MAGNETIC STRATIGRAPHY OF THE LATE HEMINGFORDIAN-?BARSTOVIAN (LOWER TO MIDDLE MIOCENE) SPLIT ROCK FORMATION, CENTRAL WYOMING

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Abstract—The Split Rock Formation consists of several hundred meters of gray volcaniclastic sandstones and tuffs with minor claystones that mantle the Granite Mountains in Fremont and Natrona Counties in central Wyoming. It yields a famous vertebrate fauna, including 13 species of reptiles, and 46 taxa of mammals. Among these are the best specimens of the dome-skulled chalicothere *Tylocephalonyx skinneri*, and the type specimens of several other mammals, including rodents, oreodonts, and carnivores. The fauna has long been considered middle Hemingfordian (younger than the Sheep Creek fauna but older than the Runningwater fauna in Nebraska), but the only age constraint is the ^{40}Ar/^{39}Ar date of 17.4 Ma at the base of the section. Magnetic samples were taken through the most complete section (UCMP localities V69190, 69191, and 69192), which produced the best-constrained localities. Samples were demagnetized in alternating fields (AF) of 25, 50, and 100 Gauss, then thermally demagnetized at 50°C steps from 200°C to 630°C. They produced a single component of remanence held mainly in magnetite that passed a reversal test. The lower part of the section is reversed in polarity, followed by a middle normal magnetozone, and then a few reversed sites at the top. Based on the ^{40}Ar/^{39}Ar date, we correlate the section with Chrons C5Br-C5Cr (15.8-17.4 Ma), which makes most of the section latest Hemingfordian. The uppermost faunas may be early Barstovian, consistent with re-examination of the fossil collections.

INTRODUCTION

The Granite Mountains Basin of central Wyoming (Fig. 1) is underlain by extensive outcrops of Precambrian granites mantled by Miocene and Pliocene fluvial and eolian sediments. These deposits filled the basin and buried the granites by the Pliocene (Love, 1970), and are only now beginning to be eroded away as the granites are exposed. Love (1961) first recognized two formations in this Cenozoic cover, the lower Miocene Split Rock Formation, and the "Pliocene" (now Barstovian-Clarendonian, or middle to late Miocene) Moonstone Formation (see Prothero et al., this volume). In 1970, Love further refined his geologic studies of the Granite Mountain region. Some authors (e.g., Denson, 1965; Reynolds, 1968; Denson and Harshman, 1969; Crist and Lowry, 1972; Denson and Pipiringos, 1974) within the USGS rejected Love's (1961) formational names, and continued to use the High Plains terminology of "Arikaree" and "Ogallala" formations in place of the Split Rock and Moonstone formations. However, Love (1970) effectively argued that the Split Rock and Moonstone formations are found in different depositional basins than those of the High Plains and are lithologically distinctive. More importantly, the Split Rock Formation continues to be recognized by other authors besides Love (e.g., Hopkins, 2002; Tedford et al., 2004), even outside of Wyoming (e.g., Colorado—Robinson, 1972).

Love (1961, 1973, p. C73) reported that the Split Rock Formation is highly variable in thickness, ranging from almost 1000 m thick in some basins down to less than 100 m in others, and covering some 1500 square miles of central Wyoming. Most of the formation consists of gray, poorly consolidated quartz sandstone with lesser amounts of volcaniclastic rocks, claystones, and even lacustrine algal limestones. It was deposited in a fluvial and lacustrine setting, with some sandstones that appear to be eolian as well.

Vertebrate fossils were first collected from the area along the Sweetwater River on August 28, 1870, by F.V. Hayden's expedition to the Wyoming Territory, and first described by Leidy (1870, 1872, 1873). Very little activity ensued in the following 67 years until the Frick Laboratory of the American Museum of Natural History began collecting there in 1937. Some of the Frick oreodonts from Split Rock were described (Schultz and Falkenbach, 1940), but the biggest impetus to research was the 1948 Society of Vertebrate Paleontology field conference in the area, which led to a number of important papers (reviewed by Munthe, 1979). The entire fauna was fully monographed by Munthe (1988), but little has been done to restudy the fauna or stratigraphy in the past 15 years until the recent efforts of one of us (SH).

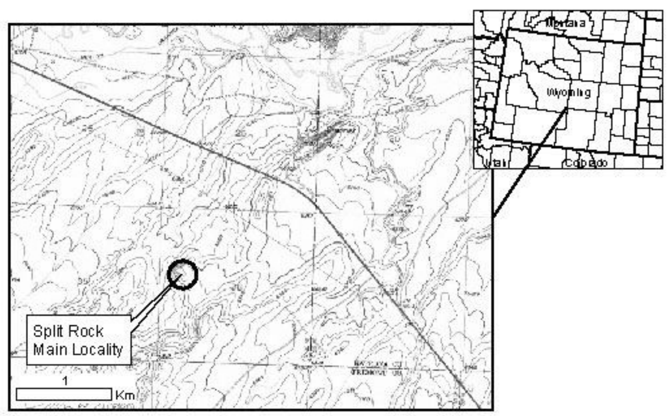

FIGURE 1. Location map of the Split Rock Formation and the main section at localities UCMP V69190-69192.

The age estimates of the Split Rock fauna have varied over the years. Some authors (e.g., Robinson, 1968; Holman, 1976) have suggested that the lower Split Rock fauna was early Hemingfordian ("Marsland" equivalent in Nebraska) and the upper Split Rock fauna was late Hemingfordian or Barstovian ("Sheep Creek" equivalent in Nebraska). Munthe (1979, 1988), however, argued that the fauna was homogeneous, and "middle" Hemingfordian in age (between the "Marsland" and "Sheep Creek" in age), and this has been followed ever since (e.g., Tedford et al., 2004). Unfortunately, the only continuous surface section with abundant fossils suitable for magnetic sampling is the uppermost part of the formation at Love's (1970, table 10) locality 11V (= UCMP localities V69192, V69191, V69190, respectively), which is late Hemingfordian or earliest Barstovian in age (see below). Love (1961, 1970, table 10), however, indicated that the lower part of the formation contains Arikareean fossils, although none of these isolated localities was suitable for magnetic sampling. Evernden et al. (1964) K-Ar dated a tuff near the base of the sequence at locality 11V at 17.0 Ma (no error estimates given), and Izett and Obradovich (2001) have redated this tuff by $^{40}Ar/^{39}Ar$ methods at 17.4 ± 0.08 Ma. This gives a constraint of the lower age of the fauna, making it no older than late Hemingfordian (Tedford et al., 2004), but does not resolve the issue of the temporal span of the formation, or its possible upper age limits. Paleomagnetic stratigraphy, coupled with new faunal analyses, should help clarify and resolve some of these questions.

METHODS

Only the bluffs of Love's (1970, table 10) locality 11V, which have the dated ash and UCMP locality V69192 at the base, and are capped by UCMP locality V69190 at the top, produced a long section suitable for magnetostratigraphic analysis. This section is located at SW SW NW sec. 36, T29N R90W, Split Rock 7.5-minute quadrangle, Fremont County, Wyoming; latitude = 42.4430°N ± 0.0008°; longitude = 107.5586°W ± 0.0011°, The section was sampled in Spring 2003, and was measured with a Brunton using the Hewett method, and also with a Jacob's staff. A total of 11 magnetic sites (3 samples per site) were collected, spanning about 70 m 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, cast 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

Orthogonal demagnetization ("Zijderveld") plots of representative samples are shown in Figure 2. 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). Indeed, Love (1970, p. C74) reported abundant magnetite in the sandstones he analyzed. Most normally magnetized samples (e.g., Figs. 2A, 2B) showed only a single component of remanence. Many reversed samples (e.g., Figs. 2C, 2D) had a normal 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 was D = 2.5, I = 48.6, k = 8.7, α_{95} = 18.5, n = 9, and the mean for the reversed samples was D = 182.2, I = -55.1, k = 13.5, α_{95} = 8.3, n = 24. These mean directions are antipodal within error estimates (Fig. 3), so the remanance is primary, and the overprinting has been removed.

The magnetic stratigraphy of the main Split Rock section is shown in Figure 4. All 11 sites were statistically significant, i.e., separated from a random distribution at the 95% confidence level (Class I sites of Opdyke et al., 1977). Sites 1-5 (basal 23 m of the section) were reversed in polarity (Fig. 4), but the middle part of the section (sites 5-8, 23-55 m on the section) was normal in polarity. The upper three sites (sites 9-11, 55-70 m on section) were of reversed polarity.

DISCUSSION

An updated faunal list for the Split Rock faunas is given in Table 2. Most of the identifications follow those of Munthe (1977, 1988), with the addition of three genera of heteromyids (*Cupidinimus*, *Mioheteromys*, and *Mookomys*). Analysis of the heteromyids from Split Rock is ongoing, but it is already apparent that this heteromyid fauna is more diverse than was indicated by Munthe's (1977, 1988) original faunal lists. Thousands of heteromyid specimens are present in the collections at the University of California, Berkeley and the University of Colorado, Boulder. Some of Munthe's referrals of indeterminate material are omitted in the cases where the material present cannot be definitely said not to belong to other taxa already named here.

Correlation of the Split Rock magnetic section is shown in Figure 5. The $^{40}Ar/^{39}Ar$ date of 17.4 ± 0.08 Ma (Izett and Obradovich, 2001) near the base of the section correlates the lower reversed magnetozone with Chron C5Cr (16.7-17.4 Ma), and this is consistent also with the late Hemingfordian fauna found at UCMP V69192 between magnetic sites 1 and 2. Similar late Hemingfordian faunas are reported from Chron C5Cr in the Barstow Formation (MacFadden et al., 1990) and from the Caliente Formation (Prothero et al., this volume) in southern California. The middle normal magnetozone is probably Chron C5Cn (16.1-16.7 Ma), based on the late Hemingfordian faunas recovered from UCMP V69191 ("Second Bench"), just above magnetic site 7.

Based on the previous correlations, and assuming no unconformities, the upper reversed magnetozone probably correlates with Chron C5Br (15.2-16.1 Ma). This is consistent with the vertebrate fauna from UCMP V69190, which has a mixture of latest Hemingfordian and earliest Barstovian taxa. Many of the oreodonts from Split Rock are similar to those present in the Box Butte Formation of Nebraska, and have been considered to indicate that the fauna is from the early part of the late Hemingfordian (Munthe and Lander, 1973). This is borne out by the appearance of the stenomyline camel *Blickomylus galushai* at the base of the section at the main outcrop (UCMP V69192); this genus last appeared in the Hemingfordian. However, the rodents are, in general, late Hemingfordian to early Barstovian in age. The abundant presence of *Harrymys irvini*, *Galbreathia novellus* and *Alphagaulus vetus* suggests a late Hemingfordian to early Barstovian age, and the presence of *Peridomys* (admittedly, an extremely rare member of the fauna), *Perognathus* (a much more abundant member of the Split Rock fauna), and *Mioheteromys* (one of the most abundant members of the fauna) indicate an early Barstovian age. Most of the taxa present at Split Rock are not diagnostic of one time or the other, and the fauna seems to be fairly uniform throughout the section at the main locality, although there are some changes in relative abundance through the section (Hopkins, 2002).

CONCLUSIONS

The main section through the upper Split Rock Formation (UCMP localities V69190, V69191, and V69192) yielded a magnetic correlation with Chrons C5Br-C5Cr (15.8-17.4 Ma) based on the faunas and the $^{40}Ar/^{39}Ar$ date of 17.4 ± 0.08 Ma (Izett and Obradovich, 2001) near the base of the section. This correlation is consistent with other magnetic sections that contain latest Hemingfordian mammals in California and elsewhere. The highest fauna (UCMP V69190) may be earliest Barstovian, based on its reversed polarity and correlation with the early part of Chron C5Br; the most abundant members of the fauna are unfortunately not diagnostic of one age or another, and many of the taxa that would clearly indicate either a Barstovian or a Hemingfordian age, such as *Copemys* or proboscideans, are simply not present in this fauna. The occurrence of *Blickomylus* definitely indicates a Hemingfordian age, but the only known specimen of this genus from Split Rock is from the

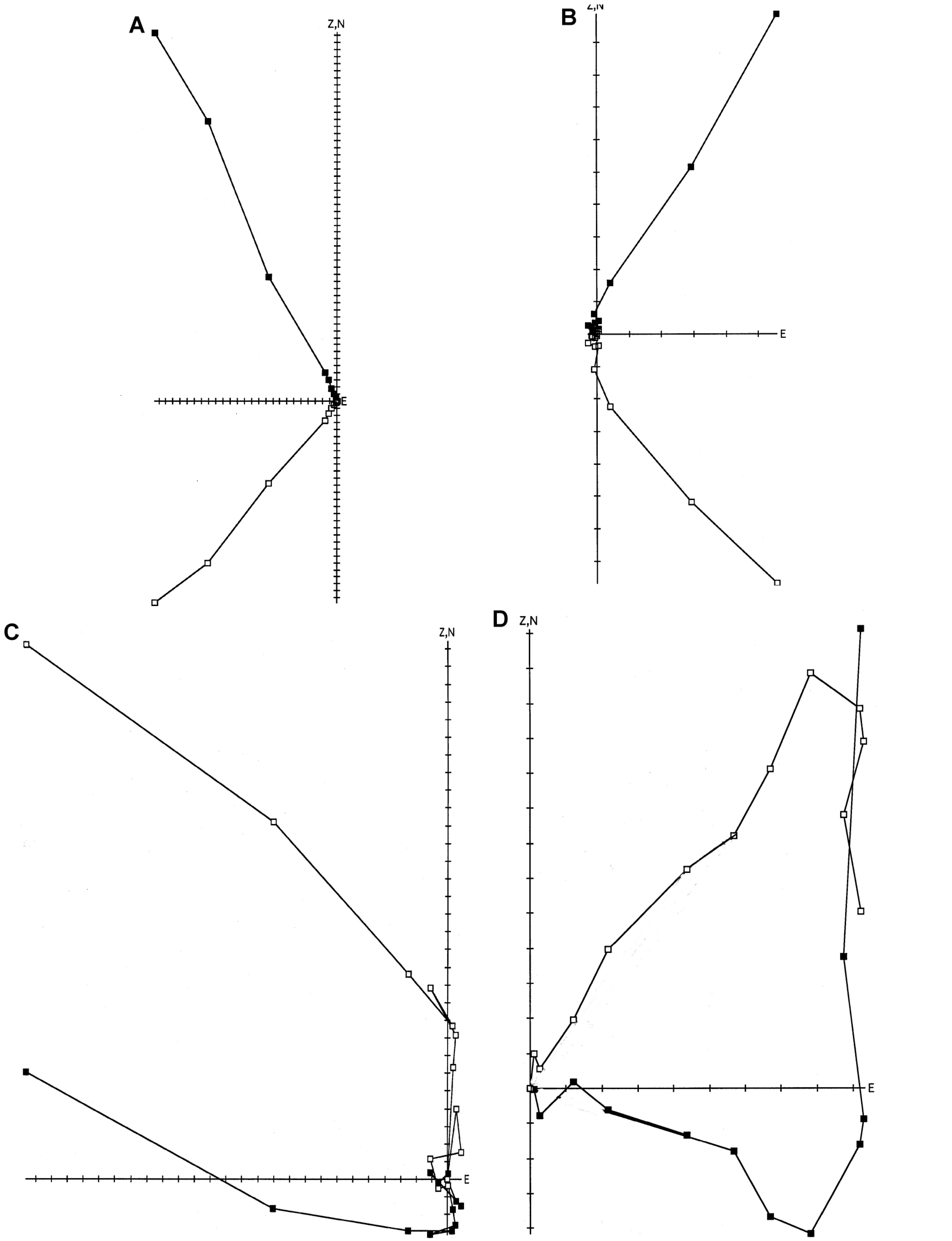

FIGURE 2. Orthogonal demagnetization ("Zijderveld") plots of representative samples. Solid squares indicate declination (horizontal component); open squares indicate inclination (vertical component). First step is NRM, followed by AF steps of 25, 50, and 100 Gauss, then thermal steps from 200° to 630°C in 50°C increments. Each division equals 10^{-5} emu.

TABLE 1. Paleomagnetic data from the Split Rock Formation. D = declination; I = inclination; K = precision parameter; α_{95} = ellipse of 95% confidence around mean.

SITE	D	I	K	α_{95}
1	192.6	-71.5	15.2	32.8
2	175.1	-52.1	20.8	27.7
3	180.5	-58.4	110.7	11.8
4	173.6	-45.2	10.4	40.4
5	187.1	-43.0	6.3	54.0
6	338.1	29.9	38.0	20.3
7	13.5	39.4	12.1	37.1
8	38.7	68.9	257.9	7.7
9	196.1	-44.2	6.8	51.6
10	170.2	-52.0	11.1	38.9
11	188.6	-69.3	289.8	7.3

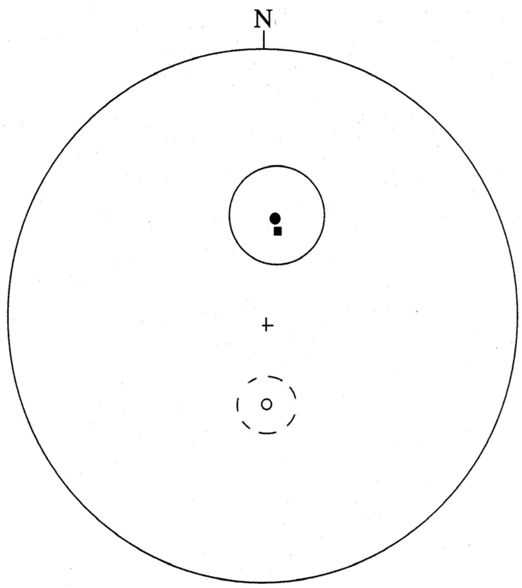

FIGURE 3. Stereonet of mean of normal and reversed sites. Solid dot and solid circle indicate mean for normal sites (lower hemisphere projection). Open dot and dashed line indicate mean of reversed samples (upper hemisphere projection). Solid square indicates projection of reversed mean to the lower hemisphere of the stereonet. This shows the directions are antipodal, and that the primary remanence has been obtained and overprinting removed.

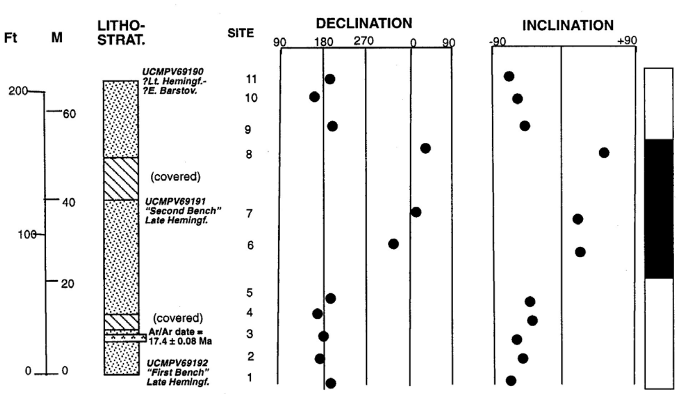

FIGURE 4. Lithostratigraphy and magnetic stratigraphy of the Split Rock Formation, showing location of UCMP localities. Radiometric date after Izett and Obradovich (2001). Declination and inclination of magnetic sites are shown. Solid circles are sites that are statistically removed from a random distribution at the 95% confidence level (Class I sites of Opdyke et al., 1977).

TABLE 2. Updated faunal list for the Split Rock Formation.

Mammalia
- Artiodactyla
  - Oreodontidae
    - *Brachycrus sweetwaterensis*
    - *Brachycrus vaughani*
    - *Brachycrus rusticus*
  - Camelidae
    - *Blickomylus galushai*
    - *Protolabis* cf. *P. heterodontus*
  - Palaeomerycidae
    - *Bouromeryx* sp.
    - cf. *Barbouromeryx* sp.
  - Antilocapridae
    - *Paracosoryx wilsoni*
    - *Merycodus* cf. *M. sabulonis*
- Perissodactyla
  - Chalicotheriidae
    - *Tylocephalonyx skinneri*
  - Equidae
    - cf. *Hypohippus*
    - *Merychippus primus*
- Carnivora
  - Canidae
    - *Protomarctus optatus*
    - *Paracynarctus kelloggi*
    - *Cynarctoides acridens*
  - Mustelidae
    - *Miomustela* sp.
    - cf. *Leptarctus*
  - ?Procyonidae indet.
- Rodentia
  - Mylagaulidae
    - *Galbreathia novellus*
    - *Alphagaulus vetus*
  - Sciuridae
    - *Protospermophilus kelloggi*
    - *Miospermophilus wyomingensis*
    - *Tamias* sp.
  - Dipodidae
    - *Schaubeumys sabrae*
  - Geomyidae
    - *Schizodontomys harkseni*
  - Heteromyidae
    - *Harrymys irvini*
    - *Proheteromys* sp.
    - *Cupidinimus* sp.
    - *Mioheteromys* sp.
    - *Perognathus* sp.
    - *Mookomys* sp.
    - *Peridiomys* sp.
- Insectivora
  - Erinaceidae
    - *?Parvericius montanus*
    - *Brachyerix macrotis*
  - Proscalopidae
    - *Mesoscalops scopelotemos*
  - Soricidae
    - *Limnoecus* sp.
    - Gen. et sp. indet.
- Lagomorpha
  - Leporidae
    - *Hypolagus* sp.
    - Gen. et sp. indet.
  - Ochotonidae
    - *Oreolagus nebrascensis*
    - *?Desmatolagus schizopetrus*
- Chiroptera
  - Gen. et sp. indet.

Reptilia
- Chelonia
  - Testudinidae
    - *Gopherus* cf. *G. edae*
- Squamata
  - Boidae
    - *Ogmophis* cf. *O. miocompactus*
    - *Charina prebottae*
    - *Calamagras weigeli*
  - Colubridae
    - *Ameisiophis robinsoni*
    - Natricinae indet.
    - *Dakotaophis greeni*
    - *Paracoluber storeri*
    - *Salvadora paleolineata*
    - *Psedocemophora* cf. *P. antiqua*
  - Viperidae
    - cf. Crotalinae indet.
  - Anguidae
    - *Gerrhonotus* sp.
    - *?Sceloporus* sp.
  - Phrynosomatidae
    - *Phrynosoma ?douglassi*

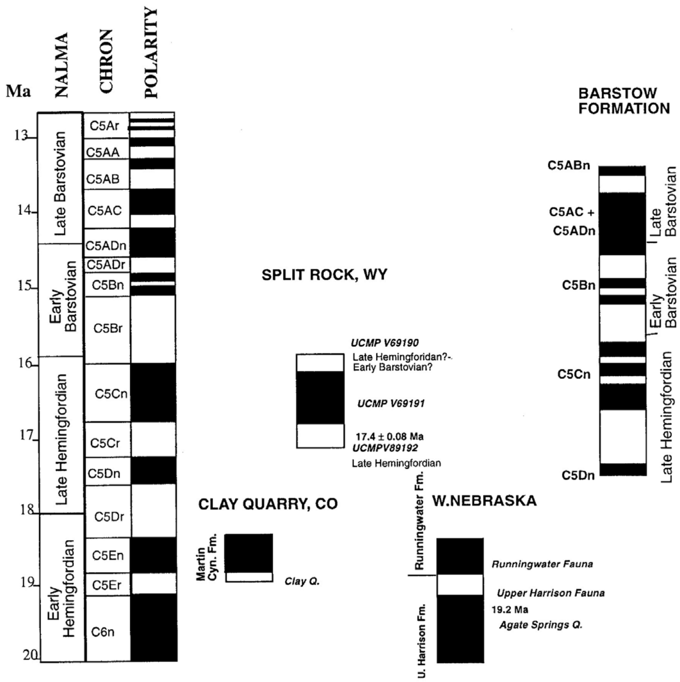

FIGURE 5. Correlation of the Split Rock Formation paleomagnetic section, based on the dates and age constraints discussed in the text. Magnetic stratigraphy of the Barstow Formation after MacFadden et al. (1990), and of the Caliente Formation section after Prothero et al. (this volume). Time scale after Berggren et al. (1995), Woodburne and Swisher (1995), and Tedford et al. (2004).

base of the main locality. If the specimen identified as cf. *Barbouromeryx* is truly from this genus, that would suggest an age no later than Hemingfordian, but this specimen is not clearly referable to a particular stratigraphic location, so, again, it does not rule out the presence of Barstovian rocks at the top of the section. Ongoing studies of the camels, heteromyid rodents, and carnivores at Split Rock will make clearer the biostratigraphic affinities of the Split Rock fauna.

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