MAGNETIC STRATIGRAPHY OF THE UPPER EOCENE FLORISSANT FORMATION, TELLER COUNTY, COLORADO

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Abstract— Florissant Fossil Beds National Monument in the Rocky Mountains just west of Colorado Springs is one of the classic Lagerstätten, world famous for its extraordinary preservation of fossil plants, arthropods (especially insects), mollusks, and a few fossil vertebrates (fish, birds, and mammals). The mammals indicate a Chadronian (late Eocene) age, based on the co-occurrence of bronotheres and the horse Mesotherium. The fossil flora includes many types of leaves and huge in situ redwood stumps, and is thought to represent a warm-temperate forest, the final phase of the late Eocene warming before the early Oligocene climatic crash (represented by the nearby early Oligocene Antero flora). The Florissant Formation consists of about 70 m of lake shales and conglomerates, interbedded with and surrounded by volcanic ashes. In the summer of 2003, we sampled the exposed parts of the section with 17 paleomagnetic sites (3 samples per site). The single-component remanence was held mainly in magnetite with only minor overprinting. All but one of the sites was reversed in polarity and antipodal to the single normal site, so they pass a reversal test, and the remanence is primary. Based on a mean 40Ar/39Ar date of 34.07 ± 0.10 Ma on four tuffs in the upper part of the section (Evanoff et al., 2001), we correlate this long reversed magnetozone with Chron C13r (33.7-34.7 Ma), consistent with the Chadronian age (based on the overlapping range of bronotheres and Mesotherium) of the mammalian fauna.

Keywords: Eocene, Florissant, Colorado, Chadronian

INTRODUCTION

Ever since its discovery in the 1870s, the Florissant area of central Colorado (Figs. 1-2) has proven to be an important Lagerstätte for late Eocene fossils (see historical review in Meyer, 2003). Extraordinary preservation of the soft tissues of plants, insects, mollusks, and many other fossils has made Florissant a critical taphonomic window (O’Brien et al., 2002) for studying uncommonly preserved taxa, such as insects, and crucial also to understanding floral and climatic changes in this region of the Rocky Mountains. More than 260 publications have described some 1400 species of insects and 150 species of plants (Meyer, 2003). As pointed out in the first comprehensive review of the flora by MacGinitie (1935) and updated by Gregory-Wodzicki (1994, 2001), Wingate and Nichols (2001), Leopold and Clay-Poole (2001), and Meyer (2003), the Florissant flora records the final phase of late Eocene warmth in the North American floral climatic curve of Wolfe (1978, 1994) before the early Oligocene climatic crash (as recorded by the cool-temperate early Oligocene Antero flora, just a few km west of Florissant). Even though it was at 2000-3000 m elevation in the Eocene, the Florissant flora is believed to represent warm-temperate climatic conditions of moderate rainfall and a mean annual temperature of 13-14°C (Meyer, 2003), compared to modern mean annual temperatures of 4°C.

Yet the dating of the Florissant fossils has long been problematic. Early authors wavered between calling the fossils Eocene, Oligocene (MacGinitie, 1953), or even Miocene (Gazin, 1935), because the biostratigraphic zonation of plants and insects was not well established. The discovery of fragmentary fossil mammals, including the horse Mesotherium sp., and some bronothere scraps, suggested that the age of the deposit was Chadronian, which was considered early Oligocene by Wood et al. (1941). However, recent 40Ar/39Ar dating by Carl Swisher and paleomagnetic stratigraphy by Prothro have shown that the Chadronian in the High Plains is late Eocene in age, about 37-34 Ma (Swisher and Prothro, 1990; Prothro and Swisher, 1992). Eips and Chapin (1975) obtained K-Ar dates of 34.9 Ma (adjusted for the new decay constants of Steiger and Jager, 1977), consistent with the new dates on the Chadronian. Finally, Evanoff et al. (2001) reported a number of 40Ar/39Ar dates on the Florissant area, which will be discussed further below. Nevertheless, magnetostratigraphic analysis would complement the recent 40Ar/39Ar dates by testing their age interpretations, and helping to determine the total temporal duration of the deposit.

GEOLOGIC SETTING

Five geologic units are found in the Florissant area (Evanoff et al., 2001). The basement rock is the 1080 Ma Pikes Peak Granite. It is overlain by the Wall Mountain Tuff, a rhyolitic ignimbrite fluvo that mantles the ancient valley in the region, and then was eroded prior to the deposition of the Florissant Formation. It yields a 40Ar/39Ar single-crystal age of 36.73 ± 0.07 Ma on sanidine (McIntosh and Chapin,
1994), so it is earliest Chadronian in age. Incised into the Wall Mountain Tuff is a conglomerate made of giant boulders and smaller clasts of Wall Mountain Tuff material. This conglomerate lies beneath the base of the Florissant Formation, and is informally called the “Tertiary boulder conglomerate” by Evanno et al. (2001). The Florissant Formation (informally known as the “Florissant lake beds”, but formally named by Evanno et al., 2001) consists of a 70-m-thick sequence of lake shales and siltstones alternating with pumice conglomerate beds, volcanic mudflow deposits (lahars), and occasional cross-bedded stream channel sandstones. The upper 30 m of the Florissant Formation has few lake shales, but consists mostly of volcanic conglomerate and lahar deposits. According to Evanno et al. (2001) and Meyer (2003), the volcanics are derived primarily from the nearby Guffey volcanic center in the Thirtynine Mile volcanic field of Wobus and Epis (1978), currently about 20 km to the southwest of Florissant. The lahar deposits formed dams across the Florissant paleovalley, which ponded the water and formed the lake in which the shales were deposited.

Evanoff et al. (2001) divided the Florissant Formation into a number of informal units (Fig. 3). Above the “Tertiary boulder conglomerate” lies a finer-grained basal conglomerate (composed largely of granitic grus from the Pikes Peak Granite) about 5 m thick. Next comes a lower paper shale unit full of fish, leaf, and insect fossils, about 6 m thick, followed by a lower mudstone unit (23 m thick), which yields most of the mammal fossils as well as the in situ Sequoia stumps. Above the lower mudstone is the middle shale unit (10 m thick), a pumiceous paper shale that yields most of the quarries within the Florissant Fossil Beds National Monument. About 42 m from the base of the Florissant Formation is the caprock conglomerate, a granular muddy conglomerate with volcanic and granitic gravel, and clasts of shale near the base. The final phase of lake deposition is represented by the upper shale unit, consisting of about 3 m of paper shale and pumice conglomerate that produces fossils of insects, leaves, and ostracodes. The uppermost 25 m of the section is the upper pumice conglomerate, composed of white and pink pumice conglomerate, with fingernail clams near the base of the unit.

McIntosh (in Evanoff et al., 2001) ran a number of \(^{40}Ar/^{39}Ar\) analyses on samples from the Florissant Formation. A sandstone sample from the top of the caprock conglomerate yielded an age of 34.03 ± 0.09 Ma. A sandstone from the top of the upper shale unit produced a date of 34.14 ± 0.08 Ma. Two sandstone samples from the upper half of the upper pumice conglomerate yielded ages of 34.07 ± 0.09 Ma and 34.01 ± 0.13 Ma. Although the ages are somewhat scattered, they overlap in age within error estimates, so Evanoff et al. (2001) interpreted the weighted mean average age of the Florissant tuffs (all from the upper half of the formation) as 34.07 ± 0.10 Ma.

The only other constraint on the age of the Florissant Formation is its mammalian fauna. Although most of the specimens are fragmentary, they include specimens of a brontothere, the oreodont *Merycoidodon* sp., the horse *Mesotherium* sp., the deer-like *Arctotherium* sp., an unidentified rhinoceros, and the mouse opossum *Herpestictis sanctum* (Gazin, 1935; Evanoff et al., 2001; Meyer, 2003). The co-occurrence of *Mesotherium* and brontotheres was one of the original criteria for the Chadronian as defined by Wood et al. (1941), so the Chadronian age (34-37 Ma, according to Swisher and Prothero, 1990) of the middle part of the section (from whence most of the mammals come) is well established. Screenwashed samples from the lower mudstone unit studied by Marie Worley yield teeth of rodents, lagomorphs, and insectivores (H. Meyer, pers. commun.), so eventually mammals

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**FIGURE 2.** Map of the localities and geology of the Florissant area (after Evanoff et al., 2001).

**FIGURE 3.** Lithostratigraphy and magnetic stratigraphy of the Florissant Formation. Lithostratigraphy and dates after Evanoff et al. (2001). Declination and inclination of magnetic sites are shown. Solid circles are sites which are statistically removed from a random distribution at the 95% confidence level (Class I sites of Opdyke et al., 1977); open circle has one vector divergent (Class III site of Opdyke et al., 1977). Arrow indicates mammal fossils.
will be reported from other levels. Presently, there are no diagnostic mammals nor 40Ar/39Ar dates on the lower half of the section, so these data provide no age constraints on the lower half of the Florissant Formation. Paleomagnetic stratigraphy could potentially resolve the issue of how much of the Chadronian is spanned by the Florissant Formation.

METHODS

Although most of the Florissant Formation is mantled by vegetation, there are patchy exposures in different parts of the Florissant valley. Evanoff et al. (2001) provided a map of the major localities in the area, and we sampled three sections that spanned most of the exposed part of the Florissant Formation. The lowest five (numbers 13-17) sites (3 samples per site) were collected from the 10 meters of exposures of the lower shale unit exposed in the privately owned Clare Quarry, north of the monument entrance (Fig. 2). The middle shale unit and the caprock conglomerate (5 sites, numbers 1-5) were sampled in Scudderd Quarry, just west of the Big Stump (#3 on the map in Fig. 2). The upper shale unit, and upper pumice conglomerate (sites 6-12) were sampled along Boulder Creek (numbers 5-6 in Fig. 2). Precise locations of all of these sites are given by Evanoff et al. (2001, table 1). Together, these 17 sites span most of the exposed part of the formation, although there are covered intervals that could not be sampled (Fig. 3).

Each sample was taken with simple hand tools by scraping a horizontally oriented surface at the top of the block of rock. In the laboratory, the block samples were cored with a drill press, or molded into disks of Zircar aluminum ceramic if they were too small or crumbly to withstand the drilling. The core samples were then measured on a 2G cryogenic magnetometer with an automatic sample changer at Caltech. After measurement of NRM (natural remnant magnetization), all samples were demagnetized in alternating fields (AF) of 25, 50, and 100 Gauss to remove any remanence caused by multi-domain grains before it is baked into the sample, and to determine the coercivity behavior of each sample. After AF demagnetization, each sample was then thermally demagnetized in 50° steps from 200°C to 630°C to remove chemical overprints due to goethite, and to see how the remanence behaved as the components were removed and the temperatures approached and exceeded the Curie points of magnetite (580°C) and hematite (630°C).

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

Representative orthogonal demagnetization plots are shown in Figure 4. In Figure 4A, the sample exhibits normal polarity at NRM (the direction is north and down), and the rapid decline in intensity through AF demagnetization shows that the remanence is held in a low-coercivity mineral, such as magnetite. In Figure 4B, a typical reversed sample shows a single component of remanence that is reversed (south and up) at NRM and decays steadily to the origin, losing all remanence as it exceeds the Curie point of magnetite (580°C). This sample apparently has a slight high-coercivity overprint of goethite, judging from the slight decline in intensity in the first three AF demagnetization steps. In Figure 4C, the sample showed a slight normal overprint (it begins south and down), but by 200°C, the overprint has been removed, and the sample decreases in intensity steadily toward the origin. The remanence in this sample is carried only by magnetite, because it loses all remanence by 600°C, and because it has a relatively low coercivity.

Mean directions for all sites are given in Table 1. As can be seen in Figure 3, all but one (site 9) of the 17 sites was reversed in polarity, and all but one (site 16) of the sites were statistically significant at the 95% confidence level (Class I sites of Opdyke et al., 1977). Only site 16 was not statistically significant, but it showed two clear vectors that
TABLE 1. Paleomagnetic data from the Florissant Formation.

<table>
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<tr>
<th>SITE</th>
<th>DEC</th>
<th>INC</th>
<th>K</th>
<th>$\alpha_{rd}$</th>
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<td>29.2</td>
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agreed, and a third that was divergent, so polarity was still interpretable (Class III site of Opydye et al., 1977).

The mean direction for the single normal site was $D = 9.4$, $I = 62.1$, $k = 66.3$, $\alpha_{rd} = 15.3$ (n = 3). The mean direction for the 16 reversed sites was $D = 177.6$, $I = -56.4$, $k = 34.6$, $\alpha_{rd} = 6.4$. As can be seen from a stereonet plot (Fig. 5), the mean directions are antipodal within error estimates, so the directions pass a reversal test. This shows that the overprints have been removed, and the cleaned vectors probably represent the primary or characteristic remanence in the samples.

DISCUSSION

Correlation of the Florissant Formation paleomagnetic results is shown in Figure 6. The fact that the entire section is reversed in polarity (except for site 9), and has a $^{40}$Ar/$^{39}$Ar date of 34.07 ± 0.10 Ma in the upper half of the formation, correlates the entire section with magnetic Chron C13r (33.7-34.7 Ma). There is no evidence that the section is older than 34.7 Ma, because no other polarity zones were encountered at the base of the section that might correlate with normal Chron C15n. The $^{40}$Ar/$^{39}$Ar date of 36.73 ± 0.07 Ma on the deeply weathered Wall Mountain Tuff, which underlies the Florissant Formation, gives an absolute lower age constraint on the unit. The isolated normal site 9 can probably be explained as one of the short intervals of normal polarity within Chron C13r, called the “tiny wiggles” by Hartl et al. (1993), or possibly it is due to incomplete removal of a normal overprint in this one site.

CONCLUSIONS

The 70 m of the Florissant Formation is almost entirely reversed in polarity. Based on the $^{40}$Ar/$^{39}$Ar date of 34.07 ± 0.10 Ma near the top of the section and the Chadronian mammals, we correlate the Florissant Formation with Chron C13r (33.7-34.7 Ma), or late Eocene in age.

Thus, the famous fossils of plants, insects, mollusks, birds, and mammals from the Florissant Formation are all late Eocene, and consistent with the interpretation that there was a late Eocene warm pulse before the early Oligocene climatic deterioration.

ACKNOWLEDGMENTS

We thank Paula Dold, Matthew Liter, Josh Ludtke, and Jingmai O’Connor for help with sampling, and Josh Ludtke for help with the lab work. We thank Dr. Joseph Kirschvink for access to the Caltech paleomagnetics lab. We thank Herb Meyer and Emmett Evansoff for help with the stratigraphy and geology, and the National Park Service (Florissant Fossil Beds National Monument) for permits to work on the Monument grounds. We thank Nancy Anderson for access to Clare Quarry. We thank Herb Meyer, Spencer Lucas, and Kate Zeigler for helpful reviews of this paper. This research was supported by grants to Prothero by the Donors of the Petroleum Research Fund of the American Chemical Society, and by NSF grant 03-09538.

REFERENCES


Mioclaenus turgidus, reconstructed palate, teeth and lower jaw (from Matthew, 1937).