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Did sea level change drive carbon isotopic trends in the Madison Shelf? Sequence stratigraphy and carbon isotopes in the Mississippian Lodgepole Formation of southwest Montana

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A R T I C L E I N F O

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A B S T R A C T

The Lower Mississippian Lodgepole Formation of Montana and Wyoming records one of the largest positive carbon isotopic excursions of the Phanerozoic. This globally recognized up to 7‰ increase in $\delta^{13}C_{carb}$ values occurs across the North American Kinderhookian-Osagean boundary (referred to as the K—O excursion). It has been argued to reflect significant organic carbon burial, possibly linked to the onset of the Late Paleozoic Ice Age. Previously proposed correlations between carbon isotopic patterns and the sequence stratigraphic framework within these strata suggests that changes in sea level could have played a significant role in the expression and/or magnitude of the K—O excursion in the Madison Shelf. This study explores the relationship between carbon isotopic values and sea level change at multiple scales. To accomplish this, we provide a comprehensive overview of the sedimentological and stratigraphic framework and address uncertainty about the number of sequences in the Lodgepole Formation. Our results support a three-sequence model for the Lodgepole Formation. Based on the number of sequences and the placement of sequence stratigraphic surfaces, we see little evidence of statistically significant correlation between carbon isotopic trends and the sequence stratigraphic framework. We argue that sea level change was not the primary driving mechanism for carbon isotopic trends in the Madison Shelf, nor the K—O excursion. Instead, we support models that invoke global ocean anoxia and/or destabilization of the global carbon cycle due to land plants.

1. Introduction

Globally-recognized, positive carbon isotopic excursions in marine carbonates are important because they are interpreted to reflect significant perturbations to the global carbon cycle. In particular, such excursions are thought to reflect changes in the flux of carbon between the atmosphere-ocean system and the sedimentary reservoir due to the net burial of organic carbon (Kump and Arthur, 1999; Cramer and Jarvis, 2020). Change in relative sea level is one, among many, potential drivers of organic carbon burial and therefore the generation of positive carbon isotopic excursions (e.g. Föllmi et al., 1994; Jenkyns, 1996; Burdige, 2005; Jarvis et al., 2006; Anisaar et al., 2010; Eltom et al., 2018). As sea level rises, the surface area for photosynthesis increases and upwelling provides nutrients that fuel primary productivity and the burial of organic carbon. As sea level falls, these processes work in reverse. The result is increasing carbon isotopic values during transgression and decreasing carbon isotopic values during regression. This effect on carbon isotopic trends can be amplified by local/regional influences like freshwater input, terrestrial carbon sources, and even changes in carbonate deposition/weathering as sea level changes the position of shoreline and/or basin restriction (Immenhauser et al., 2003; Panchuk et al., 2005; Melchin and Holmden, 2006; Fanton and Holmden, 2007; Swart, 2008; Schrag et al., 2013).

The Lower Mississippian Madison Group of Montana and Wyoming (subdivided into the Kinderhookian-Oseagean Lodgepole Formation and the Osagean-Meramecian Mission Canyon Formation; Fig. 1) records a series of positive carbon isotopic excursions that have been linked to changes in relative sea level (Katz et al., 2007). Rising limbs of these positive carbon isotopic excursions were assigned to the transgressive systems tracts and the falling limbs were assigned to the highstand

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systems tract of 3rd-order sequences in the Madison Group. This observation suggests that sea level, with its control on basin restriction, nutrient availability, and surface area for primary productivity, likely played a significant role in the generation of these carbon isotopic excursions (Katz et al., 2007). Of these excursions, the up to 7‰ excursion at the Kinderhookian-Osagean Boundary in the Lodgepole Formation (hereafter referred to as the K—O carbon isotopic excursion; also referred to as the TICE – Tournaisian Carbon Isotope Excursion) is globally recognized (e.g. North America, Europe, China) and one of the most significant positive carbon isotopic excursions of the Phanerozoic (Saltzman et al., 2000; Saltzman, 2002; Yao et al., 2015; Liu et al., 2019; Cheng et al., 2020).

The suggestion that relative sea level change in the Madison Shelf might have influenced the expression and/or magnitude of the K—O excursion in this basin has implications about the significance of sea level's influence on carbon isotopic trends. These implications deserve further explanation, particularly because there are two complications associated with previous interpretations that relative sea level was the primary driver of carbon isotopic trends in the Madison Group. Firstly, there is not a universally accepted sequence stratigraphic framework for the Lodgepole Formation. Within this unit, some authors recognize two sequences (Sonnenfeld, 1996; Smith et al., 2004; Oehlert et al., 2019) and others recognize three (Elrick and Read, 1991; Katz et al., 2007; Wallace and Elrick, 2014). The number of sequences and placement of sequence stratigraphic surfaces has profound implications for interpreting the relationship between carbon isotopic trends and changes in relative sea level. Secondly, in a recent study of many of the same sections as Katz et al. (2007), Oehlert et al. (2019) used paired carbonate and organic carbon isotopic results from the Madison Group to test the relationship between relative sea level and organic carbon burial. They suggest that a rise in relative sea level did not drive carbon isotopic excursions in the Madison group, and instead argue that the K—O excursion was solely a function of the destabilization of the global carbon cycle due to the proliferation of land plants (Oehlert et al., 2019).

In this study we address uncertainties about the sequence stratigraphy of the Lodgepole Formation and test the relationship between carbon isotopic trends and relative sea level in the Madison Group. We created detailed measured sections for five study locations (Fig. 2). We generated high-resolution carbon isotopic curves that are integrated with our sedimentological and sequence stratigraphic framework so that, if present, we could identify isotopic changes at the parasequence, systems tract, and/or sequence levels. We use a statistical test to provide quantitative measures of the relationship between our detailed carbon isotopic curves and the sequence stratigraphic framework.

2. Geologic background

The Madison Group is a thick package of limestone and dolomite deposited in an extensive paleoequatorial platform that extended across large parts of Idaho, Montana, North Dakota, Saskatchewan, South Dakota, and Wyoming during the Early Mississippian. Broadly correlative carbonates extend considerably further south and east and cover much of the western half of North America. We focus on strata deposited on the "Madison Shelf", an area bounded by the Williston Basin to the northeast, the Central Montana Trough to the north, the Antler Highlands to the west and the topographic high of the Transcontinental Arch to the southeast (Sando, 1976).

2.1. Sedimentology and stratigraphy

In this paper we adopt the lithostratigraphic nomenclature used by Sandberg and Klapper (1967), Sando (1972), Smith (1972), and Sando and Dutro Jr (1974) (Fig. 1). The Madison Group represents an unconformity-bounded second-order supersequence; the basal angular unconformity can be traced throughout much of the northern Rocky Mountains and likely developed in association with the Antler Orogeny (Sandberg and Klapper, 1967; Sonnenfeld, 1996). In the study area, the Lodgepole Formation unconformably overlies strata of the Devonian Three Forks Formation. Locally, the basal Lodgepole Formation is represented by the largely clastic/dolomite facies of the Cottonwood Canyon Member (Sandberg and Klapper, 1967; Smith, 1972). Strata of the Lodgepole Formation examined in this study are assigned to the Paine Shale Member or the overlying Woodhurst Member. The Paine Shale Member is dominated by lime mudstone, shale, skeletal

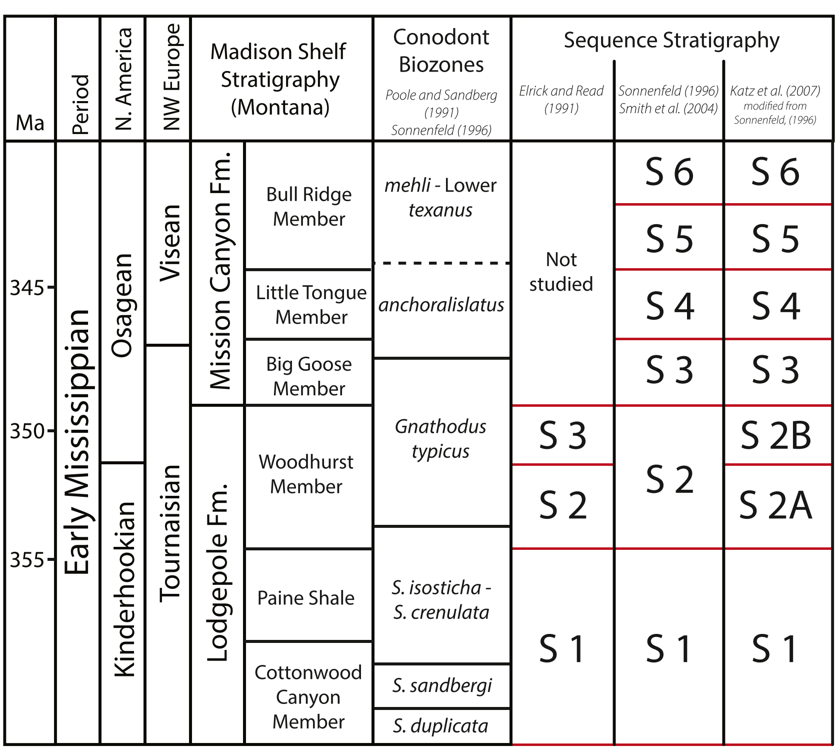


Fig. 1. Lithostratigraphy, biostratigraphy, and sequence stratigraphy of the Madison Group in southwestern Montana. The placement of member boundaries is modified from Sonnenfeld (1996) and is approximate as the contact between these lithostratigraphic units is time-transgressive across the Madison Shelf. Absolute ages are modified from Richards (2013). Sequence stratigraphic nomenclature includes terminology used in this study and an overview of the two-sequence (Sonnenfeld, 1996) and three-sequence (Elrick, 1990; Elrick and Read, 1991) models for the Lodgepole Formation. Conodont biozones are from Poole and Sandberg (1991) and approximate placement is modified from Sonnenfeld (1996).

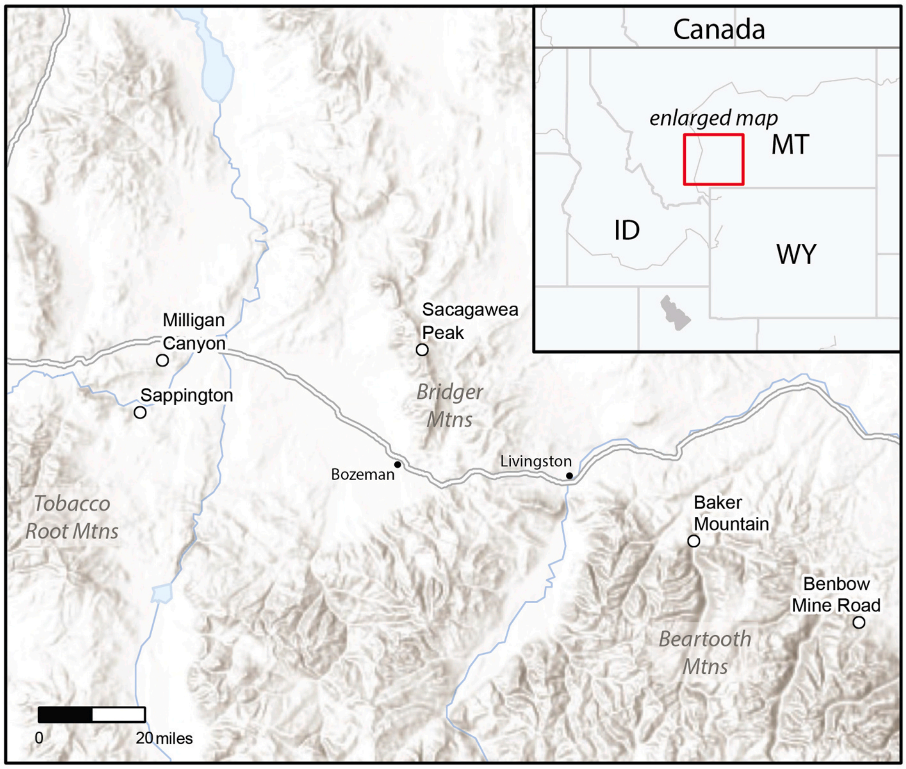


Fig. 2. Map showing the location of the Benbow Mine Road, Milligan Canyon, Baker Mountain, Sappington, and Sacagawea Peak sections.

wackestone, and subordinate amounts of skeletal to peloidal packstone and grainstone (Sando and Dutro Jr, 1974; Sonnenfeld, 1996). These facies record deposition largely in shoreface to outer ramp water depths (Elrick and Read, 1991; Sonnenfeld, 1996). The overlying Woodhurst Member consists of stacked shallowing upward successions that can include almost the entire spectrum of facies and water depths shown in Fig. 3. Although strata of the Mission Canyon Formation represent an equally diverse spectrum of facies, relatively shallow water peloidal/finely skeletal grainstones and laminated lime mudstones make up a higher percentage of this unit (Reid and Dorobek, 1993; Sonnenfeld, 1996). Dolomitization in the Madison Group is highly variable and may be influenced by lithology/fabric, paleogeographic position, and/or position within depositional sequences (Smith et al., 2004).

Cyclicity has long been recognized within the Madison Group (Laudon and Severson, 1953; Andrichuk, 1955; Smith, 1972; Sando and Dutro Jr, 1974; and Smith, 1977). Modern sedimentological and sequence stratigraphic studies variously advocate for either a two (Sonnenfeld, 1996; Buoniconti, 2008) or three (Elrick, 1990; Elrick and Read, 1991; Wallace, 2011; Wallace and Elrick, 2014) sequence model for the Lodgepole Formation in southwest Montana (Fig. 1). For clarity, we adopt the nomenclature of Katz et al. (2007) and Katz (2008) where the Lodgepole Formation contains sequences 1 (oldest), 2A, and 2B (youngest) and Mission Canyon Formation contains sequences 3 (oldest), 4, 5, and 6 (youngest). Previous studies largely agree on the placement of the boundary between sequences 1 and 2A near the contact of the Paine and Woodhurst Members. However, none of the sequence stratigraphic publications nor the geochemical studies built upon them adequately discuss the disagreement about whether the Woodhurst Member contain one or two depositional sequences.

2.2. Study sections

For this study we focused on five sections in Montana: Benbow Mine Road (N45.37669°, W 109.77188°), Milligan Canyon (N 45.87831°, W 111.68111°), Baker Mountain (N45.5331°, W 110.2219°), Sappington (N 45.77791°, W 111.74519°; note this section is on private property), and Sacagawea Peak (N49.89984°, W110.96972°) sections (Fig. 2; coordinates are for the base of each section). Keys for the measured sections are provided in Fig. 4, summary measured sections are provided in Figs. 5-9, and detailed measured sections are provided in the supplemental materials.

2.3. Carbon isotopes and the Madison Group

Several studies have documented carbonate carbon isotopic trends in the Madison Group (Saltzman, 2003; Smith et al., 2004; Katz et al., 2007; Buoniconti, 2008; Oehlert et al., 2019). Saltzman (2003) identified the K—O carbon isotopic excursion in the Lodgepole Formation at two sections not included in this study. Smith et al. (2004) reported carbon isotopic results from dolomites in the Lodgepole Formation, but that study was focused on constraining diagenetic processes. The most comprehensive record of carbon isotopic trends in the Madison Group comes from Katz et al. (2007). That study reported carbon isotopic records for the Lodgepole and Mission Canyon Formation from seven sections in Montana and Wyoming (including the Sacagawea Peak and Benbow Mine Road sections also described herein). As discussed above, Katz et al. (2007) use their data set to argue that relative sea level change was driving the carbon isotopic patterns.

3. Methods

3.1. Sedimentology and sequence stratigraphy

Each of our sections was measured and described in detail (see supplemental materials file); field observations were supplemented by petrographic analysis of 98 thin sections. Our facies analysis is built upon a modified version of Sonnenfeld (1996)'s regional scheme. Facies analysis was used to identify parasequences which, in turn, were used to identify important sequence stratigraphic surfaces, systems tracts, and sequences. Summary measured sections with facies associations and

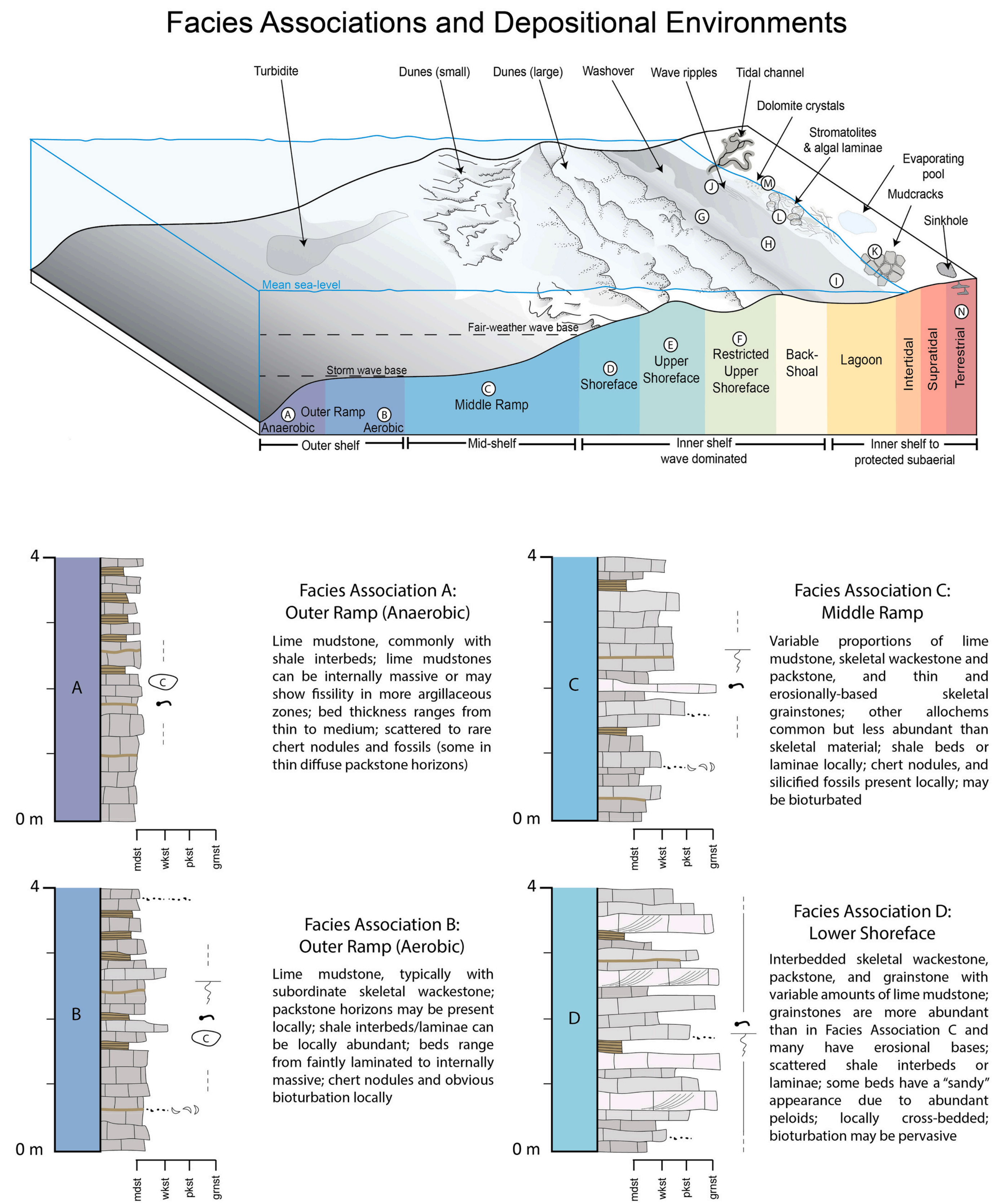


Fig. 3. Summary of the facies associations and depositional environments recognized in this study (modified from Sonnenfeld, 1996).

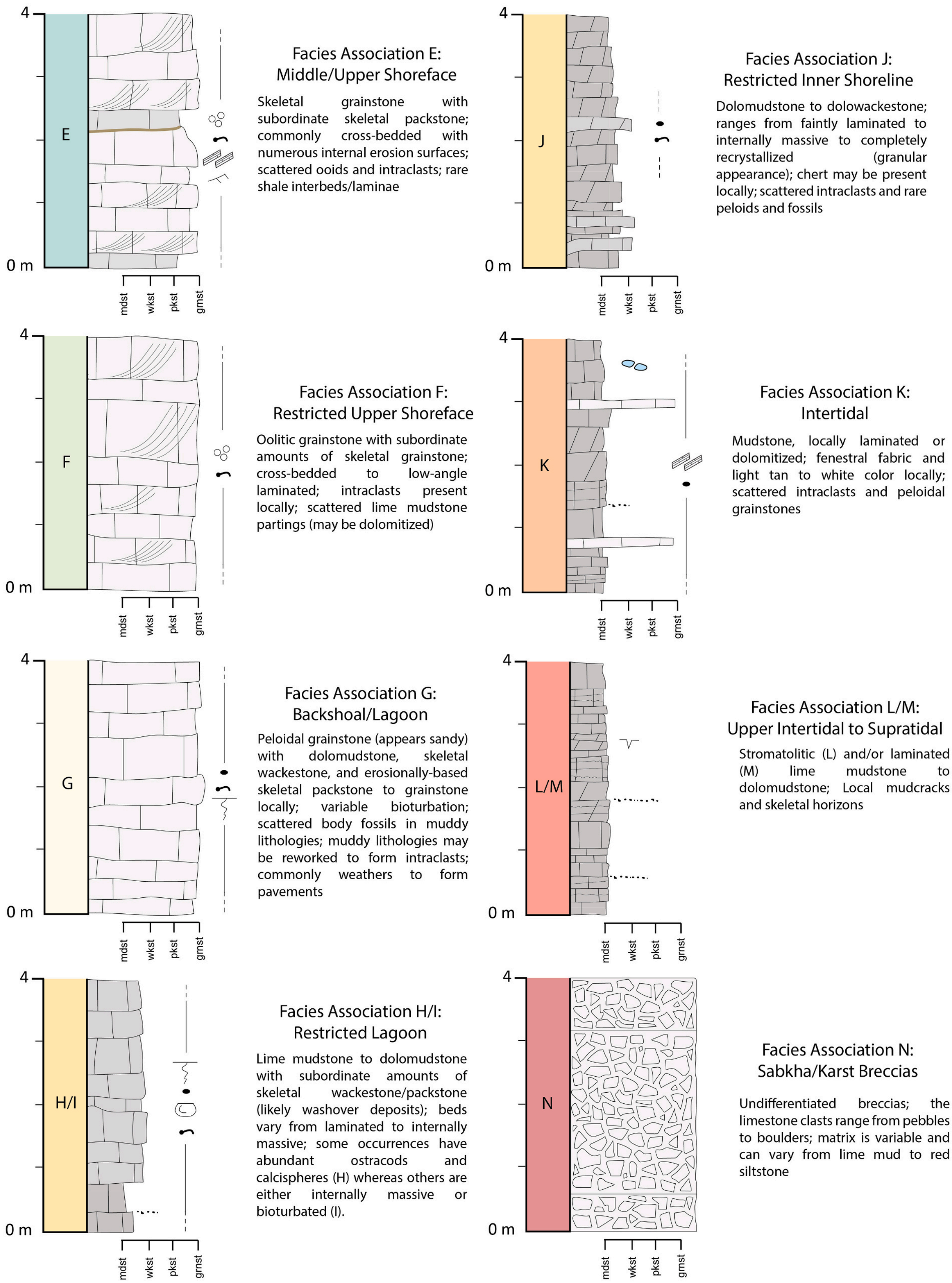


Fig. 3. (*continued*).

sequence stratigraphic interpretations are provided in Figs. 5-9.

As mentioned above, we adopt the nomenclature of Katz et al. (2007) and Katz (2008) so that we can clearly refer to the findings of previous authors no matter whether they recognize six or seven sequences in the Madison Group (our seven sequences are numbered 1, 2A, 2B, 3, 4, 5, and 6). We refer to important sequence stratigraphic surfaces using the number associated with that sequence (ex: Sequence 1 contains maximum flooding surface 1 (MFS 1) and is capped by sequence

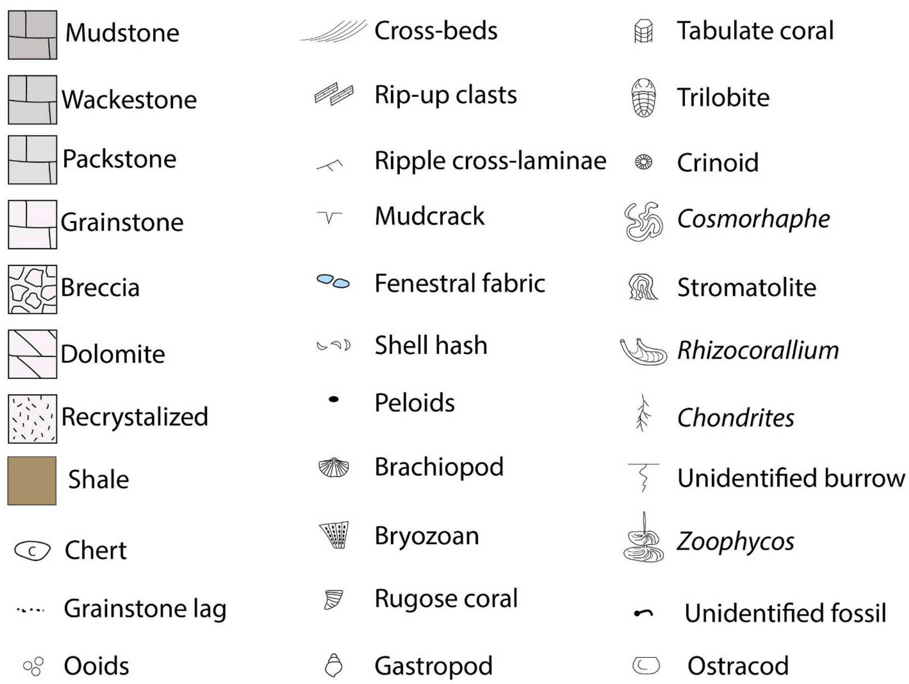


Fig. 4. Lithology and symbol key for the summary measured sections in Figs. 3 and 5-9.

boundary 1 (SB 1)).

3.2. Carbon isotopic samples and analyses

Samples for carbonate carbon isotopic analyses were precisely tied to the measured sections and thus their sedimentological and sequence stratigraphic context. Sample powders were generated from freshly exposed surfaces using a low-speed drill. When possible, we targeted micritic portions of the samples because the lower permeability of this lithology is less susceptible to post-depositional alteration when compared to allochems (e.g. Hayes et al., 1989) and recent work has demonstrated that micrite is a reliable record of the ocean $\delta^{13}C_{DIC}$ (dissolved inorganic carbon) value (Geyman et al., 2022). Sample lithologies and details are provided in the supplemental materials file. Sample powders were analyzed for bulk carbonate $\delta^{13}C$ and $\delta^{18}O$ values on a ThermoFinnigan Delta Plus Dual Inlet isotope ratio mass spectrometer connected to a Kiel III Carbonate Interface at the University of Missouri Stable Isotope and Biogeochemistry Laboratory and a ThermoFinnigan Delta V Plus Dual Inlet isotope ratio mass spectrometer connected to a Kiel IV Carbonate Interface at the University of Michigan PACE Laboratory. At the University of Missouri analytical precision is $\pm 0.04‰$ (1 standard deviation) for $\delta^{13}C$ and $\pm$ 0.06‰ (1 standard deviation) for $\delta^{18}O$ for this study and is calculated from multiple analyses of NBS-19 run throughout the course of the study. At the University of Michigan analytical precision is $\pm 0.04‰$ (1 standard deviation) for $\delta^{13}C$ and $\pm$ 0.08‰ (1 standard deviation) for $\delta^{18}O$ based analyses of NBS-19 and an internal laboratory standard analyzed during this study.

3.3. Statistical methods

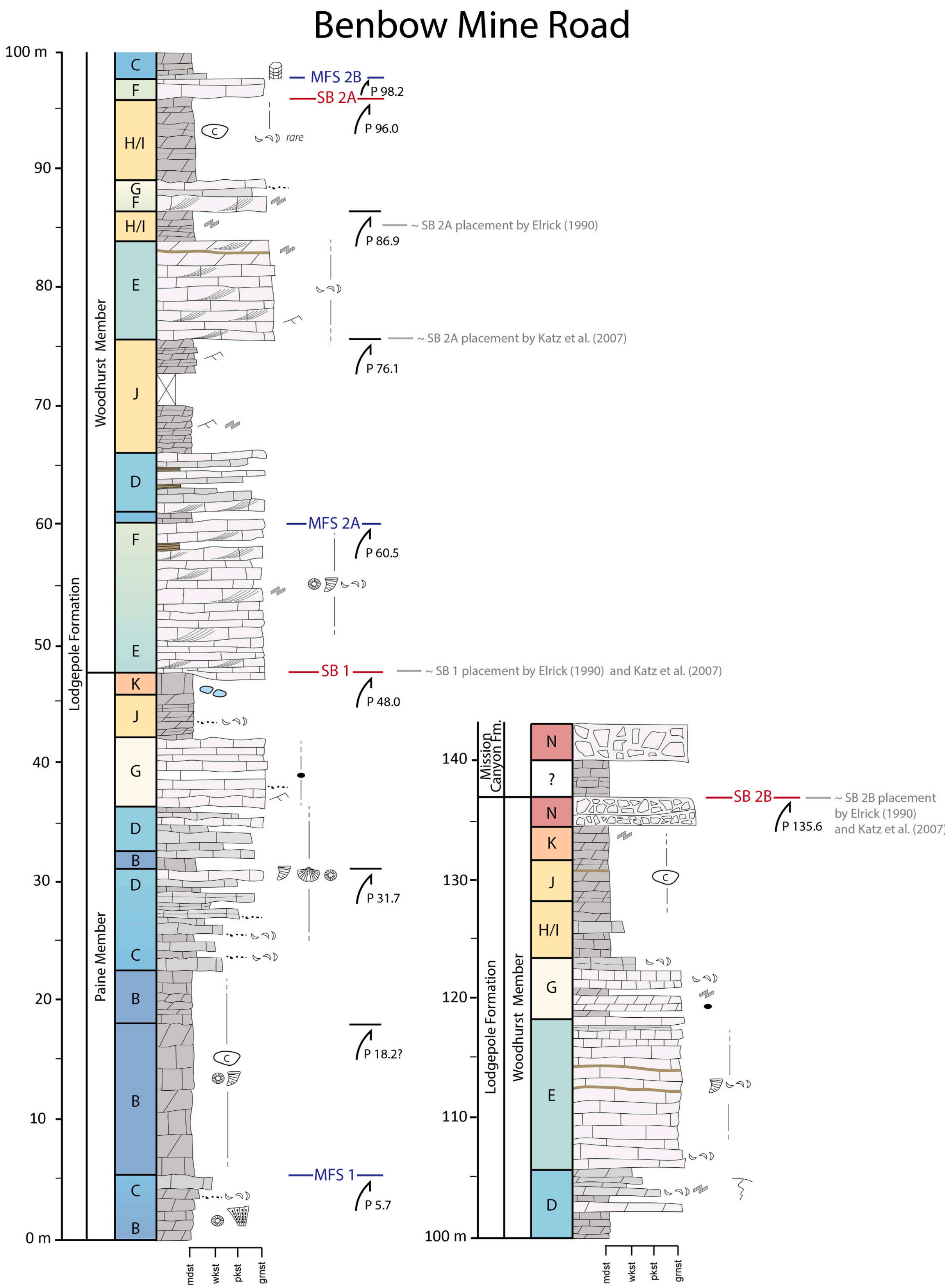
We used statistical tests for correlation to provide the first quantitative constraints on the relationship between carbon isotopic trends and sequence stratigraphic framework in the Madison Group. Specifically, we used a Spearman's Rank Correlation test which is a nonparametric test that assesses the relationship between bivariate data when the relationship in question is monotonic, that is all values with a greater x value will have a greater y value as well (or vice versa). The Spearmen Rank Correlation test can assess linear or a curvilinear function while the Pearson's Correlation can only assess linear relationships (Altman and Krzywinski, 2015). For this reason, we prefer the Spearmen Rank Correlation test in this study, but all data were analyzed using Pearson's Correlation as well and these results are included in the supplemental materials file.

All statistical tests were performed using the IBM SPSS Statistics 22 package (IBM Corp, 2021). Correlation strength is indicated with a Spearmen Rank Correlation Coefficient (ranges from -1 to 1), where -1 is a strong negative correlation and 1 is a strong positive correlation. The cut off for strong correlation was set at $+/-$ 0.5. The statistical significance of a correlation is indicated with the *p* value (ranging from 0 to 1), in this study we used a standard value of 0.05 as the cut off for statistical significance where a p value of <0.05 indicates statistical significance of the correlation (i.e. we can reject the null hypothesis that the correlation is due to chance). A carbon isotopic excursion is said to pass the test for correlation with the sequence stratigraphic framework if there was a strong, statistically significant correlation between carbon isotopic values and meterage (e.g. stratigraphic position) in the transgressive systems tract (TST) followed by a strong, statistically significant correlation in the opposite direction between carbon isotopic values and meterage (e.g. stratigraphic position) in the highstand systems tract (HST). That is, we expect carbon isotopic values to change monotonically in one direction through the meterage of the TST then change monotonically in the opposite direction through the meterage of the HST. Carbon isotopic trends that pass this requirement are interpreted to reflect a correlation between carbon isotopes and the sequence stratigraphic framework (which is a proxy for sea level change). Fig. 10 illustrates the requirements for statistically significant correlation described above.

4. Results and Interpretation

4.1. Facies analysis

Strata described in our sections were classified using a slightly modified version of the Sonnenfeld (1996) regional facies scheme. Our sections on the Madison Shelf occur in the basinward side of Sonnenfeld (1996)'s regional cross section and although we were able to recognize



(caption on next page)

Fig. 5. Summary graphic log for the Benbow Mine Road section on the northern flank of the Beartooth Range in Stillwater County, Montana. Parasequences are labeled with a P and the meterage of each parasequence top, sequence boundaries are red and labeled with a SB, and maximum flooding surfaces are blue and labeled with an MFS. Previous sedimentological work on the Benbow Mine Road section includes Sando (1972) and Elrick (1990). Elrick (1990)'s measured section was later modified and incorporated into a regional sequence stratigraphic study by Sonnenfeld (1996). Elrick (1990)'s section was also used in a diagenetic study by Smith et al. (2004), which was in turn integrated into carbon isotopic studies by Katz et al. (2007) and Oehlert et al. (2019). This section was examined in this study because it is publicly accessible, at the center of the sequence stratigraphic debate about the number of sequences, is one of the sections in Katz et al. (2007) that shows the most compelling relationship between carbon isotopic trends and sequence stratigraphy, and because it does not appear to have been described in detail since Elrick (1990). Because we needed to be able to directly tie carbon isotopic trends to our sedimentological framework, we generated a new high-resolution carbon isotopic data set for the Benbow Mine Road section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the full spectrum of environments, we were unable to differentiate some of the shallow water facies associations. Specifically, we combine Sonnenfeld (1996)'s "restricted lagoon" and "restricted inner lagoon" facies association into our "H/I: restricted lagoon", "upper intertidal-supratidal" and "supratidal" into our "L/M: Upper intertidal to supratidal", and the three brecciated facies association into our "N: sabkha/karst breccias" (Fig. 3). To build upon existing work rather than reinventing it, we use Sonnenfeld (1996)'s descriptive facies names in Fig. 3 and add letter/colour designations for brevity on diagrams and to aid with pattern recognition during sequence stratigraphic analysis. All five study sections have been classified using this facies association scheme (Figs. 5-9).

4.2. Sequence stratigraphy

4.2.1. Depositional Sequence 1 (Lodgepole Formation)

Nearly complete transects through Sequence 1 were available at the Sacagawea Peak, Baker Mountain, and Benbow Mine Road sections; the Milligan Canyon and Sappington sections had good (~80%) and incomplete (~30%) exposure, respectively (Fig. 11). Although the Cottonwood Canyon Member of the Lodgepole Formation was reported at the Benbow Mine locality (Elrick and Read, 1991; Sonnenfeld, 1996), that portion of the outcrop is no longer exposed, and it was not recognized in any of our other sections. The sharp, erosional sequence boundary at the base of the Lodgepole Formation (the base of Sequence 1) contact was observed at the Baker Mountain and Sappington sections where it overlies the dark gray shale and orange bioturbated siltstone of the Three Forks Formation (Devonian), respectively. The basal sequence boundary is typically overlain by a 3–10 m thick transgressive lag of skeletal packstone to grainstone (Facies Association C and/or D). These transgressive deposits are overlain by a thick package of outer ramp (Facies Association A and/or B) and/or middle ramp (Facies Association C) deposits. Although this facies succession records progressive deepening during the transgressive systems tract, parasequences are difficult to recognize purely within outer ramp deposits (Facies Association A and B) and MFS 1 is placed at the base of the parasequence with the highest percentage of deepwater facies (Baker Mountain and Benbow Mine Road), deepest water deposits, or - if multiple occurrences are present - at the base of the thickest occurrence (Sacagawea Peak). If there is a significant covered interval (Sappington and Milligan Canyon) then the MFS placement represents an approximate position within a likely stratigraphic range.

Strata of the highstand systems tract of Sequence 1 are organized into relatively well defined shallowing upward parasequences with a progradational architecture. Within these parasequences, facies associations range from anaerobic outer ramp (Facies Association A) to lower shoreface (Facies Association D) in more basinward sections (Sacagawea Peak and Sappington) and anaerobic outer ramp (Facies Association A) to intertidal (Facies Association K) in more landward sections (Baker Mountain, Milligan Canyon, and Benbow Mine Road). Strong evidence for SB 1 is present at 48 m in the Benbow Mine section, where a fenestral limestone (Facies Association K – Intertidal) is separated from the overlying skeletal packstone to grainstone (Facies Association E – Upper Shoreface) by a sharp erosional surface with several decimeters of erosional relief. In the four other sections, SB 1 is placed where there is a marked deepening above the first significant occurrence of shoreface grainstone (Facies Association D or E) and thus where a case can be made for a shift from progradational to retrogradational architecture.

4.2.2. Depositional Sequence 2A (Lodgepole Formation)

Depositional Sequence 2A occurs within the lower part of the Woodhurst Member of the Lodgepole Formation and was described from almost complete exposures in the Milligan Canyon and Benbow Mine Road sections and partial (60%) exposure in the Sappington section (Fig. 11). The transgressive systems tract consists of one or more parasequences composed of middle ramp to lower shoreface deposits (Facies Association C and D) at the more basinward Sappington and Milligan Canyon sections and middle to restricted upper shoreface deposits (Facies Association E and F) in the more landward Benbow Mine Road section. In all three of these sections, the maximum flooding surface occurs at the base of a parasequence marked by the deepest water deposits in the sequence (Facies Association B or C) which is also the level at which parasequence architecture shifts to a clearly progradational architecture. Progradational parasequences in the highstand systems tract deposits at Sappington consist of aerobic outer ramp to lower shoreface deposits (Facies Association B through D) and three parasequences composed of middle ramp to restricted lagoon deposits (Facies Association B through H) at Milligan Canyon and Benbow Mine Road.

The need for SB 2A primarily comes from the Benbow Mine Road section (Fig. 5), where a 2.2 m thick occurrence of restricted shoreface deposits (Facies Association F; 96.0–98.2 m) sits atop the three progradational parasequences of the highstand systems tract. The restricted shoreface deposits are, in turn, overlain by 1.8 m of middle ramp deposits (Facies Association C; 98.2–100.0 m) with an in situ *Syringiapora* near the base and 6.2 m of middle ramp to lower shoreface deposits (Facies Association C grading into D; 100.0–106.2 m). Although there is no direct evidence of an unconformity, the middle ramp and shoreface deposits record a marked deepening and the base of this package must represent a maximum flooding surface (MFS 2B). A sequence boundary must be present between MFS 2A and MFS 2B and it is best placed at the base of the restricted shoreface deposits at 96.0 m. With these picks, the transgressive systems tract is composed of a single thin parasequence composed of middle shoreface deposits (P 98.2) and the overlying highstand systems tract is composed of a single thick parasequence of middle ramp to intertidal deposits (Facies Association C through K; P 135.6). This parasequence is capped by a 1.1 m thick breccia that represents SB 2B.

A broadly similar facies succession occurs above MFS 2A at Milligan Canyon where a dolomitized and difficult to interpret occurrence of middle ramp deposits (Facies Association F; 118.2–121.1 m) can reasonably be interpreted as MFS 2B. This necessitates the existence of SB 2A and that its best placement is at 107.2 at the base of a parasequence composed of shoreface to upper shoreface (Facies Association D and E) deposits. This interval is poorly exposed at Sappington and the placement of SB 2A is approximate.

4.2.3. Depositional Sequence 2B (Lodgepole Formation)

Depositional sequence 2B is almost completely exposed at Milligan Canyon and Benbow Mine Road; it is partially exposed (60%) at

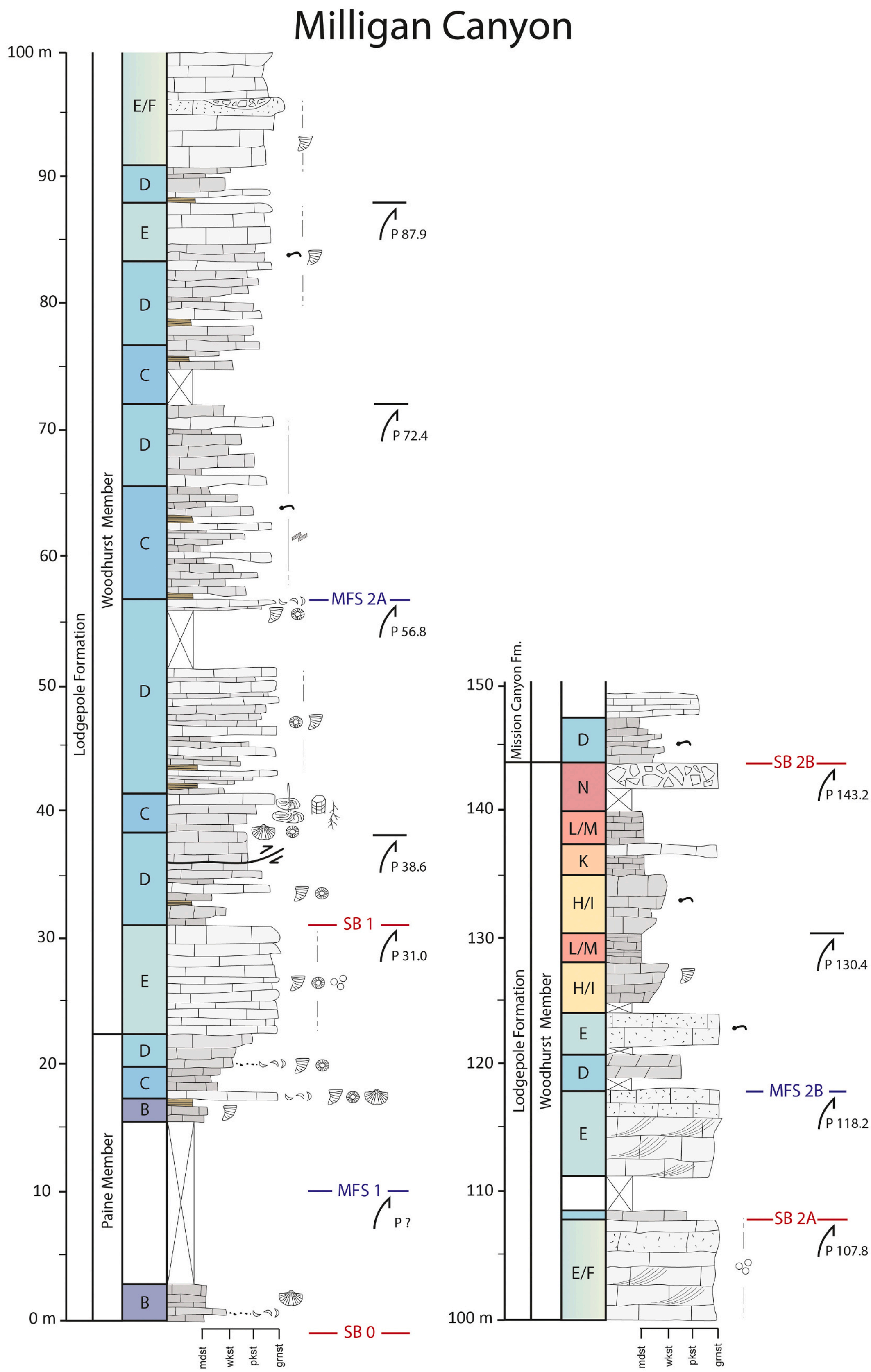


Fig. 6. Summary graphic log for the Milligan Canyon section which is northeast of the Tobacco Root Range and is exposed along Milligan Canyon Road in Jefferson County, Montana. Sequence stratigraphic nomenclature is labeled using the approach described in Fig. 4. This section was selected because it has not been previously described, is well exposed and publicly accessible.

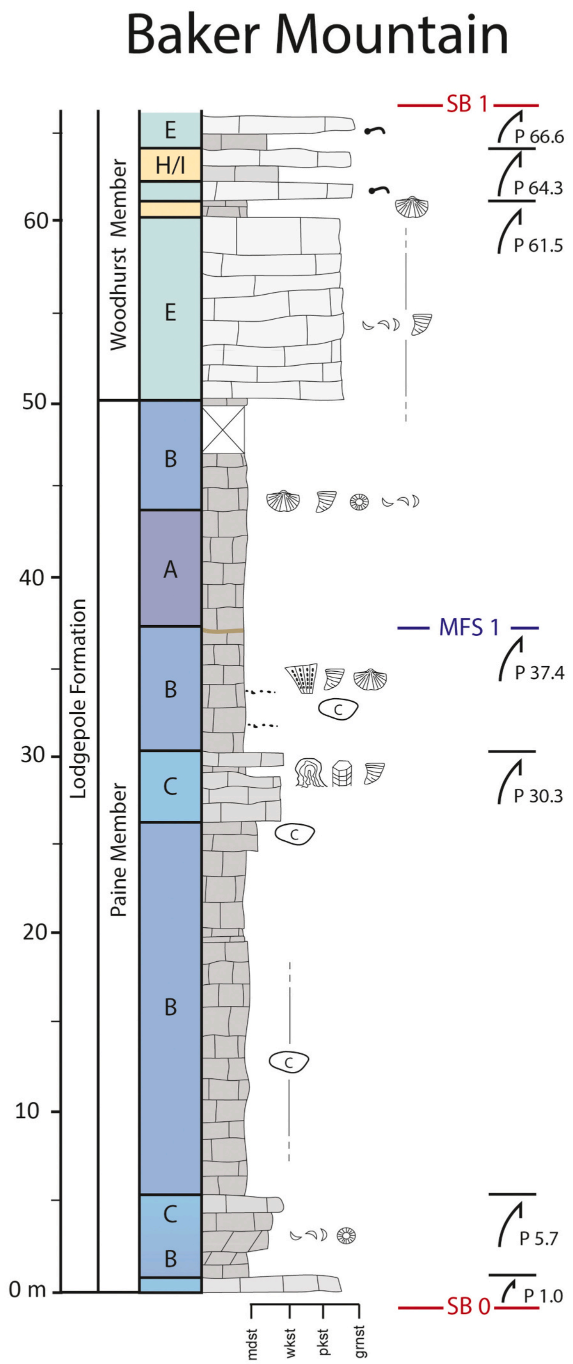


Fig. 7. Summary graphic log for the Baker Mountain section on the north flank of the Beartooth Range in Park County, Montana. Sequence stratigraphic nomenclature is labeled using the approach described in Fig. 4. Previous sedimentological work on the Baker Mountain section includes Sando (1972) and Elrick (1990). Elrick (1990) measured section was later modified and incorporated into Sonnenfeld (1996). We included this section because it has not been described since Elrick (1990), is publicly accessible, there is no geochemical data published for it, and because we wanted to determine if parasequence-level carbon isotopic trends could be identified in deep water facies.

Sappington (Fig. 11). As described above, relatively deep-water deposits at 118.2 m Milligan Canyon and 98.2 m in the Benbow Mine Road section determine the placement of MFS 2B in these sections. In both sections, the underlying deposits of the transgressive systems tract consist of a single parasequence composed of upper shoreface to restricted upper shoreface deposits (Facies Associations E and F). Progradational parasequences in the highstand systems tract at these locations have a much higher percentage of backshoal through supratidal deposits (Facies Associations H, I, and J/K) than in the underlying sequences. At Sappington, exposed parasequences in the highstand systems tract are dominated by restricted upper shoreface and backshoal deposits (Facies Associations F and G). Sequence boundary 2B is placed atop well-developed breccias at 143.2 m at Milligan Canyon and 135.6 m in the Benbow Mine Road section. At Sappington, SB 2B is placed at 187.1 m at the contact between backshoal grainstones (Facies Association G) and a covered interval that likely occurs because of a thick package of mudstone-dominated outer to middle ramp deposits (Facies Associations A through C).

4.2.4. Depositional Sequence 3 (Mission Canyon Formation)

Depositional Sequence 3 was only examined at the Sappington section (Fig. 8). Although the basal 30 m of Sequence 3 is poorly exposed and could not be measured, the talus is dominated by lime mudstones and this interval can reasonably be interpreted as outer to middle ramp deposits (Facies Association A through C) and MFS 3 is placed within this interval. Overlying parasequences have a progradational architecture dominated by lower shoreface to intertidal deposits (Facies Association D through K/L). Sequence Boundary 3 is placed at 287.0 m where aerobic outer ramp deposits overlie a thick package of intertidal to supratidal mudrocks (Facies Association K and L).

4.3. Carbon isotopic data

We present 753 bulk carbonate $\delta^{13}C$ values from five sections of the Madison Group in Montana, 294 of them are from the previously undescribed sections at Milligan Canyon and Sappington. All values from the Lodgepole Formation are plotted on Fig. 11 with a three-point moving average. At the Sappington section we describe 112.9 m of the Mission Canyon Formation, and those carbon isotopic values are plotted on Fig. 12. Detailed plots of carbon isotopic values for Benbow Mine Road and Milligan Canyon are included in Figs. 13 and 14, respectively. Detailed carbon isotopic plots of Baker Mountain, Sappington, and Sacagawea Peak are included in the supplementary materials file. A complete data table with lithology for each sample is included in supplementary materials file.

Trends and values reported here are similar to those reported elsewhere (e.g. Katz et al., 2007; Buggisch et al., 2008; Maharjan et al., 2018). Generally, values increase from ~2‰ to between ~5 to 7‰ in Sequence 1. The one exception is Milligan Canyon, where values fluctuate between 4‰ and 5‰ with no obvious trend. In Sequence 2A, values increase by between ~1‰ – 2.5‰ with the greatest magnitude of increase at Benbow Mine Road. In Sequence 2B carbon isotopic values decrease by ~1‰ to 3‰. At Sappington, we have data from Sequence 3 in the Mission Canyon where values decrease from ~6‰ to ~3‰.

We document a total of twelve sequences (multiple occurrences of S 1, S 2A, S 2B, and S 3) in our five sections; of them, nine are complete enough to test for statistical significance. Eight of the nine fail to show a statistical relationship between the carbon isotopic values and sequence stratigraphic framework. Results from the statistical tests are reported in Table 1 and in the supplementary materials file. Only Sequence 2A at Milligan Canyon passes the test for statistically significant correlation between carbon isotopic values and sequence stratigraphic framework.

Where possible, we generated carbon isotopic trends at high enough resolution to test for systematic trends at the parasequence level. If sea level was exerting a significant influence on carbon isotopic values, one might expect to observe systematic patterns at a variety of scales (e.g. Quinton et al., 2021). This might be especially true in nearshore settings where small scale changes in relative sea level could result in relative changes in carbonate mineralogy (aragonite vs. low magnesium calcite), freshwater input, terrestrial organic carbon input, and/or reduced mixing and water mass restriction. Combined, we might expect to see progressively decreasing carbon isotopic values through a parasequence

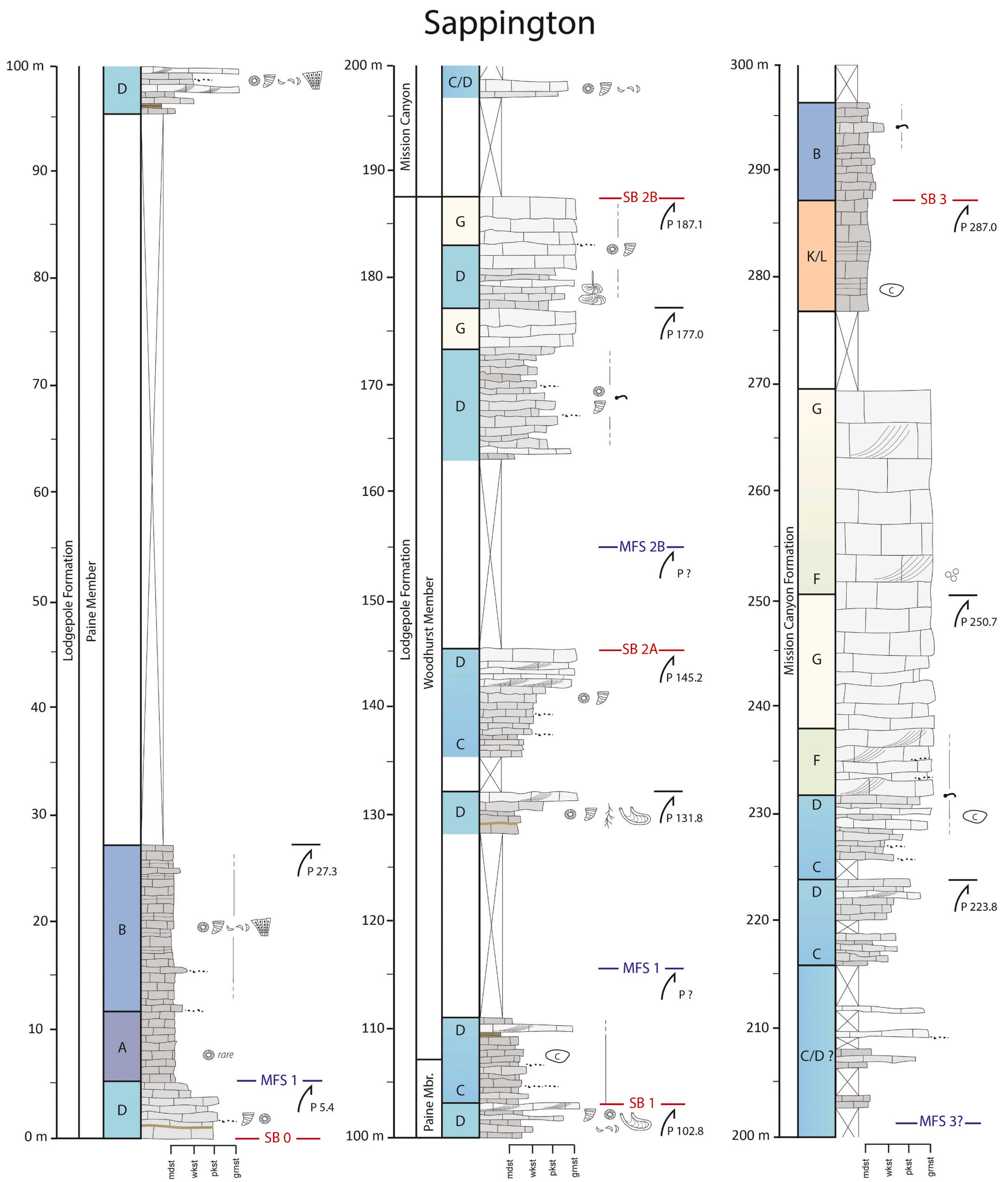
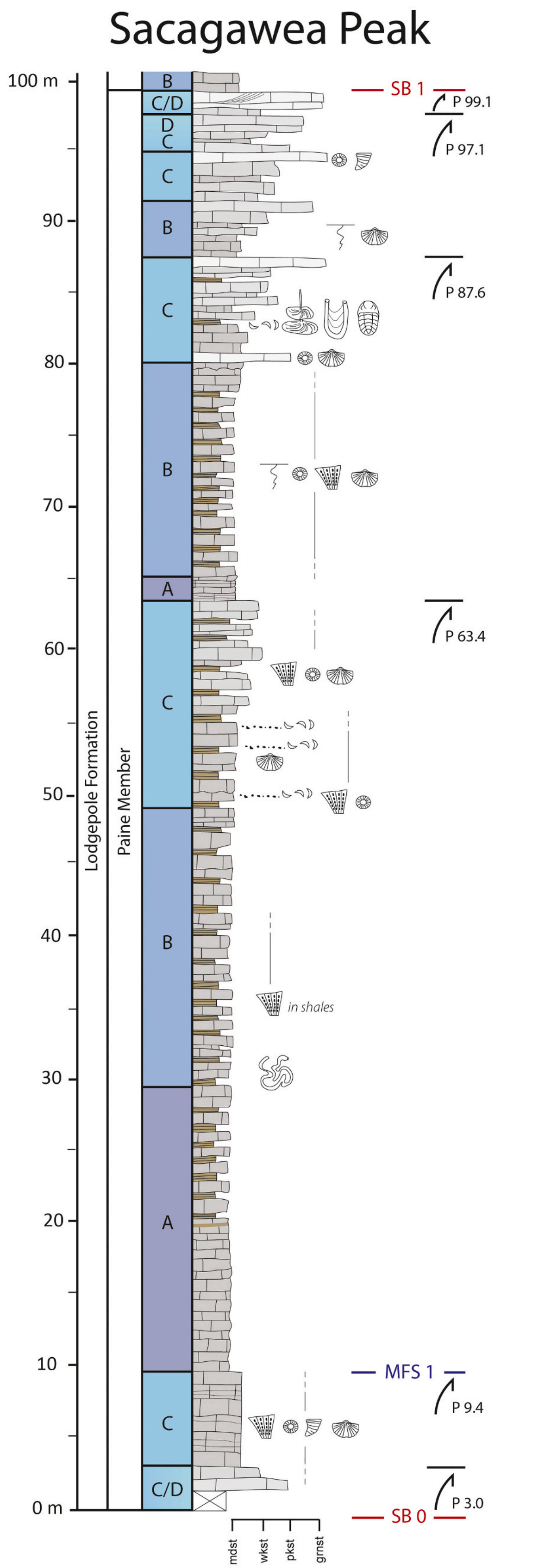


Fig. 8. Summary graphic log for the Sappington section which is northeast of the Tobacco Root Range and occurs entirely on private property along MT 287 in Madison County, Montana. Sequence stratigraphic nomenclature is labeled using the approach described in Fig. 4. This section was targeted because it has not been previously described and because it provides good exposures of the restricted facies that are typical of the lower part of the Mission Canyon Formation.



(caption on next column)

Fig. 9. Summary graphic log for the Sacagawea Peak section in the Bridger Range, Gallatin County, Montana. Sequence stratigraphic nomenclature is labeled using the approach described in Fig. 4. Sedimentological and stratigraphic descriptions of this section were provided by Laudon and Severson (1953), Smith (1972), and Elrick (1990). Descriptions and carbon isotopic data were provided by Wallace (2011; uppermost part of Sequence 1 and all of 2A and 2B) and almost the entirety of both the Lodgepole and Mission Canyon Formations by Katz et al. (2007) and Buoniconti (2008). This location was selected because it is publicly accessible and it provides a second test for small-scale carbon isotopic trends in deepwater facies and for possible relationships between carbon isotopes and sequence stratigraphy.

followed by a sharp change in values near the base of the next parasequence where deepening occurs. Despite these predictions, there are no systematic trends in carbon isotopes within parasequences across our study sections (Figs. 13-14; and supplementary materials file).

5. Discussion

5.1. Sequence stratigraphy – comparison with previous studies

Our measured sections from Sacagawea Peak, Baker Mountain, and Benbow Mine Road correlate well with the original sections from Elrick (1990) and we can tie the top of our Sacagawea Peak section with the lower portion of Wallace (2011) section at the level of individual beds. However, doing a detailed comparison between our sequence stratigraphic picks and those of other sequence stratigraphic and carbon isotopic studies is challenging because, a) only very simplified sections are provided in those studies, b) authors use different definitions and criteria to define cycles and sequence stratigraphic surfaces, and/or c) the exact placement of sequence stratigraphic surfaces is not always provided on the measured sections and can't be determined from written descriptions. Despite these challenges, some general comparisons can be made between our picks and those of previous authors at Sacagawea Peak, Baker Mountain, and Benbow Mine Road.

5.1.1. Sequence 1

Overall, there is very good agreement between our sequence stratigraphic picks for Sequence 1 and all previous studies. Specifically, we agree with Elrick (1990) and Buoniconti (2008) that MFS 1 is best placed within the package of deep-water lime mudstones in Paine Member of the Lodgepole limestone. These deposits are thick, monotonous, and often poorly exposed and placement within this zone is only approximate (Elrick, 1990). Although the rationales vary, we also agree with Elrick (1990) and studies built upon it (Sonnenfeld, 1996; Smith et al., 2004; Katz et al., 2007; Oehlert et al., 2019) that SB 1 is best placed atop or within the package of mudrocks between 42 and 48 m in our Benbow Mine Road section. Our placement of SB 1 at Sacagawea Peak and Baker Mountain matches well with Elrick (1990), Buoniconti (2008), and is at the same position shown in Wallace (2011). Facies and facies stacking patterns are similar at our Sappington and Milligan Canyon sections and we used the same criteria to place sequence stratigraphic surfaces at these locations as we did at our other sections.

5.1.2. Sequence 2A

The debate about a two or three sequence model for the Lodgepole Formation centers on the presence/absence of a sequence boundary (2A) within the Woodhurst Member at the Livingston, Baker Mountain, Benbow Mine Road, and Clark's Fork Canyon, sections that were shown in both Elrick (1990) and Sonnenfeld (1996). We focus on Benbow Mine Road because a) the facies evidence for a sequence boundary presented by Elrick (1990) is equivocal (it is within a package of what the author interprets as foreshoal deposits and there is no obvious change in facies association), b) because this section features prominently in later carbon isotopic studies, c) the other sections either show reasonable sedimentological evidence for a sequence boundary or are farther away from our

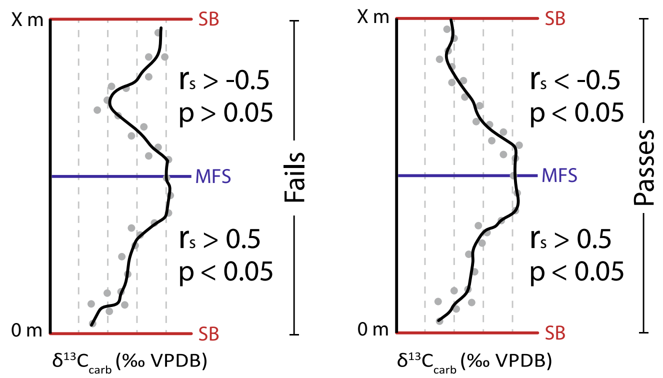


Fig. 10. Illustration of the statistical methods used to test for correlation between carbon isotopic trends and position within the sequence stratigraphic framework. To pass the test for correlation, there must be statistically significant correlation ($p < 0.05$) in one direction in the TST and statistically significant correlation ($p < 0.05$) in the opposite direction in the HST. The Spearman Rank Correlation (r_s) value indicates the direction and strength of the correlation. Note that as displayed here, the TST is defined by positive correlation while the HST is defined by negative correlation. The opposite pattern, TST negative correlation and the HST positive correlation, would also meet requirements for statistically significant correlation within this hypothetical sequence.

new sections where we hope to provide new data to help resolve the debate.

In all cases, previous authors agree that a maximum flooding surface (MFS 2A) occurs in the package of mudrocks between 60.5 m and 76.1 m in our Benbow Mine Road section. Elrick (1990) and thus all studies derived from it (Sonnenfeld, 1996; Smith et al., 2004; Katz et al., 2007; Oehlert et al., 2019), show the entirety of this interval as deep ramp and place the MFS in the top half of this interval. Although this interval is almost completely dolomitized, weathered surfaces reveal abundant low angle laminae, ripple cross laminae, rip-up clasts and an overall appearance that is nearly identical to restricted inner shoreline deposits (Facies Association J) that are widely recognized and agreed upon higher in the section. Given that, we place MFS 2A near the base of the mudrock interval (60.5 m) in strata that both Elrick (1990) and Sonnenfeld (1996) both interpret as deep to middle ramp.

Given the facies evidence presented above (Section 4.2.2), we support the three-sequence model for the Benbow Mine Road section and the Lodgepole Formation more broadly. Our placement of SB 2A appears to be 2.2 m away from Elrick (1990) placement, but we arrive at this interpretation for slightly different reasons. Both sections show a progression from a lower lime mudstone (89.5 m to 96.0 m) to an oolitic/skeletal grainstone (96.0 to 98.2) to an upper lime mudstone (98.2 to 102.6). Elrick (1990) interprets the entirety of this interval as foreshoal deposits and arbitrarily(?) places the sequence boundary atop the grainstone. We interpret the lower mudstone as restricted lagoon (Facies Association H), place SB 2A at the base of what we interpret as a restricted upper shoreface grainstone (Facies Association F), and then place MFS 2A at the base of the upper mudstone, which we interpret as a middle ramp deposit (Facies Association C). In short, we place SB 2A very close to where Elrick (1990) does and provide what we think is an even more compelling reason for doing so.

At Benbow Mine Road, Katz et al. (2007) place SB 2A at the base of a thick package of grainstone at ~76.1 m in our measured section, which is over 20 m lower than where we and Elrick (1990) placed it. This lower placement is problematic for several reasons:

1) Katz et al. (2007) modify their section from the measured section presented in Smith et al. (2004). Although Katz et al. (2007) show three sequences in the Lodgepole and Smith et al. (2004) show only two, no sedimentologic evidence or justification for this difference is provided.
2) The two-sequence model for Benbow Mine Road shown by Smith et al. (2004) was modified from the three-sequence Lodgepole measured section shown by Elrick (1990). Although overlap in authorship suggests that Smith et al. (2004) may have been influenced by the two-sequence model of Sonnenfeld (1996), neither of these papers discuss the differences.
3) Katz et al. (2007) provide no justification for their placement of SB 2A other than saying that the two excursions seen in the carbon isotopic data are consistent with the three-sequence model proposed by Elrick (1990). This could be interpreted to mean that the position of the sequence boundary was determined by patterns in the carbon isotopic curve. This approach is problematic especially if one is trying to determine cause and effect relationships between relative sea level and changes in carbon isotopes.

Our work, and that of all previous sequence stratigraphic studies of the Lodgepole Formation, shows that the lack of breccias and striking facies juxtapositions makes SB 2A the most difficult sequence boundary to justify and identify. Unless a section has strata that record a marked deepening (that can thus be interpreted as MFS 2A), it is entirely reasonable to have the progradational parasequence stacking pattern that began with HST 2A continue and simply interpret the Lodgepole Formation as having two sequences. It is possible that the cryptic nature of SB 2A reflects some combination of a low-magnitude change in relative sea level or peculiarities in the paleogeomorphology of the coast at that time. If it was a more modest drop in relative sea level than the ones that created SB 1 and SB 2B, then the sedimentological record of SB 2A would be hard to recognize in deep water deposits in the slope/outer shelf, lost in the shallow water grainstones and intertidal deposits of the inner shelf, and preserved only on parts of the shelf where the most pronounced facies changes occurred. In short, justifying three sequences requires either the good fortune of having preserved and exposed deep-water facies in TST 2B or the willingness to pick the position of SB 2A based on relatively subtle facies changes.

5.1.3. *Sequence 2B*

Although the position of MFS 2B is not shown at Benbow Mine Road in Elrick (1990), our relatively thin TST and placement of MFS 2B at 98.2 m broadly aligns with their work. Despite the differences in the placement of the underlying sequence boundary at Benbow Mine Road, our placement of MFS 2B at the base of a package of middle ramp deposits (Facies Association C) appears to be only two meters higher than it is placed in Katz et al. (2007) Benbow Mine Road section. Because of differences in sequence stratigraphic nomenclature and approach, there is some minor disagreement about the exact placement of SB 3 relative to the lowest breccia in the section (base at 134.4 m in our section), but all previous studies agree that SB 3 is closely associated with it. This sequence boundary represents the contact between the Lodgepole and Mission Canyon Formations and is accompanied by significant changes in lithology and weathering profiles.

5.2. *Carbon isotope geochemistry of the Madison Shelf*

The carbon isotopic results in this study are interpreted as primary values and trends for three reasons. Firstly, our values and trends are similar to those reported elsewhere in the Madison Group (Saltzman, 2002; Katz et al., 2007) and more broadly for the Early Mississippian (Buggisch et al., 2008; Maharjan et al., 2018; Chen et al., 2021). It is unlikely that diagenetic processes would alter values and trends in the same way across a broad area and multiple basins. Secondly, there is no evidence of a systematic relationship between carbonate mineralogy (calcite vs. dolomite) and carbon isotopic values (student *t*-test $p = 0.204$, calcite $n = 652$ and dolomite $n = 101$) as would be expected if diagenetic processes related to dolomitization effected the carbon

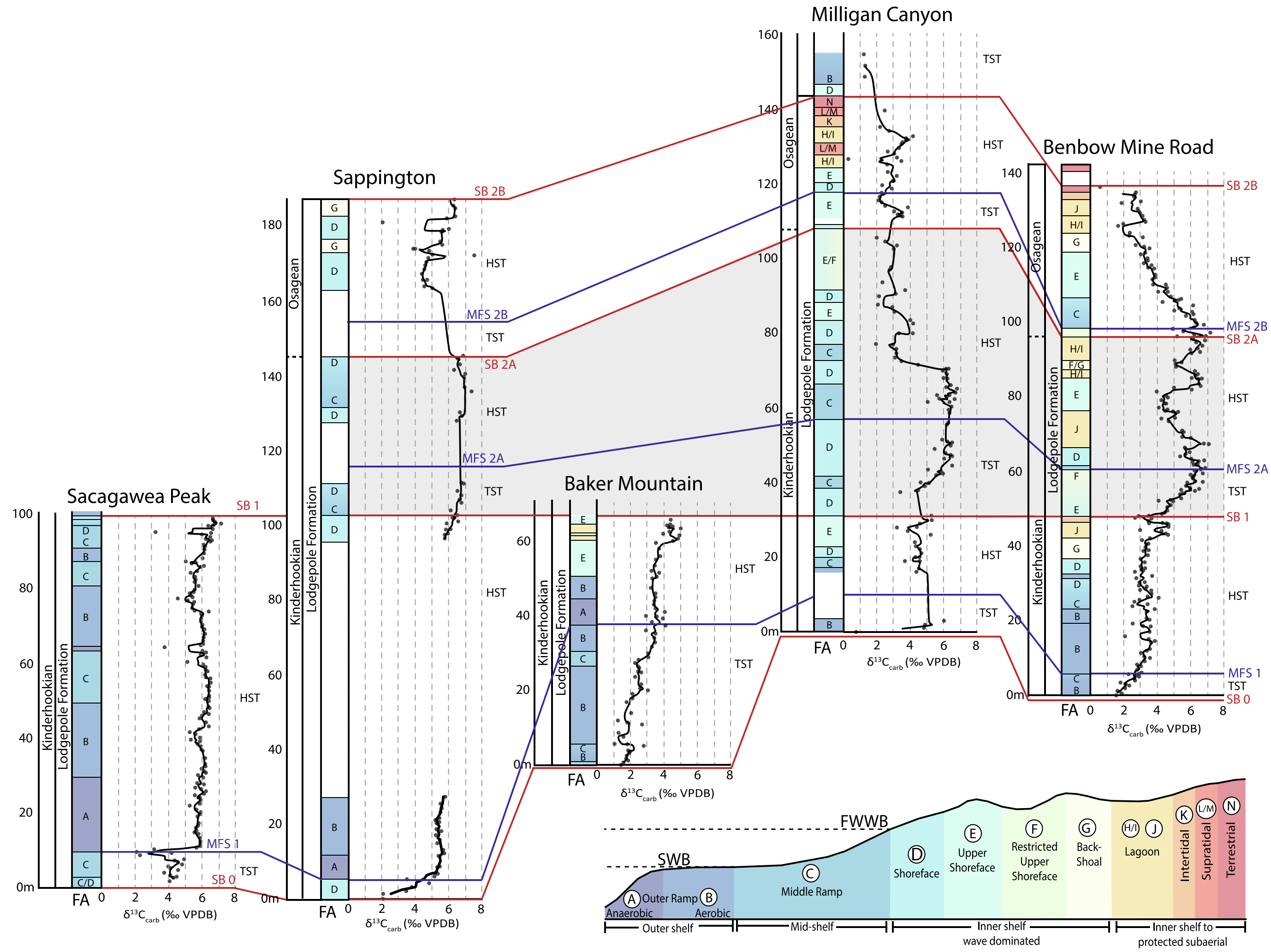


Fig. 11. Sequence stratigraphic correlation and carbon isotopic trends from this study. Three point moving averages for the carbon isotopic data are plotted as a black line. Sequence boundaries are indicated with horizontal red lines and maximum flooding surfaces with horizontal blue lines. Transgressive systems tracts are indicated with TST and highstand systems tracts are indicated with HST. Facies associations (FA) are colour coded and described in Fig. 3. The study sections are arranged so that the most proximal section (Benbow Mine Road) is on the right and the most distal study section (Sacagawea Peak) is on the left. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

isotopic values. Lastly, we do not observe any systematic relationship between carbonate lithology (e.g. mudstone, wackestone/packstone, and grainstone) and carbon and oxygen isotopic values (supplementary materials file) as would be excepted if meteoric diagenesis or vital effects were significantly influencing δ^{13}C values (e.g. Allan and Matthews, 1982; Geyman and Maloof, 2021).

Carbon isotopic values increase through Sequence 1, peak in Sequence 2A, and return to baseline values in 2B; we interpret this pattern as the K—O positive carbon isotope excursion (Fig. 11). Our most complete records of this excursion are at Benbow Mine Road and Milligan Canyon. As previously documented (e.g. Saltzman, 2002; Katz et al., 2007), the magnitude of the excursion varies, even across the Madison Shelf. At Benbow Mine Road the total recorded change is up to 7‰ and the excursion has two peaks. In the more basinward Milligan Canyon and Sappington sections, the recorded change is 2.5‰. This variation in magnitude and expression of the excursion is likely a function of local influence and the development of carbon isotopic gradients across the Madison Shelf. The presence of carbon isotopic gradients is supported by the statistically significant difference (student *t*-test $p < 0.001$) in carbon isotopic values between deep (A,B,C, and D) and shallow water facies associations (F, G, H, I, J, K, L) (Fig. S12 in supplementary materials file). Values are nearly identical in the three sections that capture the peak of the excursion in Sequence 2A, suggesting that the gradient disappears at the peak of the excursion, likely due to complete mixing of the basin and/or the loss of local influences on δ^{13}C values.

A shoreline to basin gradient in δ^{13}C values is consistent with previous studies on the Madison Group (Katz et al., 2007) and studies of modern carbonate platforms like Florida Bay (Patterson and Walter, 1994). In the modern, gradients in the carbon isotopic value of the dissolved inorganic carbon (DIC) pool are the result of respired ^{12}C in meteoric fluids, terrestrial organic carbon entering the marine system, net photosynthesis, and non-equilibrium conditions with atmospheric CO_2 (e.g. Patterson and Walter, 1994; Geyman and Maloof, 2021). The result is lower δ^{13}C values in nearshore settings. These same conditions would have influenced the δ^{13}C values along the Madison Shelf. Oehlert et al. (2019) note that the most important difference between the modern and Mississippian is that terrestrial organic carbon in the Early Mississippian would have averaged approximately − 22‰ (Peters-Kottig et al., 2006), which is 6‰ higher than average marine organic matter at the time (Hayes et al., 1989). So, instead of terrestrial organic carbon contributing a higher proportion of ^{12}C like it does in the modern, any terrestrial organic matter would have contributed a greater proportion of ^{13}C. Since shallow water settings in the Madison Shelf are

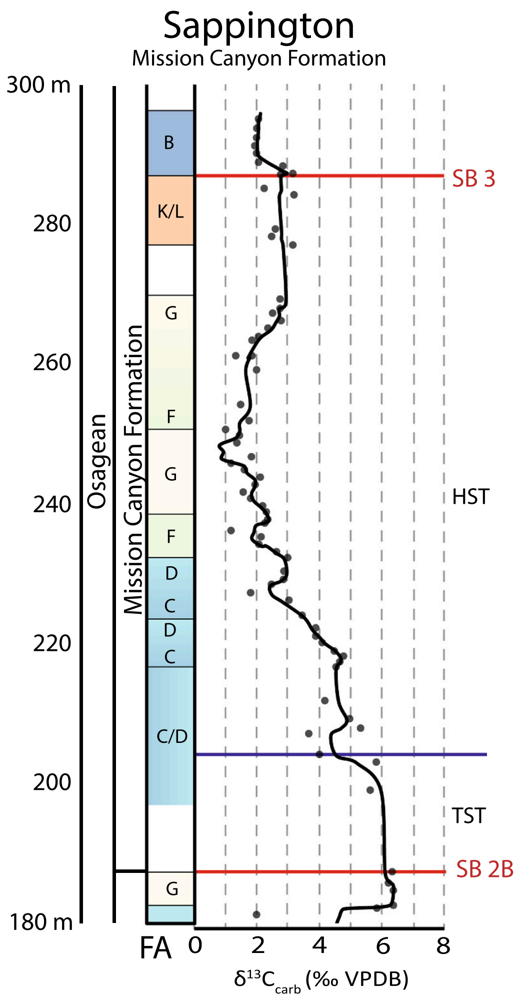


Fig. 12. Carbon isotopic results for the Mission Canyon Formation at Sappington. The three point moving averages for carbon isotopic data are plotted as black lines. Sequence boundaries are indicated with red lines and maximum flooding surfaces with blue lines. Transgressive systems tracts are indicated with TST and highstand systems tracts are indicated with HST. Facies associations (FA) are colour coded and described in Fig. 2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

marked by lower $\delta^{13}C$ values this would suggest that terrestrial organic carbon did not play a significant role in the generation of spatial gradients in this basin.

5.3. Sea level and carbon isotopic trends

With evidence of spatial gradients in $\delta^{13}C$ values controlled by position relative to shore, one would expect to observe a noticeable relationship between carbon isotopic trends and relative sea level fluctuations. However, in this study, eight of the nine sequences with enough data to test for statistical significance fail the test for correlation between carbon isotopic values and the sequence stratigraphic framework.

The basin became increasingly restricted during deposition of the Mission Canyon Formation (Sonnenfeld, 1996; Burgess, 2019) and if sea level was influencing carbon isotopic trends, the relationship between relative sea level and the carbon isotopic values would be more pronounced when the basin is restricted and/or mixing is limited. We examined Sequence 3 at Sappington in order to test for that relationship. Although the presence of a covered interval in the TST does not give us enough values to test for statistical significance, the data we do have

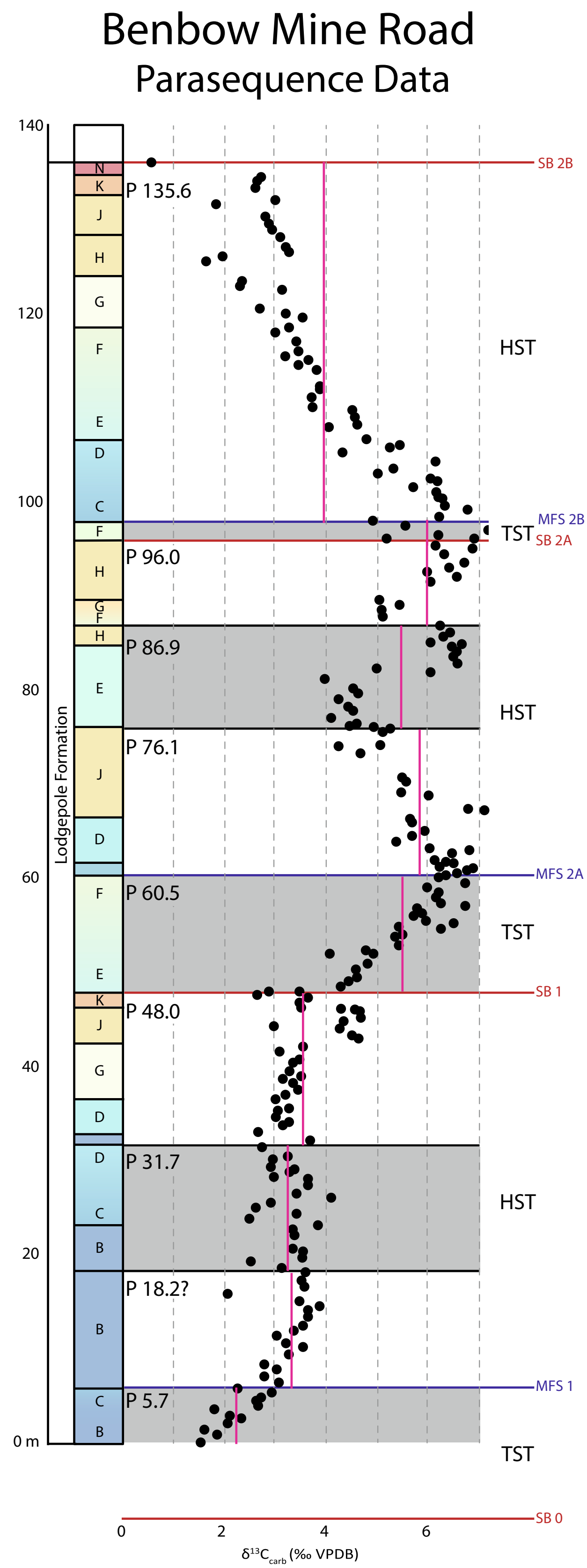


Fig. 13. Detailed carbon isotopic data plotted by parasequence for the Benbow Mine Road section. Each parasequence is numbered with meterage at its top and the carbon isotopic average is plotted as a pink line within that parasequence. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

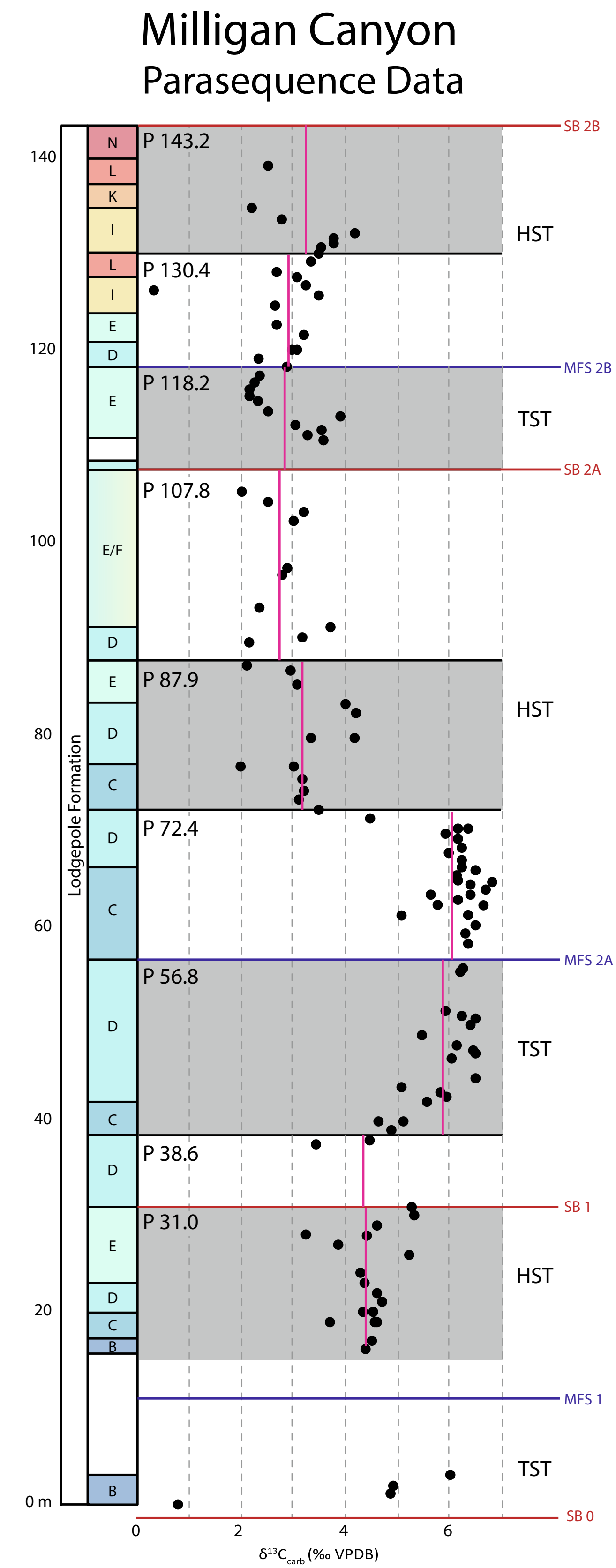


Fig. 14. Detailed carbon isotopic data plotted by parasequence for the Milligan Canyon section. Each parasequence is numbered and the carbon isotopic average is shown as a pink line within that parasequence. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

suggest stable isotopic values in the TST (Fig. 12). This pattern is consistent with Katz et al. (2007) values from the TST in Sequence 3 at other locations and supports our interpretation that there is no correlation between sequence stratigraphy and carbon isotopic values. This interpretation is further reinforced by the absence of systematic trends at the parasequence level.

The one sequence within which we see statistically significant results is Sequence 2A at Milligan Canyon, where we observe progressively increasing carbon isotopic values in the TST and decreasing values in the HST. At the parasequence level, we also see systematically lower average values in progressively shallowing parasequences (P72.4, P87.9, P107.8), which are similar to patterns reported in Quinton et al. (2021). Although it would be tempting to place significance on the results from this interval, the results are anomalous and when taken together with all the other sequences in this study, it is difficult to make a compelling argument for meaningful overall correlation between carbon isotopic trends and sequence stratigraphic framework in the Madison Group.

We chose to include Benbow Mine Road in this study because Katz et al. (2007) carbon isotopic curve from this section provides one of the most compelling examples of a relationship between carbon isotopes and the sequence stratigraphic framework in the Madison Group. We produced a strikingly similar carbon isotopic curve for Benbow Mine Road and make very comparable sequence stratigraphic picks through most of the Lodgepole Formation (Fig. 15). This isn't surprising given that Katz et al. (2007) is derived from Smith et al. (2004) which is in turn derived from Elrick (1990) and our work compares very well with the original source. As described in section 5.1.2, Katz et al. (2007) made a significant and unexplained change to the position of SB 2A that resulted in a a compelling example of correlation between carbon isotopic trends and sequence stratigraphic framework for Sequences 2A and 2B (Fig. 15). However, as we have shown in Fig. 15 that relationship falls apart when sequence stratigraphic surfaces are placed independently based on sedimentological evidence.

5.4. Wider implications

We found no compelling evidence that relative sea level rise in the Madison Shelf was a major influence on the expression of the K—O carbon isotopic excursion. That is not to say that the trends we observed were not influenced by processes like marine organic carbon burial as proposed by Katz et al. (2007). But, the lack of a systematic relationship between carbon isotopes and sequence stratigraphic framework in the Madison Shelf indicates that explanations for the K—O excursion cannot rely on relative sea level change as a primary driver.

Previously proposed explanations for the K—O excursion invoke increased nutrient supply combined with ocean anoxia resulting in net organic carbon burial in the marine realm (Saltzman et al., 2000; Liu et al., 2019; Cheng et al., 2020). In this scenario, an increased flux of nutrients into the marine realm acted as a catalyst fueling primary productivity. When combined with the development and expansion of anoxia, the result was increased burial of marine organic carbon (enriched in ^{12}C). Mechanisms invoked to explain the influx of nutrients and development of anoxia include: relative sea level change in the Madison Shelf (Katz et al., 2007), development of the Antler Foreland Basin (Saltzman et al., 2000), and/or ocean reorganization and upwelling due to global cooling (Liu et al., 2019; Cheng et al., 2020). Evidence from uranium isotopes, redox sensitive metals, and pyrite framboid abundance does provide support for widespread anoxia in the Early Mississippian (Cheng et al., 2020).

There are also proposed explanations for the K—O excursion that invoke the evolutionary history of land plants (Oehlert et al., 2019; Chen et al., 2021), a concept popularized by Algeo and Scheckler (1998). In their model, the proliferation of vascular plants altered the carbon cycle in the Devonian by increasing carbon storage in the terrestrial realm and supplying nutrients via increased weathering fluxes. Increased nutrient

Table 1
Statistical test results.

Section	Sequence	Systems Tract	Spearman Rank Correlation (r_s)	*p value*	n	Passes or Fails Test
Benbow Mine Road	S 1	TST	0.783	0.003	12	Fails
		HST	0.206	0.075	76	
	S 2A	TST	0.879	<0.001	29	Fails
		HST	−0.500	0.706	59	
	S 2B	TST	−0.348	0.499	6	Fails
		HST	−0.943	<0.001	51	
Milligan Canyon	S 1	TST	Not enough data		4	NA
		HST	0.100	0.703	17	
	S 2A	TST	0.718	<0.001	22	**Passes**
		HST	−0.828	<0.001	50	
	S 2B	TST	−0.782	0.004	11	Fails
		HST	0.230	0.316	32	
Sappington	S 1	TST	0.771	0.720	6	Fails
		HST	0.748	<0.001	35	
	S 2A	TST	0.355	0.388	8	Fails
		HST	−0.176	0.547	14	
	S 2B	TST	Not enough data		0	NA
		HST	0.585	0.002	26	
	S 3	TST	Not enough data		3	**Possible**
		HST	−0.437	<0.001	57	
Sacagawea Peak	S 1	TST	−0.057	0.840	15	Fails
		HST	0.239	0.005	140	
Baker Mountain	S 1	TST	0.792	<0.001	39	Fails
		HST	0.707	<0.001	31	

Results from the statistical tests used in this study. The Spearman Rank Correlation (r_s) indicates the direction and strength of correlation. The *p*-value indicates the statistical significance, where a *p*-value <0.05 is considered statistically significant. The number of carbon isotopic analyses utilized in each test is indicated with 'n'. Only those sequences that meet the requirement of strong, statistically significant correlation in one direction in the TST and strong, statistically significant correlation in the opposite direction in the HST pass the test for statistically significant correlation between carbon isotopic trends and sequence stratigraphic framework.

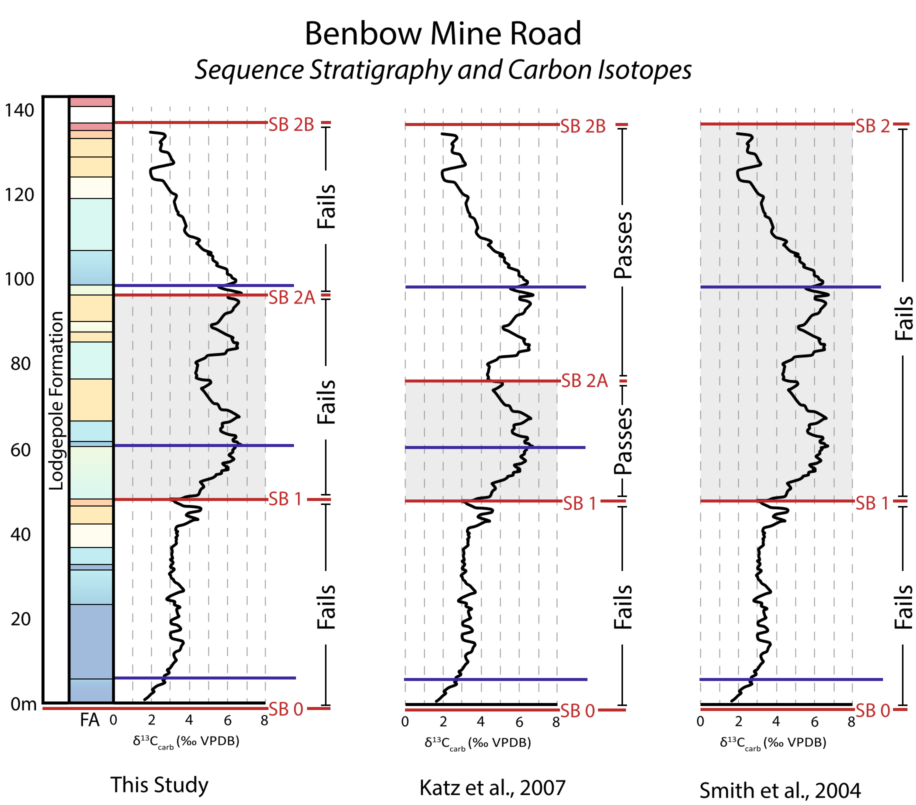


Fig. 15. Carbon isotopic data for the Benbow Mine Road section (from this study) plotted against different interpretations of the sequence stratigraphy. Sequence 2A is the one that has been most debated; it is highlighted in gray. Smith et al. (2004) used a two-sequence model for the Lodgepole Formation while Katz et al. (2007) used a three-sequence model modified from Elrick (1990). Our results require a three-sequence model for the Lodgepole Formation. The only difference between our framework and that used in Katz et al. (2007) is the placement for Sequence Boundary 2A. Our placement for SB 2A is based on the detailed sedimentological analysis completed as part of this study, whereas Katz et al. (2007) appear to have placed it based on patterns in the carbon isotopic data. This figure illustrates how different picks for sequence stratigraphic boundaries can affect interpretations of the relationship between carbon isotopic trends and the sequence stratigraphic framework.

supply to the ocean fueled primary productivity in marine ecosystems and led to widespread organic carbon burial in the marine realm. The continued diversification of land plants in the Early Carboniferous led to increased terrestrial biomass as plants were able to colonize upland dry ecosystems (Dahl and Arens, 2020). Increased terrestrial biomass could have led to increased weathering flux, supplying nutrients to the marine realm (Algeo and Scheckler, 1998; Quirk et al., 2015) that fueled primary productivity and the burial of organic carbon. Evidence from organic carbon isotopes and strontium isotopes (a proxy for weathering rates) have been invoked to support the interpretation (Oehlert et al., 2019; Chen et al., 2021). While it is difficult to directly tie events in land plant evolution to specific geochemical excursions, diversification and expansion of land plants did continue through the Late Devonian into the Early Mississippian (Dahl and Arens, 2020).

6. Conclusions

We build upon the existing sedimentological framework for the Madison Group and establish a sequence stratigraphic framework for our five study sections. Our results indicate that a three-sequence framework is required for the Lodgepole Formation; we use this framework to test for statistical correlation between trends in carbon isotopic values and position in the sequence stratigraphic framework. Eight of nine sequences with near complete exposure indicate that there is no statistically significant correlation between carbon isotopic trends and sequence stratigraphy, suggesting that relative sea level fluctuations were not the primary driver of carbon isotopic trends in the Madison Shelf. This is an important finding as the presence of an ~2‰ depth gradient in average $\delta^{13}C$ values and statistically significant differences between deep and shallow water deposits suggests that processes like freshwater input (rich in respired ^{12}C), differences in the relative proportion of terrestrial organic carbon vs. marine organic carbon, and non-equilibrium conditions were influencing recorded carbon isotopic values. The result was lower $\delta^{13}C$ values in proximal settings like we observe in modern carbonate platforms. Even with these local/regional processes influencing recorded $\delta^{13}C$ values they were not enough to result in a systematic relationship between carbon isotopic trends and relative sea level. Our results highlight the importance of detailed sedimentological and sequence stratigraphic analysis when interpreting carbon isotopic trends and the utility of simple statistical methods in establishing relationships between sea level and geochemical datasets. Finally, the lack of evidence for relative sea level as the primary control on carbon isotopic trends in the Madison Shelf has wider implications; these results suggests that relative sea level change was not the primary driver of the globally recognized K—O excursion.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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