proboscidea first appeared in North America. In fact, the "Proboscidean Datum" as a marker of the late Barstovian is now applicable only to the High Plains and New Mexico, because early Barstovian (and in a few places, late Hemingfordian) appearances of Proboscidea are known from almost every other region of North America.

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