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PALEOENVIRONMENTS CONTAINING *CORYPHODON* IN THE FORT UNION AND WILLWOOD FORMATIONS SPANNING THE PALEOCENE-EOCENE THERMAL MAXIMUM (PETM), BIGHORN BASIN, WYOMING

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INTRODUCTION

The burning of fossil fuels supports many modern conveniences, but their emissions are also raising greenhouse gas concentrations in the atmosphere, which are increasing global temperature and therefore leading to global climate changes. The Paleocene-Eocene Thermal Maximum (PETM), a rapid (~150,000 years) global warming event (5-8°C over less than 20,000 years) about 55.5 million years ago that was due to a massive release of carbon into the atmosphere (McInerney and Wing, 2011; Gingerich, 2019). Therefore, the PETM can act as an analogy for future global warming if fossil fuel emissions continue their upward trend (Gingerich, 2019).

The Bighorn Basin in Wyoming is one locality where PETM-aged rock units are exposed, which makes it an excellent location to study the environmental, floral, and faunal responses to the PETM (Wing et al., 2005; Kraus et al., 2015). Studying these responses can offer insights into how modern-day flora and fauna might respond to modern climate change. Previous research has concluded that some key adaptations, such as dwarfing, helped certain fauna survive the PETM (Secord et al., 2012). However, it is unclear why some of these mammals survived this much drier climate (Clementz et al., 2008; Secord et al., 2012).

The hippopotamus-like Coryphodon (Mammalia, Pantodonta) was the first mammalian megaherbivore (body mass > 1000 kg) (Uhen and Gingerich, 1995). Previous studies have hypothesized that Coryphodon was semi-aquatic based on morphological features of their skeleton and enamel $\delta^{18}O$ values (Clementz et al., 2008). This study tests the hypothesis that Coryphodon will mainly be found in aquatic or semi-aquatic facies throughout the PETM by inferring its depositional environments through sedimentary analysis.

STUDY AREA

The Bighorn Basin is located in northern Wyoming and southernmost Montana. Its well-exposed Fort Union and Willwood Formations in the Sand Coulee area of the northern part of the basin are the focus of this study. This intermontane basin was formed during the Laramide Orogeny within the foreland basin of the earlier Sevier Orogeny (Mackin, 1937; DeCelles, 2004). Its surrounding mountain ranges provided most of the sediment to the basin (Kraus et al., 2015).

The Sand Coulee area has been previously subdivided into a multitude of fossil localities by Gingerich (2001). Specimens observed during our fieldwork were assigned to these localities based on GPS coordinates and elevation data.

METHODS

Field Methods

Data for this study were collected in the Sand Coulee area of the northern Bighorn Basin. We prospected for Coryphodon in a range of biozones surrounding the PETM. The data consist of 14 stratigraphic sections in total, each with a Coryphodon bearing unit. Of these, 11 contained fossils in situ; for the other three, the bone-bearing layer was estimated based on the highest layer where fossils could be surface collected and similarities between bone color and matrix and mottling colors. Sections were measured on freshly exposed bedrock in narrow trenches. Thickness, grain size, matrix type and color, mottling percent and colors (using a Munsell Color Chart), abundance and type of nodules, shrink-swell features such as slickensides and clay cutans, sharpness of contacts, presence of organic matter, vertebrate and invertebrate fossils, and presence or absence of laminations were recorded for each unit.

Soil Morphology Index (SMI) Calculation

Using the methods described in Adams et al. (2011) a soil morphology index (SMI) number was calculated for each paleosol unit, which serves as a proxy for soil moisture at the time of deposition. This index can be used to determine changes in drainage between the units where Coryphodon was found. SMI is based on matrix chroma and the characteristics of nodules. Matrix chroma ranged from 1 to 3 in the study area and is scored accordingly. The presence, size, and abundance of carbonate nodules and yellow-brown siderite nodules are scored with either 0, 3, or 6 points for each of the two types of nodules. The sum of these scores in the SMI number of that unit.

R was used to run a range of statistical tests using the SMI numbers. A chi-square test was run to determine if there is a relationship between the SMI numbers of Coryphodon units and the biozones these units are from. The average SMI of the Coryphodon units in each biozone is normally distributed. Therefore, an ANOVA was run since it is parametric and assumes a normal distribution of the data. A Tukey test was then run to determine which pairing of biozones contained statistically different means of SMI values. Z-score tests were also run between the SMIs of the biozones that the Tukey test found to be significantly different to verify these results. A Z-score above 1.96, which represents the 95th percentile value, means that the sample is statistically different from the population it is being compared to. Finally, a Mann-Whitney U test was run to compare the SMI numbers of pre- and post-PETM stratigraphic units containing Coryphodon. This test was selected because the pre-PETM SMI numbers are not normally distributed ($W = 0.55$, p-value = 1.4e-05).

Stratigraphic Column Creation

Stratigraphic columns were created for each section in Adobe Illustrator and grouped by North American mammalian biozone. U.S. Geological Survey lithology patterns (Illustrator swatches) were used to indicate rock types. The percentage of mottling was roughly portrayed by the number of mottling shapes present in the unit. Matrix and mottling colors were derived from a Munsell Color Chart.

RGB values were determined using the Virtual Online Color Wheel, which is a visual representation of RGB values calculated by The Munsell Color Science Laboratory (http://www.andrewwerth.com/color/). Since exact RGB equivalents only exist for Munsell colors with even chroma, the other representative colors were estimated. To do this, Munsell colors with exact RGB equivalents were blended in Illustrator using the blending tool to generate RGB representative colors for the Munsell colors with no exact RGB equivalent (i.e. a chroma of 2 and a chroma of 4 to create a color for a chroma of 3).

RESULTS

Stratigraphic Columns

Clarkforkian 2 is represented by 4 columns, Clarkforkian 3 by 6 columns, Wasatchian 1 by 1 column, Wasatchian 2 by 1 column, and Wasatchian 4 by 2 columns. A selection of stratigraphic columns for these biozones is shown in Figures 1-3, the full list of sections containing Coryphodon and their paleoenvironmental interpretations is given in Table 1.

Table 1. Paleoenvironmental interpretations based on soil features of the *Coryphodon* units in the measured stratigraphic columns, sorted from youngest on top to oldest on bottom.

Biozone	Sampling Location	Paleoenvironmental Interpretations
Wasatchian 4	19-59	Intermediate soil
Wasatchian 4	19-57	Wetter soil with wet and dry cycles
Wasatchian 2	19-67	Drier soil
Wasatchian 1	19-58	Drier soil
Clarkforkian 3	19-54	Fluvial deposit
Clarkforkian 3	19-32	Soil with wet and dry cycles
Clarkforkian 3	19-29	Pond or swamp
Clarkforkian 3	19-23	Soil with wet and dry cycles
Clarkforkian 3	19-22	Soil with wet and dry cycles
Clarkforkian 3	19-13	Soil with wet and dry cycles
Clarkforkian 2	19-52	Fluvial deposit
Clarkforkian 2	19-34	Drier soil
Clarkforkian 2	19-35	Swap or water-logged soil
Clarkforkian 2	19-53	Pond

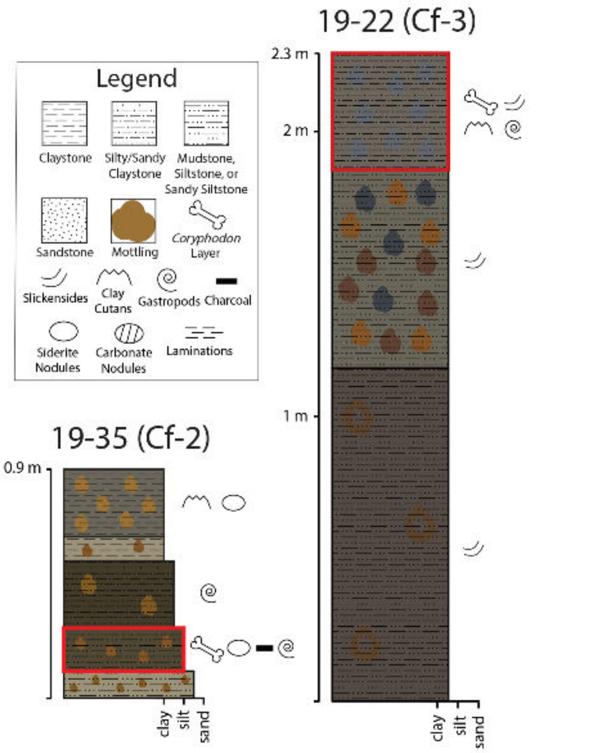

Figure 1. Stratigraphic columns from Clarkforkian (Cf) 2 and 3 mammalian biozones (Pre-PETM). Coryphodon bearing layer outlined in red. Matrix and mottling colors derived from Munsell Color Chart.

Soil Morphology Index (SMI) Numbers

SMI numbers were used to determine if there are statistically significant differences in the wetness of Coryphodon bearing layers among mammalian biozones (Fig. 4). Higher numbers indicate drier conditions whereas lower numbers indicate wetter conditions.

Chi-Square Test

The chi-square test was significant (p-value = 0.014). Therefore, the distribution of counts across categories is not random, so SMI numbers of Coryphodon units are dependent on mammalian biozone. The residuals for a chi-square are the difference between the observed and expected counts by table cell. The greater that residual the more it affects the significance of the chi-square test. The residuals with the greatest contribution to the significant result are a SMI of 15 for Wasatchian 1 (residual contribution of 39.05%), a SMI of 13 for Wasatchian 2 (16.63%), a SMI of 4 for Wasatchian 4 (6.63%), a SMI of 5 for Clarkforkian 2 (5.78%), and a SMI of 7 for Clarkforkian 3 (3.85%).

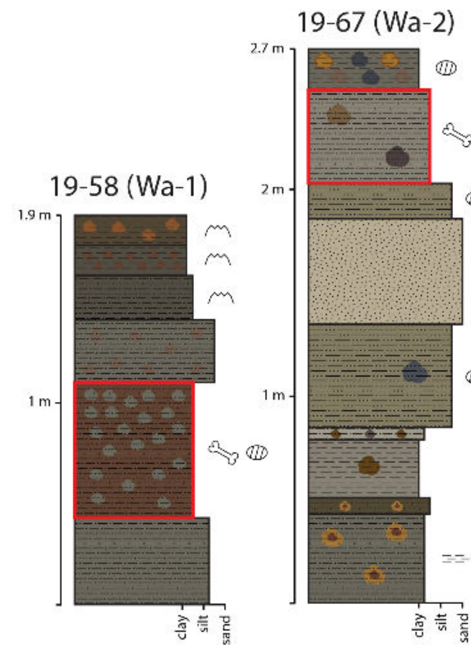

Figure 2. Stratigraphic columns from Wasatchian (Wa) 1 and 2 mammalian biozones (Post-PETM). Coryphodon bearing layer outlined in red. Matrix and mottling colors derived from Munsell Color Chart. Legend in Figure 1.

ANOVA & Z-scores

The ANOVA was significant (p-value = 0.020), which means that the null hypothesis can be rejected and the means of SMI values from at least one pairing of biozones from which these samples were drawn are significantly different. A Tukey test showed that there is a significant difference between the SMI means of Clarkforkian 3 and Wasatchian 1 (p-value = 0.041) as well as Wasatchian 1 and Wasatchian 4 (p-value = 0.03).

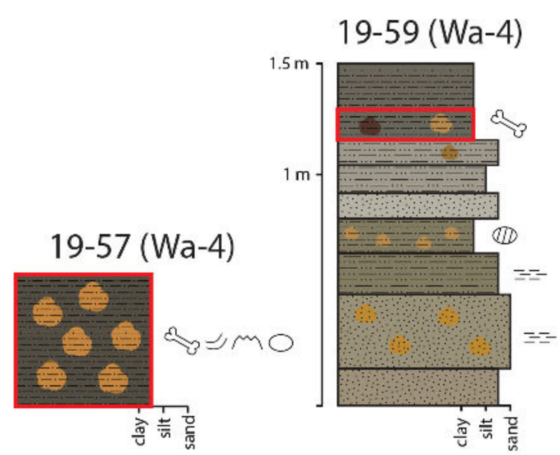

Figure 3. Stratigraphic columns from Wasatchian (Wa) 1 and 2 mammaliaStratigraphic columns from Wasatchian 4 mammalian biozone (Post-PETM). Coryphodon bearing layer outlined in red. Matrix and mottling colors derived from Munsell Color Chart. Legend in Figure 1.

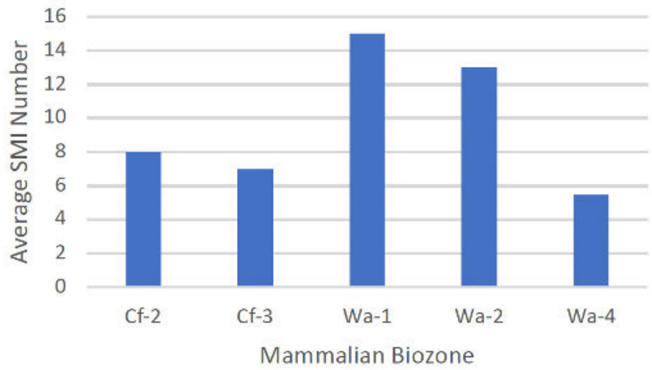

Figure 4. Average SMI number for units containing Coryphodon in each mammalian biozone (except for Wasatchian 0 or 3). Higher number represents a drier stratigraphic unit. Drying of the PETM interval can be observed between Clarkforkian 3 and Wasatchian 1.

Z-score tests supported the results of the Tukey test and showed that the SMI of the Wasatchian 1 sample is an outlier of the SMIs of the Wasatchian 4 "population" and Clarkforkian 3 "population" with respective Z-scores of 4.48 and 0 (standard deviation is 0).

Mann-Whitney U Test

A Mann-Whitney U test yielded a non-significant p-value of 0.5. Therefore, the null hypothesis that the difference in the medians of SMI numbers of the pre- and post-PETM stratigraphic units containing Coryphodon is zero cannot be rejected. This means that these two samples are not statistically significant from one another.

DISCUSSION & CONCLUSIONS

My hypothesis, that the proposed semi-aquatic mammal Coryphodon would mainly be found in aquatic or semi-aquatic facies, is partly supported by the data. In the Clarkforkian 2 and 3, Coryphodon was found mainly in aquatic and semi-aquatic facies as well as in soils with evidence of wet and dry cycles, supporting my hypothesis. However, following the PETM, in Wasatchian 1, 2, and 4, there is only one instance of Coryphodon being found in a wetter soil, and no instances of them in a pond, swamp, or fluvial deposit (Table 1). This preliminary data suggest that Coryphodon was preserved, and might have lived, in wetter habitats before the PETM, but was possibly able to adapt to drier habitats post-PETM.

This potential shift in Coryphodon habitat preference, from aquatic and semi-aquatic to drier paleoenvironments, may be evidence that the changing paleoenvironments that Coryphodon lived in were in large part due to the PETM. However, this result might be influenced by the smaller sample size of specimens post PETM. Additionally, it may be possible that Coryphodon did live in these types of facies but were for some reason fossilized in or at least preserved better in soils as opposed to in swamps, ponds, and rivers in later biozones.

As the sample size of this study is relatively small, especially within biozone groupings, error is an important consideration. Wasatchian 0 and 3 were not represented and only one sample was collected for Wasatchian 1 and 2. Therefore, while the preliminary data does show trends, more fieldwork is crucial to increase the sample size and see if the observed differences of Coryphodon units between biozones still hold.

Additionally, the SMI system, created by Adams et al. (2011), may not be the best way to numerically analyze the data from this area, as many of the layers do not contain any nodules, and the chroma only spanned 1 through 3 (as opposed to 2-6 for Adams et al. (2011)). This means that a large number of the Coryphodon bearing units have an SMI number between 6 and 8, which statistically skews the data towards these central SMI numbers even though there were paleoenvironmental changes between units with the same or very similar SMI numbers. This was particularly evident between soils that contained slickensides or clay cutans, and therefore indicated the presence of wet and dry cycles, and those that did not. Therefore, I propose that the presence or absence of additional sedimentary features should be included in calculating SMI numbers in this study area to have them better represent changing paleoenvironments, as well as make it easier to statistically analyze the differences between these paleoenvironments. Finally, the problem with the current SMI system was evident statistically when running a Mann-Whitney U test to comparing the SMI numbers of the pre- and post-PETM stratigraphic units containing Coryphodon, as this test did not yield a significant result. However, when considering all of the observations, there is a likely shift in the paleoenvironments of Coryphodon that should be studied further through continued fieldwork.

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