Article

Carbon Isotope Stratigraphy of the mid-Cretaceous Cloverly Formation, Wyoming

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| Academic Editor: Firstname Lastname  Received: date  Revised: date  Accepted: date  Published: date  **Citation:** To be added by editorial staff during production.  **Copyright:** © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/). |

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**Abstract**

A single paragraph of about 200 words maximum. For research articles, abstracts should give a pertinent overview of the work. We strongly encourage authors to use the following style of structured abstracts, but without headings: (1) Background: Place the question addressed in a broad context and highlight the purpose of the study; (2) Methods: briefly describe the main methods or treatments applied; (3) Results: summarize the article’s main findings; (4) Conclusions: indicate the main conclusions or interpretations. The abstract should be an objective representation of the article and it must not contain results that are not presented and substantiated in the main text and should not exaggerate the main conclusions.

**Keywords:** keyword 1; keyword 2; keyword 3 (List three to ten pertinent keywords specific to the article yet reasonably common within the subject discipline.)

1. Introduction

The introduction should briefly place the study in a broad context and highlight why it is important. It should define the purpose of the work and its significance. The current state of the research field should be carefully reviewed and key publications cited. Please highlight controversial and diverging hypotheses when necessary. Finally, briefly mention the main aim of the work and highlight the principal conclusions. As far as possible, please keep the introduction comprehensible to scientists outside your particular field of research. References should be numbered in order of appearance and indicated by a numeral or numerals in square brackets—e.g., [1] or [2,3], or [4–6]. See the end of the document for further details on references.

*\*\* Why care? \*\**

The mid-Cretaceous (Aptian-Turonian) was a time of extreme and dynamic climatic conditions and major terrestrial biotic turnovers on the North American continent (Cifelli et al., 1999; Cifelli et al., 1997; Harper et al., 2021; Jones et al., 2022; Ludvigson et al., 2010; Rodríguez-López et al., 2016). North American mid-Cretaceous terrestrial biotas are known from deposits in the Western Interior Basin (WIB), primarily the Cedar Mountain Formation of Utah, the Antlers Formation of Oklahoma and Texas, and the Cloverly Formation of Wyoming and Montana (Andrzejewski & Tabor, 2020; Cifelli et al., 1997; Oreska et al., 2013; M. B. Suarez et al., 2021; Tucker et al., 2020). Although the Cedar Mountain Formation is well exposed and has produced abundant mid-Cretaceous vertebrates, relatively few of these fossils are from the Aptian-Albian interval of the formation (Kirkland et al., 1999). The Antlers Formation is considered latest Aptian to earliest Albian in age and has produced an abundant vertebrate fauna. However, the Antlers Formation is poorly exposed at the surface, so establishing a high-resolution chronostratigraphic framework has proven challenging. In contrast, the Cloverly has yielded one of the world’s most prolific Aptian-Albian terrestrial vertebrate faunas and is well exposed at the surface. Recent work has begun to reconstruct the Cloverly paleoenvironment using quantitative geochemical proxies (Kalu, 2023; Allen, 2024; Allen et al., in prep). Integrating paleontological and paleoclimate data from the Cloverly may help us understand terrestrial ecosystems of the Early Cretaceous greenhouse world and how those ecosystems changed through time.

*\*\* What’s the problem? \*\**

However, spatially complex lithostratigraphy confounds our understanding of the Cloverly paleoenvironmental and paleobiological records. Correlation requires the use of other stratigraphic tools. Palynomorph biostratigraphy is useful in the mid-Cretaceous nonmarine WIB, but studies of the Cloverly palynoflora have only provided coarse correlations (D’Emic et al., 2019; Wilborn, 2008). Magnetostratigraphy has been applied to the Cloverly, but the results have been inconsistent and high-resolution magnetochronology is difficult in middle Cretaceous deposits due to stable polarity during the Cretaceous Normal Superchron from ~126-84 Ma (Helsley & Steiner, 1968; Douglass, 1984; Swierc, 1990). Fission-track dating of zircons has been applied to the Cloverly but only constrain deposition to the Aptian-Albian (May et al., 1995). Zircon U\Pb geochronology is more precise and has been applied to the Cloverly, but additional data is needed. Additional data is available since these were published.

and carbon isotope chemostratigraphy have proven viable geochronological approaches in the nonmarine realm. In recent decades, these methods have been successfully applied to the middle Cretaceous WIB, including the Cloverly Formation (D’Emic et al., 2019; Carrano et al., 2022; Joeckel et al., 2023; Ludvigson et al., 2010; Ludvigson et al., 2015; M. B. Suarez et al., 2019; Tucker et al., 2020). Recently reported radiometric dates from the Cloverly Formation support an Aptian-Albian depositional age (Carrano et al., 2022; D’Emic et al., 2019), but

Still, radiometric data is resource intensive and requires penecontemporaneous zircons, so stratigraphic sampling resolution is often limited. Integrating these radiometric data with high-resolution carbon isotope chemostratigraphy can facilitate robust stratigraphic correlations to other better dated reference sections.

Correlations can be achieved because changes in carbon isotope values of sedimentary carbon reservoirs are geochronologically synchronous and can be correlated between both marine and terrestrial deposits (Herrle et al., 2004; Ludvigson et al., 2010; Ludvigson et al., 2015; Scholle & Arthur, 1980). More specifically, several carbon isotope excursions occur in the Aptian to Albian stages, the time slice that the Cloverly Formation is thought to span. Carbon isotope stratigraphy has been applied to other mid-Cretaceous nonmarine units such as the Cedar Mountain Formation but has not yet been applied to the Cloverly (Gulbranson et al., 2022; Joeckel et al., 2023; Ludvigson et al., 2010; M. B. Suarez et al., 2023; Tucker et al., 2020).

*\*\* How does this study address the problem? \*\**

*Herein perhaps you should introduce your study sections and what data are already available from those sections.*

2. Materials and Methods

In this section, where applicable, authors are required to disclose details of how generative artificial intelligence (GenAI) has been used in this paper (e.g., to generate text, data, or graphics, or to assist in study design, data collection, analysis, or interpretation). The use of GenAI for superficial text editing (e.g., grammar, spelling, punctuation, and formatting) does not need to be declared.

2.1. Zircon U/Pb Geochronology

2.1.1. Sampling Methods

2.1.2. Sample Preparation

2.1.3. CA-TIMS Analyses

2.1.4. LA-ICP-MS Analyses

2.1.5 Depth-Age Modelling

2.2. Carbon Isotope Stratigraphy

2.2.1. Sampling Methods

We collected bulk rock hand samples at 25 to 100 cm intervals from the Little Sheep and Himes members at CCC and CLC. To access fresh rock we removed surficial weathered surface material using hand tools (small picks and shovels).

2.2.2. Sample Preparation

Samples were prepared at the University of Arkansas Stable Isotope Laboratory (UASIL) and the NSF-Keck Paleoenvironment and Stable Isotope Laboratory (KPESIL) at the University of Kansas. We powdered the samples using mortar and pestle. Samples were then treated with 0.5 M hydrochloric acid to remove carbonate. Samples were rinsed, dried, and weighed into tin capsules.

2.2.2. Isotope Ratio Mass Spectrometry

Mass of weighed samples varied from ~ 1-10mg depending on color as a proxy for total organic carbon (TOC) by weight. Target sample weights by color were determined through pilot analyses. Sample analysis occurred at the University of Arkansas Stable Isotope Lab and combusted via IsoLink Elemental Analyzer coupled to a Delta V Plus isotope ratio mass spectrometer. Values were corrected to the VPBD scale using internal and international standards (sandy soil, White River trout, corn maize, benzoic acid, ANU sucrose). Reproducibility was reported at s = 0.18 ‰.

2.2.3. Chemostratigraphic Correlation

We used a combination of manual correlation (i.e. “wiggle-matching”) and quantitative correlation methods. We used our geochronological age models to predict the age of each sample and plotted our carbon isotope data against stratigraphic height and then against age. We compared d13C-depth curves and d13C-age curves between the Crooked Creek and Cody Landfill section.

We then used XYZ statistical method to explore for correlations. CHATGPT recommended these statistical methods, helped generate the R code, and helped with interpretation of the results. This can be reproduced using the script “script\_name.R” in the R Project “Cloverly\_chemostrat.Rproj” in Supplementary file XYZ.

3. Results

3.1. Lithofacies Characterization

Take the detailed facies description and interpretation from your paleoclimate manuscript and introduce it first here

The Cody Landfill and Crooked Creek sections expose a succession of fluvial and overbank deposits that include channel sandstones, crevasse splay sandstones, and fine-grained overbank mudstones and siltstones. Channel sandstones, equivalent to Ostrom’s (1970) “Unit VI,” are present only at Crooked Creek near the base of the Himes Member. These thick, massive sands contain ripples and mud rip-up clasts near their base. In contrast, crevasse splay sandstones—thin (<2 m), upward-fining beds locally cemented with carbonate—occur in both the Little Sheep and Himes Members at both sites.

The fine-grained overbank deposits include both pedogenically altered and unaltered facies. Non-pedogenic laminated silts and muds in the upper Himes likely represent paralic environments and contain plant debris, leaves, and charcoal. Pedogenic facies are further subdivided into well-drained (red-purple) and poorly drained (drab) paleosols, with both showing evidence of bioturbation and shrink-swell (vertic) features. At Cody, carbonates occur primarily in well-drained paleosols and include aquatic fossils; at Crooked Creek, carbonates are less common and occur in one interval of poorly drained paleosols in the Little Sheep Member. Ostracods were identified in this interval at both sites. While some of these deposits may reflect shallow lacustrine or palustrine conditions (cf. Orchard, 2024), the scarcity of sedimentary structures and diagnostic minerals such as chalcedony or gypsum makes such interpretations tentative.

3.1. LA-CIP-MS

3.2. CA-TIMS

3.3 Depth-Age Models

3.4 Bulk Organic Carbon IRMS

3.5 Chemostratigraphic Correlation Analyses

4. Discussion

4.1. Interpretation and key findings

Based on our depth-age models derived from zircon geochronology, the Crooked Creek and Cody Landfill sections are largely diachronous. Out of the whole 30 Ma that Cloverly deposition seems to record, only about 1.5 Ma of overlap occurs between these two sections. Most of the mudstone interval of the Cloverly seems to have been deposited over a relatively short amount of time (<<10 Ma). But

4.2 Implications for Cloverly chronostratigraphy

The upper Little Sheep Member is likely Albian in age throughout the basin, while the lower Little Sheep appears to be older in some parts of the basin and is likely separated from the upper interval by a local unconformity. New zircon geochronology from the western flank of the Horse Center Anticline supports the interpretation of a significant unconformity (~120–112 Ma) approximately 14 meters above the Pryor Conglomerate at HCA as suggested by previous data from the Cody Landfill site (D’Emic et al., 2019). We are unable to recognize a lithostratigraphic indication of a significant erosional unconformity or extensive (105-107 years) period of non-deposition. There is no unconformable, sharp contact, and there is no notable change in the degree of pedogenesis expected to accompany a landscape that is stable for millions of years. Still, the geochronological evidence for a hiatus here is robust. The Himes Member is also likely entirely Albian, with no evidence supporting the presence of Cenomanian deposits within the Cloverly Formation as suspected by D’Emic et al. (2009).

High-resolution, correlative carbon isotope records from key fossil-bearing sections of the Cloverly Formation have the potential to establish a high-precision spatiotemporal framework for fossil occurrences and paleoenvironmental records, which is essential for detailed paleoecological reconstruction. However, our results do not support the use of carbon isotope stratigraphy for this purpose in the Cloverly. Local heterogeneity in depositional and environmental conditions appears to have overwhelmed any regional or global influence on the carbon isotope composition of soil organic matter. This interpretation assumes that our geochronology-based age models are as accurate and precise as reported. While we observe a possible carbon isotope excursion in both the Crooked Creek and Cody Landfill sections, our age models indicate that these strata are diachronous. It remains possible that other sections in the Cloverly better capture regional or global signals and may eventually support broader application of carbon isotope stratigraphy, but our current results do not.

4.3 Implications for carbon isotope stratigraphy of the mid-Cretaceous Western Interior

Previous works have found that carbon isotopes of ancient soil organic matter are potentially subject to processes that confound the use of carbon isotope stratigraphy as a high-precision, broadly applicable, correlative tool (Baczinsky et al., 2013?; others!). Among the factors that may influence the Cloverly carbon isotope compositions are reworking of older, allochtonous organic carbon into younger deposits, mixing carbon pools and changing the mean d13C of organic carbon in the floodplain deposits. This reworking is a likely possibility in the Cloverly, given the evidence that the Cloverly mudstones were deposited during a low-accommodation systems tract where erosion and sediment bypass are the predominant processes (Foreman et al.., 2022; this study). Another key local influence likely at play in the Cloverly floodplain paleosols is variation in soil drainage and therefore microbial respiration (Baczinsky et al., 2013?; others!).

If these factors affect the Cloverly paleosols, we should be careful to interpret carbon isotopes in other mid-Cretaceous paleosols, especially if they are thought to have formed under low-accommodation settings. Here I should really comment on which stratigraphic units, and even which carbon isotope studies, should be reconsidered considering carbon isotope stratigraphy.

4.4 Implications for terrestrial carbon isotope stratigraphy as a chronostratigraphic tool

Well, I guess my main thoughts here are that based on (Baczinsky et al., 2013?; others!)and our data here, you really need substantial CIE’s to overwhelm local carbon variations in floodplain paleosols. If your section doesn’t happen to encompass such an interval that has significant CIE’s, you might not be able to resolve regional or global signals in your floodplain paleosol records. And, as I suggested above, maybe this is particularly a concern in heterogeneous landscapes and in nonmarine low-accommodation systems tracts.

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

5. Conclusions

This section is not mandatory but can be added to the manuscript if the discussion is unusually long or complex.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/doi/s1, Figure S1: title; Table S1: title; Video S1: title.

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**Funding:**

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Abbreviations

The following abbreviations are used in this manuscript:

|  |  |
| --- | --- |
| MDPI | Multidisciplinary Digital Publishing Institute |
| DOAJ | Directory of open access journals |
| TLA | Three letter acronym |
| LD | Linear dichroism |

Appendix A

Appendix A.1

The appendix is an optional section that can contain details and data supplemental to the main text—for example, explanations of experimental details that would disrupt the flow of the main text but nonetheless remain crucial to understanding and reproducing the research shown; figures of replicates for experiments of which representative data is shown in the main text can be added here if brief, or as Supplementary data. Mathematical proofs of results not central to the paper can be added as an appendix.

**Table A1.** This is a table caption.

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| **Title 1** | **Title 2** | **Title 3** |
| entry 1 | data | data |
| entry 2 | data | data |

Appendix B

All appendix sections must be cited in the main text. In the appendices, Figures, Tables, etc. should be labeled starting with “A”—e.g., Figure A1, Figure A2, etc.

References

References must be numbered in order of appearance in the text (including citations in tables and legends) and listed individually at the end of the manuscript. We recommend preparing the references with a bibliography software package, such as EndNote, ReferenceManager or Zotero to avoid typing mistakes and duplicated references. Include the digital object identifier (DOI) for all references where available.

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2. Author 1, A.; Author 2, B. Title of the chapter. In *Book Title*, 2nd ed.; Editor 1, A., Editor 2, B., Eds.; Publisher: Publisher Location, Country, 2007; Volume 3, pp. 154–196.
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THIS WAS CUT FROM SECTION 3:

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All figures and tables should be cited in the main text as Figure 1, Table 1, etc.

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AI-generated content may be incorrect.**

**Figure 1.** This is a figure. Schemes follow the same formatting.

**Table 1.** This is a table. Tables should be placed in the main text near to the first time they are cited.

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| **Title 1** | **Title 2** | **Title 3** |
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| entry 2 | data | data 1 |

1 Tables may have a footer.

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| (**a**) | (**b**) |

**Figure 2.** This is a figure. Schemes follow another format. If there are multiple panels, they should be listed as: (**a**) Description of what is contained in the first panel; (**b**) Description of what is contained in the second panel. Figures should be placed in the main text near to the first time they are cited.

**Table 2.** This is a table. Tables should be placed in the main text near to the first time they are cited.

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This is example 1 of an equation:

|  |  |
| --- | --- |
| a = 1, | (1) |

the text following an equation need not be a new paragraph. Please punctuate equations as regular text.

This is example 2 of an equation:

|  |  |
| --- | --- |
| a = b + c + d + e + f + g + h + i + j + k + l + m + n + o + p + q + r + s + t + u + v + w + x + y + z | (2) |

the text following an equation need not be a new paragraph. Please punctuate equations as regular text.

Theorem-type environments (including propositions, lemmas, corollaries etc.) can be formatted as follows:

**Theorem 1.** Example text of a theorem. Theorems, propositions, lemmas, etc. should be numbered sequentially (i.e., Proposition 2 follows Theorem 1). Examples or Remarks use the same formatting, but should be numbered separately, so a document may contain Theorem 1, Remark 1 and Example 1.

The text continues here. Proofs must be formatted as follows:

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The text continues here.