**Chronostratigraphy of the mid-Cretaceous Cloverly Formation**

**Abstract**

The mid-Cretaceous was a time of major evolutionary, biogeographic, and climatic change in the continental realm of North America.

**1 Introduction**

*\*\* 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? \*\**

## **2. Background**

### **2.1 Tectonic Setting**

The Cloverly Formation is a series of fluviolacustrine deposits in the Western Interior Basin (WIB). The WIB was a retroarc foreland basin formed east of the Sevier Thrust Belt, which developed as the Farallon plate began to subduct beneath the North American plate during the Late Jurassic and continued into the Late Cretaceous (CITE). WIB Jurassic nonmarine deposits (i.e. Morrison Formation) are often separated from overlying Cretaceous deposits by a major unconformity. Overlying Cretaceous deposits thin eastward, reflecting classic retroarc foreland basin geometry (CITE).

**2.2 Stratigraphic Context**

in the Bighorn and Wind River Basins in northwestern Wyoming and southeastern Montana that have been dated to the mid-Cretaceous (Fig. 1). Like other Lower Cretaceous nonmarine WIB deposits, the Cloverly’s stratigraphy is spatially complex (D’Emic et al., 2019; Ostrom, 1970). The Cloverly overlies the nonmarine Late Jurassic Morrison Formation and is overlain by the marginal marine Sykes Mountain Formation (D’Emic et al., 2019; Moberly, 1960; Ostrom, 1970). A major unconformity separates the Cloverly from the underlying Late Jurassic deposits across much of its area. Resumption of Sevier orogenesis to the west is recorded in the Cloverly as basal conglomerates shed from the Sevier highlands and deposited by broad east-flowing braided river networks. These conglomerates interfinger with and underlie fine-grained deposits comprised mostly of bentonitic mudstones with interspersed channel sands. Lower Cloverly mudstones are generally more smectite-rich and chromatic than mudstones in the upper part of the formation. Moberly (1960) proposed three formal stratigraphic members based on the differences between the three intervals. These are the Pryor Conglomerate, Little Sheep Mudstone, and Himes Mudstone Members, in order of deposition. Ostrom (1970) also recognized this general pattern across the Bighorn Basin but proposed an alternative nomenclature that included the Jurassic Morrison Formation, four units within the Cloverly Formation, and the Sykes Mountain Formation. These two frameworks are generally similar, differing only in that Ostrom (1970) formally recognized a sand body (“Unit VI”) which is present at some sites. Subsequent studies of the Cloverly have primarily used these two stratigraphic nomenclatures (Fig. 2). D’Emic et al. (2019) proposed a facies-based stratigraphic model which integrates the observations of Moberly (1960) and Ostrom (1970) (Fig. 2). This model recognizes Moberly’s (1960) formal members but also addresses the spatial variability within the members. D’Emic et al. (2019) propose that sand bodies occurring in the Little Sheep and Himes intervals represent isolated channel deposits. This model implies that a channel sand near the Little Sheep and Himes boundary at any given locality is asynchronous with channel sands occurring near the boundary at other sites. Historically, Cloverly fossil localities have been reported from Ostrom’s (1970) Units V, VI, and VII, which generally correspond with the Little Sheep Mudstone and Himes Mudstone intervals (D’Emic et al., 2019). D’Emic et al., (2019) suggested that “Unit VI” sands are not necessarily directly age-equivalent to “Unit VI” sands at other sites. This interpretation also implies that a unit VII mudstone may interfinger and stratigraphically underly a unit VI sand in some instances. Discordant but similar radiometric dates reported from “Unit VI” sands at different sites in the Bighorn Basin support this (Carrano et al., 2022; D’Emic et al., 2019).

**3 Materials and Methods**

**3.1 Zircon U/Pb Geochronology**

* + - Sites and Sampling Methods
    - Mineral Separation
    - CA-TIMS analysis
    - LA-ICP-MS analysis

**3.2 Carbon Isotope Chemostratigraphy**

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). 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. 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 ‰.

**3.3 Age Modeling**

**4 Results**

**4.1 Lithofacies Characterization**

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. For a detailed facies description and interpretation, see Allen et al. (2025).

**4.2 LA-ICP-MS**

**4.3 CA-TIMS**

**4.4 d13Corg via IRMS**

At Crooked Creek, bulk organic matter carbon isotope values (δ13CBOM) range from –30.1‰ to –21.0‰, with an average of –23.97‰. The curve was divided into seven intervals based on consistent trends in the smoothed, three-point average data. The lowest interval exhibits a positive carbon isotope excursion (PCIE) beginning in the Pryor Conglomerate and peaking in the lower Little Sheep Member at –20.88‰ near 15 m. This is followed by a gradual negative shift to –26.41‰ at 20.25 m, then a rapid rebound to –22.9‰ by 20.5 m. A sustained positive trend follows, with values averaging –23.25‰ over a 7.5 m interval. This is succeeded by a pronounced negative excursion reaching –27.48‰ at 33.5 m in the lower Himes Member (Unit VI), followed by a positive excursion that peaks at –23.32‰ at 36.55 m, primarily within the bone bed of Unit VI. Above this, δ13CBOM values in the upper Himes Member (Unit VII) show a more gradual positive trend, punctuated by alternating negative shifts, continuing into the overlying Sykes Mountain Formation.

At Cody Landfill, δ13CBOM values range from –28.2‰ to –22.6‰, with an average of –25.6‰. The first ~10 m above the Pryor Conglomerate–Little Sheep contact was not sampled due to surface cover, and six intervals were identified in the remaining section. The first sampled interval records a gradual ~3‰ positive shift from ~–28‰ to ~–25‰ between ~11.5 m and ~25 m. This is followed by a ~2‰ decline to ~–27‰ near 24 m, and then a more complex interval marked by a sharp increase of ~2‰, a rapid drop of ~3‰, and a rebound of ~4‰, with values exceeding –24‰ by 30 m. A ~7 m sampling gap follows. Above the gap, values decrease from ~–24.5‰ to ~–26.5‰ between ~37 m and ~40 m, followed by another gap extending to ~51 m. In the upper part of the section, values rise from ~–26.5‰ to ~–24‰ and then fall back to ~–26.5‰ by ~62 m, defining a well-resolved feature in the upper Himes Member. Above this point, values fluctuate between –24‰ and –26‰ with no clear trend, ending below the Rusty Beds sandstone unit of the Sykes Mountain Formation. A single sample from the top of that unit yielded a value of –26.5‰.

**5 Discussion**

* 1. **Key Findings**

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). The Himes Member is also likely entirely Albian, with no evidence supporting the presence of Cenomanian deposits within the Cloverly Formation. Chemostratigraphy shows promise as a tool for high-resolution chronostratigraphic correlation in the upper Little Sheep and Himes Members, though further data are needed. Notably, the Cloverly record does not contain major carbon isotope excursions associated with Oceanic Anoxic Events (OAEs).

**5.2 Interpretation**

* + 1. **Tectonostratigraphic Framework**

The Cloverly Formation records a tectonically driven sequence of nonmarine systems tracts that reflect the progressive eastward migration of the Sevier forebulge. Stratigraphically, the succession transitions from a low-accommodation systems tract (LAST) to a high-accommodation systems tract (HAST), and finally to a transgressive systems tract (TST) (Orchard, 2024). The initial LAST is indicated by erosion or nondeposition across the Jurassic–Cretaceous boundary, coarse amalgamated channel deposits of the Pryor Conglomerate, and Aptian-aged, well-developed, well-drained paleosols in the lower Little Sheep Mudstone. These features are consistent with forebulge passage, which typically generates stratigraphic omission, enhanced drainage, and sediment bypass (CITE). The subsequent shift to poorly drained, moderately developed paleosols in the upper Little Sheep marks the onset of HAST as the region transitioned into the foredeep. Continued subsidence led to the development of a TST within the Himes Member, culminating in marginal marine deposition as the Skull Creek Seaway advanced into the basin.

* + 1. **Facies Variability and Autocyclic Overprinting**

The inferred presence of LAST deposits in the lowermost Little Sheep seemingly contrasts with Orchard’s (2024) recognition of a HAST–LAST–LST/TST succession. This might be because Orchard (2024) did not study sections from the western margin of the basin where we have observed older LAST deposits which seem to be absent on the eastern margin of the basin. The lower LSM at HCA may therefore record a regional Aptian LAST associated with tectonic uplift and base-level fall during forebulge arrival. As the basin transitioned into the foredeep, subsidence and increased accommodation produced HAST conditions (e.g., immature, poorly drained paleosols), followed by a TST as marine influence from the Skull Creek Seaway advanced. A secondary LAST near the LSM–Himes boundary, as identified by Orchard, deviates from the broader tectonic pattern. We interpret this interval as the result of autocyclic processes, such as fluvial reorganization or increased sediment supply driven by regional hydroclimate change. These changes may have sharply increased runoff and sediment flux, temporarily raising the sedimentation-to-accommodation ratio (S/A > 1), even as tectonic subsidence continued. Alternatively, the correlation between lithofacies, paleoclimate proxies, and the carbon isotope excursion at the LSM/Himes transition may reflect a broader climatic signal. The excursion coincides with anomalous facies patterns and geochemical evidence for a shift to wetter, warmer conditions. This convergence of evidence suggests potential links between global carbon cycle perturbation, regional climate change, and the stratigraphic architecture of the Little Sheep and Himes Members.

* + 1. **Comparison with Previous Work**

Our results provide several important comparisons with previous studies. First, our new geochronologic and chemostratigraphic data suggest that the proposal by D’Emic et al. (2019) that local nonmarine deposition in the Cloverly Formation extended into the Cenomanian is unlikely. Second, our new 120 Ma U-Pb zircon date from the West Flank Horse Center Anticline (WFHCA) corroborates D’Emic’s earlier 125 Ma date, providing strong support for the presence of an Aptian-aged wedge of deposits in the lower Little Sheep Mudstone (LSM) at Horse Center Anticline. Third, our 111.6 ± 0.06 Ma date from an ash bed at the Cloverly type section, combined with Carrano et al.’s matching dates from the same tuff at multiple Shell area localities, D’Emic’s 109 Ma date from the Cody Landfill, and our 110 ± 0.05 Ma date from Crooked Creek, collectively indicate that stratigraphic preservation across the basin improved significantly by ~111 Ma. This provides a reasonable chronostratigraphic marker for the transition from a low-accommodation systems tract (LAST) to a high-accommodation systems tract (HAST), interpreted as the onset of regional foredeep subsidence. Additionally, we find that several lithologic features commonly used to infer stratigraphic position—such as the presence or absence of gastroliths, chalcedony nodules, and carbonate development—are inconsistently distributed across measured sections and are not confined to specific members, in contrast to Ostrom’s (1970) earlier generalizations.

More detailed comparisons highlight key discrepancies and agreements. At Crooked Creek, our new dates (~109 Ma ± <1 Ma) disagree strongly with D’Emic’s 103 Ma date from the base of the Himes Member; we interpret this discrepancy as likely resulting from Pb loss or analytical artifact and suggest that D’Emic’s 103 Ma date does not represent a crystallization age. At the Cody Landfill site, D’Emic’s 107 ± 1.3 Ma date from the top of the LSM falls between his own dates from deeper in the LSM (109.9 ± 1.1 Ma and 124.06 ± 0.12 Ma) and our new 106.5 ± 0.08 Ma date from the top of the Himes, supporting a younging-upward trend consistent with our broader chronostratigraphic framework. Carrano et al. dated what appears to be the same tuff as our type section sample, with results suggesting ~111 ± <1 Ma; our high-precision 111.6 Ma date closely aligns with these, further reinforcing that the middle LSM near the type section is Albian in age.

Comparison with Orchard’s sequence stratigraphic framework in the northeastern Bighorn Basin yields further insight. If the unconformities (UC-1 and UC-2) identified by Orchard are present at Crooked Creek, our geochronology suggests they likely represent relatively minor temporal gaps on the order of ~10^4 years. This implies that such unconformities, while potentially lithologically conspicuous, may be relatively insignificant chronostratigraphically, at least in some parts of the basin. However, the lower LSM on the western side of the basin (e.g., HCA) appears to record a much larger paraconformity, possibly representing 6–8 million years of missing section.

Finally, earlier work by May et al. (1995) and Swierc (1990) offers additional regional context. Fission-track dating of zircons from tuff beds in the Wind River Basin yielded ages of 125–128 Ma, suggesting a correlation between the mudstone interval there and the upper LSM in the Bighorn Basin. Additional fission-track ages from the Bighorn Basin LSM indicate significant pyroclastic activity between 118–128 Ma, with notable events at ~120 and ~127 Ma. Swierc’s correlation of a long magnetic reversal in the LSM to the M3 reversal zone of the Global Magnetic Polarity Scale supports a model in which the base of the LSM is ~128 Ma and the top is ~116 Ma, broadly consistent with our radiometric data.

* + 1. **Limitations and Uncertainty**

Geochronologic and chemostratigraphic sampling of the Cloverly Formation remains incomplete. The current stratigraphic sampling resolution of zircons at Crooked Creek cannot detect evidence of unconformities within the Himes interval predicted by Orchard’s (2024) interpretation. Higher resolution zircon data or multiple high-resolution chemostratigraphic profiles from the Crooked Creek area will likely be needed to test for the presence of these unconformities. The Cody Landfill chemostratigraphic profile is limited by sampling gaps, confounding comparison with the higher resolution Crooked Creek profile. Given the stratigraphic complexity of the Cloverly, additional high-resolution chemostratigraphic profiles from a network of sites in across the Cloverly will be needed to confidently identify chemostratigraphic markers.

* + 1. **Broader Implications and Future Directions**

Our findings highlight a significant reinterpretation of the temporal context of Cloverly fossil assemblages. Contrary to some earlier assumptions, most Cloverly vertebrate fossils are not contemporaneous with those from the Cedar Mountain, Antlers, or Arundel formations. However, a subset of localities from the lower Little Sheep Mudstone may preserve Aptian-aged deposits, potentially aligning them temporally with certain fossil sites from the Ruby Ranch Member of the Cedar Mountain Formation. To further test and refine this framework, additional research is needed. Expanding the sequence stratigraphic framework across the basin, developing more chemostratigraphic profiles to assess correlatability, and generating a broader set of LA-ICP-MS zircon dates from multiple stratigraphic sections would provide crucial data for reconstructing the basin’s depositional and tectonic evolution.

**6 Conclusions**