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Carbon isotopic record of a platform-to-basin transect through the Permian Reef Complex (Guadalupian) in the Delaware Basin of Texas and New Mexico

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A B S T R A C T

The Guadalupian Permian Reef Complex of the Delaware Basin is one of the most studied carbonate reef systems of the Paleozoic. Despite extensive work on the carbonate sedimentology, sequence stratigraphy, and diagenetic history of the Delaware Basin, a high-resolution carbonate carbon isotope record along a platform to basin transect for the Capitanian (264.3–259.5 Ma, the youngest age of the Guadalupian Epoch) does not yet exist. The carbon isotopic record of the Delaware Basin is important because 1) it allows us to test hypotheses about controls on the carbon isotope proxy, 2) it provides constraints on how well modern carbonate platforms like the Great Bahama Banks serve as analogues for ancient carbonate settings, and 3) these types of restricted basins likely played an important role in Permian carbon cycling and the Capitanian extinctions.

In this study we present 493 new Capitanian carbonate carbon isotopic values paired with a detailed sedimentological and sequence stratigraphic framework from the platform, slope, toe of slope, and deep basin of the Delaware Basin. The bulk of the new $\delta^{13}C$ values fall within the range of previously reported unaltered carbonates from the basin, suggesting that these results record primary environmental processes and were not significantly altered by diagenetic overprinting. With this dataset, we test hypotheses about sources of carbon isotopic variability in shallow carbonate platforms. Our results indicate that in the Delaware Basin there are no systematic and resolvable depth or lateral gradients in carbon isotopic values, that $\delta^{13}C$ values do not vary as a function of grain type, and that there is no resolvable relationship between carbon isotopic composition and sea level change. However, we do document statistically significant differences in $\delta^{13}C$ distributions among facies associations which we attribute to the isotopic evolution of an upwelling water mass due to direct precipitation of mud along the slope. Our results support the idea that increasing carbon isotopic values through the Capitanian were driven by increased organic carbon burial in restricted basins.

1. Introduction

As eloquently stated by Kues and Giles (2004, p. 125), the Guadalupian Permian Reef Complex of the Delaware Basin in west Texas and New Mexico is the “largest, best preserved, most accessible, and most intensively studied Paleozoic reef complex in the world” (see reviews and overviews by Bebout and Kerans, 1993; Tinker, 1998; Saller et al., 1999). Uplift and modern erosion follows paleotopography and has exposed a broadly correlative package of rocks that includes platform top facies atop the Guadalupe Mountains, reef and slope facies at and along the front of the range, and deepwater basinal deposits in the adjacent lowlands. The diversity of carbonate facies is as impressive as the quality of the exposure and includes grape-sized pisoids, *in situ* reef boundstones, and imbricated fusilinid foraminifera up to one inch long. Correlative units in the subsurface are important hydrocarbon producers and represent source, reservoir, and seal rocks. The nature and importance of these rocks has led to the creation of a robust biostratigraphic (Wilde et al., 1999) and sequence stratigraphic framework (e.g. Tinker, 1998; Kerans and Tinker, 1999; Rush and Kerans, 2010) as well as a sound understanding of their diagenetic history (Given and Lohmann, 1985, 1986; Mutti and Simo, 1993; Melim and Scholle, 2002; Bishop et al., 2014).

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Despite decades of work in this area, a high-resolution carbonate carbon isotopic record along a platform to basin transect for the Capitanian (the youngest stage of the Guadalupian Series) does not yet exist for the Delaware Basin. Some carbon isotopic work has been done (e.g. Jin et al., 2012; Present et al., 2019; Smith et al., 2020). Jin et al. (2012) focused on a single section in the basin while Smith et al. (2020) generated a data set that focused on comparing clusters of values from shallow and deep-water sections from the Capitanian. Present et al. (2019) primarily focused on carbonate associated sulfur and used the carbon isotopic data generated to constrain environmental and diagenetic parameters that might have influenced $\delta^{34}S$ values. However, none of these studies paired high resolution carbon isotopic data with detailed sedimentological and sequence stratigraphic information in a way that could allow for investigation into the potential processes driving observed trends. Understanding the details of the Delaware Basin carbon isotopic record is important for the two main reasons described below.

First, the Delaware Basin provides an opportunity to test some of the hypotheses about sources of carbon isotopic variability in carbonate platforms. The Great Bahama Banks (GBB) is one of our best modern analogues for the steep rimmed carbonate platform that formed in the Delaware Basin during the Capitanian (Tinker, 1998; Miall, 2019). The GBB is a flat-topped carbonate platform that formed during the Cretaceous on transitional continental-oceanic crust (Miall and Balkwill, 2019). The modern and ancient environments that comprise the GBB are widely considered to be a classic setting for understanding carbonate sedimentology and sequence stratigraphy. More recently the GBB has become an important location for studies focused on understanding the processes that influence carbon isotopic values of shallow carbonate settings (e.g. Swart, 2008; Geyman and Maloof, 2019, 2021). Studies of this nature are extremely important, especially for carbon isotopic investigations of Paleozoic rocks where shallow epicontinental basins represent the primary record of marine carbonates.

In the last three decades, studies of the GBB have demonstrated that the $\delta^{13}C$ records from shallow carbonate settings are influenced by many processes not linked to changes in global ocean chemistry (e.g. Patterson and Walter, 1994; Swart, 2008; Geyman and Maloof, 2019, 2021). Particularly important findings from the GBB include:

- The carbon isotopic composition of the dissolved inorganic carbon (DIC) in shallow water settings varies by as much as 4 ‰ and can result in systematic $\delta^{13}C$ gradients across the platform (Patterson and Walter, 1994; Geyman and Maloof, 2019, 2021).
- As much as 10 ‰ variability in the $\delta^{13}C$ record of carbonate sediments across the platform has been attributed to systematic differences in the carbon isotopic signature of different carbonate grain types (Geyman and Maloof, 2021).
- Studies of Miocene to Holocene sediment from the GBB suggest that there is a direct causal link between sea level change and recorded $\delta^{13}C$ not related to changes in global ocean chemistry (Swart and Eberli, 2005; Swart, 2008; Smith and Swart, 2022).

These studies of the GBB indicate that the $\delta^{13}C$ records from shallow carbonate settings are significantly influenced by factors that are not related to changes in global ocean chemistry, which complicates efforts to use these archives to reconstruct changes in the global carbon cycle. This begs the question, how many of these observations from the GBB typify shallow carbonate platforms from the ancient record and how many of these findings are unique to the GBB? In this study of the Permian Reef Complex in the Delaware Basin, we attempt to test many of the hypotheses derived from work on the Great Bahama Banks. These results allow us to test how well modern carbonate platforms like the GBB serve as analogues for ancient carbonate settings, and aid in distinguishing between global versus platform specific influences on carbon isotopic patterns.

If platform-specific processes have not completely overwhelmed the carbon isotopic signal, detailed documentation of the $\delta^{13}C$ record from the Delaware Basin could provide important information about carbon cycling in the Permian and the role of restricted basins in the Capitanian extinction events. Korte et al. (2005) generated one of the first comprehensive $\delta^{13}C$ compilation curves for the Permian using diagenetically-screened brachiopods. The Capitanian portion of that curve comes from the Delaware Basin and Korte et al. (2005) noted the systematically higher $\delta^{13}C$ values recorded in that basin and interpreted them to likely be a "geographic effect" due to the restriction of the Delaware Basin. However, Isozaki et al. (2011) noted similarly high carbon isotopic values (>4 ‰) from Capitanian strata in Croatia, Japan, East Greenland, and Svalbard and they argued that because this "Kamura event" was observed in geographically widespread basins that it must be global. Isozaki et al. (2011) interpreted the "Kamura event" as the product of eutrophication of shallow marine waters and linked it to extinction events in those affected basins. This idea has been expanded further by studies of carbon isotopes in China that also record systematically high carbon isotopic values (Cao et al., 2018). Cao et al. (2018) noted that the timing of high values varies across basins and argue that the difference in timing could reflect multiple episodes of anoxic upwelling during the Capitanian. Overall, it's clear that multiple basins record higher carbon isotopic values during the Capitanian but the timing and relationship to environmental perturbations remains uncertain. Assessing the "Kamura event's" timing and relationship to environmental conditions requires high resolution $\delta^{13}C$ records linked to a detailed sedimentological and sequence stratigraphic framework in areas with good chronostratigraphic control.

In this study we provide the first high resolution carbon isotopic record along a platform to basin transect in the Capitanian portion of the Delaware Basin. This $\delta^{13}C$ record is integrated with paired sedimentological observations made within the established sequence stratigraphic framework. We use this dataset to test hypotheses about sources of carbon isotopic variability based on observations from the Great Bahama Banks. Specifically, we assess whether $\delta^{13}C$ values vary because of:

1. Spatial gradients in the Delaware Basin
2. Differences in the type of carbonate component sampled
3. Differences between depositional environments (facies associations)
4. Changes in sea level.

Our Delaware Basin carbon isotopic dataset also contributes to the type of information that is needed to compile a high-resolution dataset that can be used to understand the nature of the Permian carbon cycle, the role that these semi-restricted basins played in carbon cycling, and the connection to Permian extinction events.

2. Geologic background

The Delaware Basin is an epicontinental basin that developed during the Middle-Late Mississippian (Ewing, 2019). It is one of three main basins that comprise the Permian Basin of western Texas and southeastern New Mexico and is of economic significance because it hosts significant oil, gas, and potash resources. During the Guadalupian, the Delaware Basin was positioned near the equator and had an intermittent connection with the Panthalassa Ocean through the Hovey and/or Diablo channels (Ward et al., 1986; Hill, 1999). The connection with the ocean allowed for the development of the extensive carbonate deposits that are the focus of this study.

2.1. Sedimentology and stratigraphy

Lithostratigraphic subdivisions of the Permian Reef Complex generally follow major sub-environments in the basin (Fig. 1). In this study we focus on the carbonate-dominated shelf deposits of the Yates and Tansill Formations (Artesia Group), shelf-margin reef deposits of the Capitan Formation (a minor part of this study), and the slope-basin

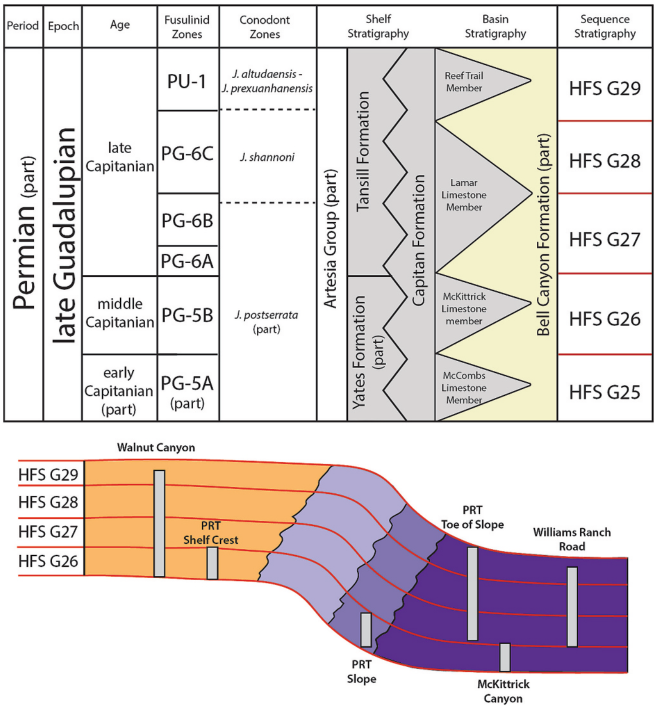

Fig. 1. Lithostratigraphy, biostratigraphy, and sequence stratigraphy for the Delaware Basin modified from Rush and Kerans (2010) and Wu et al. (2020) - which build upon Tyrrell (1962)), Esteban and Pray (1983), Tinker (1998), Kerans and Tinker (1999), Wilde et al. (1999), and Lambert et al. (2002). Fusilinid zone abbreviations are: PG-5A – *Polydiexodina* (Skinner, 1971), *Codonofusiella paradoxica* (Dunbar and Skinner, 1937), *Leella bellula* (Dunbar and Skinner, 1937); PG-5B - *Codonofusiella extensa* (Skinner and Wilde, 1955); PG-6A - *Yabeina texana* (Skinner and Wilde, 1955); PG-6B - *Paradoxiella pratti* (Skinner and Wilde, 1955); PG-6C - *Reichelina lamarensis* (Skinner and Wilde, 1955); PU-1 – *Paraboultonia* (Skinner and Wilde, 1954) -*Lantschichites* (Tumanskaya, 1953), *Cordonofusiella, Reichelina*. Conodont names are: *Jinogondolella postserratta* (Mei et al., 1998), *Jinogondolella shannoni* (Wardlaw and Mei, 1998), *Jinogondolella altudaensis* (Kozur, 1992), *Jinogondolella prexuanhanensis* (Mei et al., 1998). Relative position and stratigraphic duration of the sections targeted in this study are indicated with the grey bars. PRT refers to Permian Reef Trail locations.

carbonates of the Bell Canyon Formation (including the McKittrick limestone, Lamar Limestone, and Reef Trail Members). Previous studies placed these units into fusulinid-based biozones (Fig. 1) and recent U—Pb dates from ash beds in the Delaware Basin provide additional chronostratigraphic constraints (Wu et al., 2020).

Cyclicity related to eustatic fluctuations and likely the demise of the Late Paleozoic Ice Age has long been recognized in the Delaware Basin (Ross and Ross, 1987; Gardner, 1992; Tinker, 1998; Kerans and Tinker, 1999; Rygel et al., 2008; Rush and Kerans, 2010). Tinker (1998) applied a formal sequence stratigraphic framework to the upper Guadalupian exposures in the Delaware Basin; the framework was later modified and extended into Leonardian strata by Kerans and Tinker (1999). Although it can be challenging to track the evolution of sequence stratigraphic terminology applied to these strata, we use the relatively recent summary provided by Rush and Kerans (2010) who describe four levels of stratigraphic architecture including parasequences (their "cycles"), lowstand, transgressive, and highstand systems tracts (which closely match their "cycle sets"), sequences (their "high-frequency sequences" which are designated with the prefix "HFS", a letter for age ["G" for Guadalupian and "L" for Leonardian] and sequentially numbered from oldest to youngest), and composite sequence cycles (generally designated with "SR" for those in the Seven Rivers Formation and a "Y" for those in the Yates Formation).

2.2. Study sections and intervals

We generated a carbon isotopic record for a platform to basin transect for the Capitanian, when the platform geometry was fully established in the Delaware Basin (Kerans and Tinker, 1999). To accomplish this, we built upon previous studies and focused on the following locations and intervals (Figs. 1 and 2; all coordinates are in WGS 84):

1. Walnut Canyon in Carlsbad Caverns National Park: Shelf deposits in Rush and Kerans' (2010) Sections E and F (uppermost HFS G25 through mid-HFS G29) in the Yates and Tansill Formations. The base of our Walnut Canyon measured section is 32.18343 N, 104.38291 W.
2. Permian Reef Trail (PRT) in Guadalupe Mountains National Park: Outer shelf and shelf crest deposits (Stops 23–28; HFS G26) of the Yates and Tansill Formations, slope deposits (Stops 9–14; HFS G26) adjacent to the Capitan Formation, and toe of slope (Stops 2–8; HFS G27 through mid-HFS G29) of the Lamar Limestone Member of the Bell Canyon Formation (the "stops" are from Bebout and Kerans, 1993). The base of our PRT – Shelf Crest section is 31.99830 N, 104.75622 W. The base of our PRT – Slope section is 31.99314 N, 104.76001 W. The base of our PRT – Toe of Slope section is 31.98409 N, 104.75591 W.
3. Mouth of McKittrick Canyon in Guadalupe Mountains National Park: Toe of slope deposits (HFS G26) in the McKittrick Limestone member of the Bell Canyon Formation described by Present et al. (2019). The base of our McKittrick Canyon section is 31.97982 N, 104.75631 W.
4. Williams Ranch Road in Guadalupe Mountains National Park: Basinal deposits (HFS G27 through part of HFS G29) of the Lamar Limestone and Reef Trail Members of the Bell Canyon Formation described by Fall (2010). The base of our William Ranch Road section is 31.83080 N, 104.86811 W.

2.3. Previous carbon isotopic studies

Previous Capitanian carbon isotopic studies of the Delaware Basin generally focused on constraining the diagenetic history of these rocks (Given and Lohmann, 1985, 1986; Mutti and Simo, 1993; Melim and Scholle, 2002; Chafetz et al., 2008; Bishop et al., 2014; and Present et al., 2019). Diagenetic studies focused on carbon and oxygen isotopic constraints on marine cements (Mutti and Simo, 1993; Bishop et al., 2014), meteoric cements (Given and Lohmann, 1985, 1986; Bishop et al., 2014), and dolomite (Melim and Scholle, 2002) in the basin. Chafetz et al. (2008) identified preserved aragonitic cements from tepee structures in the Yates Formation. Aragonite is easily altered, and these cements are interpreted to record primary sea water chemistry. Combined, these digenetic studies demonstrate that primary Capitanian δ^{13}C values can be recovered from the Delaware Basin (even from the shallow shelf environments) and that values generally range from 4 to 7 ‰ (Given and Lohmann, 1985; Chafetz et al., 2008; Present et al., 2019). These studies also provide a framework for identifying diagenetic phases, because post-depositional cements are characterized by systematically low δ^{13}C and δ^{18}O values ($<$0.5 ‰ and < -6.8 ‰ respectively; Mutti and Simo, 1993).

In addition to these diagenetic studies, other studies have tried to improve our understanding of Capitanian carbon cycling in the Delaware Basin (Jin et al., 2012; Smith et al., 2020). Jin et al. (2012) generated high-resolution carbonate δ^{13}C and δ^{18}O, organic carbon δ^{13}C, total organic carbon, and Ca/Mg records for a 9 m section of the Lamar Limestone Member. This geochemical dataset was paired with detailed sedimentological information. Smith et al. (2020) measured carbonate δ^{13}C and δ^{18}O values and elemental concentrations from shelf and basin sections to test for basin stratification and anoxia. It is important to note that Smith et al. (2020) were comparing carbon isotopic distributions from the shelf and basin during select time slices and did not present high-resolution records paired with detailed

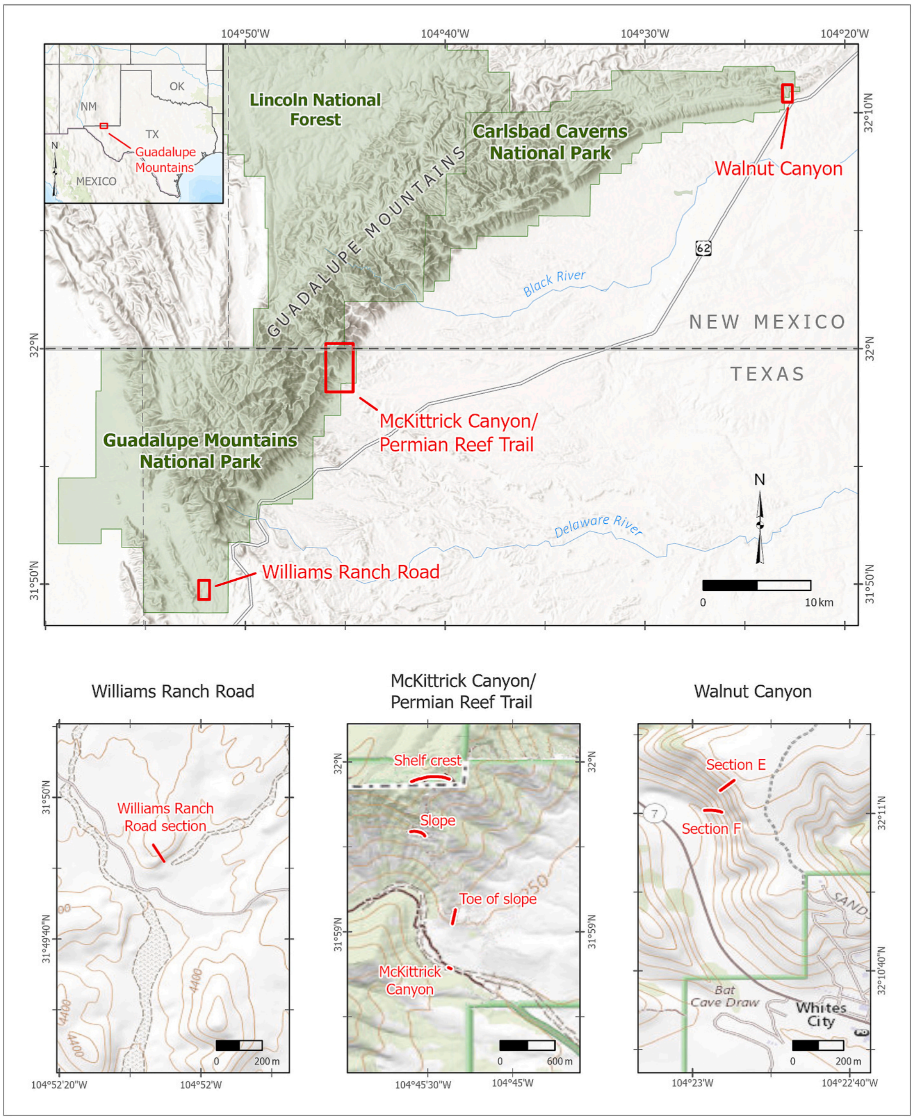

Fig. 2. Map showing the study areas in Guadalupe Mountain National Park and Carlsbad Caverns National Park. The approximate extent of measured sections in this study are shown as red lines on the detailed location maps; coordinates for the base of the sections are provided in the body of the text. Basemap data from Texas Parks & Wildlife, CONANP, TomTom, Garmin, SafeGraph, FAO, METI/NASA, USGS, EPA, NPS, USFWS, Esri, TomTom, NOAA, NGA, USGS The National Map: National Boundaries Dataset, 3DEP Elevation Program, Geographic Names Information System, National Hydrography Dataset, National Land Cover Database, National Structures Dataset, and National Transportation Dataset; USGS Global Ecosystems; U.S. Census Bureau TIGER/Line data; USFS Road data; Natural Earth Data; U.S. Department of State HIU; NOAA National Centers for Environmental Information. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sedimentological information. Based on this data, Smith et al. (2020) argued that increased salinity, reduced mixing, and anoxia were likely primary drivers of faunal turnover in the Delaware Basin.

3. Methods

3.1. Measured sections and petrographic samples

Our work was conducted entirely within the Guadalupe Mountains National Park (permit # GUMO-2023-SCI-0001) and Carlsbad Caverns National Park (permit # CAVE-2023-SCI-0001) and any samples not destroyed in analysis were returned to the respective parks and archived there. The study intervals were, to varying degrees, described and measured by previous authors (Bebout and Kerans, 1993; Fall, 2010; Rush and Kerans, 2010; Present et al., 2019). We identified key stratigraphic markers in these sections and made our own detailed measurements that were calibrated to the existing sedimentological and stratigraphic framework (see supplemental materials for detailed measured sections).

We collected 88 brick-sized samples to provide additional sedimentological information and document any patterns in dolomitization. All samples were cut in half and one side was polished for targeted geochemical sampling and more detailed lithological description. Based on preliminary observations from these slabbed samples, we selected 51 for additional petrographic analysis. The non-polished halves of these samples were made into a thin sections that were stained with potassium ferricyanide to detect ferrous iron and Alizarin Red to distinguish between calcite and dolomite (thin sections were prepared by Spectrum Petrographics Inc.).

3.2. Carbon isotopic samples and analyses

Samples for carbonate carbon isotopic analyses were tied to the measured sections and thus their sedimentological and sequence stratigraphic context. Samples were broken in half to expose a fresh surface. One half of the sample was tested for calcite vs. dolomite by applying a small drop of 10 % HCL. The other half of the sample was powdered using a low-speed drill. For carbonate mudstones and wackestones, we targeted micritic portions of the samples because the lower permeability of mud is less susceptible to post-depositional alteration when compared to allochems (e.g. Hayes et al., 1989). For packstones and grainstones, we targeted the dominant allochem(s) in the sample (skeletal fragments, pisoids, peloids, and/or ooids) so that we could test for systematic differences in geochemical composition among the grain types. When drilling, we avoided fractures, stylolites, and clear cements. For 11 of our PRT-Slope samples, we cut paired slabs and used one half for petrographic analysis and the other was polished and selectively drilled for sample powders. This technique allowed us to constrain δ^{13}C variability by targeting a variety of lithologies including recrystallized mud and fossils, pristine mud and fossils, intraclasts, spar, and *Archaeolithoporella*. Sample lithologies and details are provided in the supplemental materials file.

Sample powders were analyzed for bulk carbonate δ^{13}C and δ^{18}O values on 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. Analytical precision is ±0.04 ‰ (1 standard deviation) for δ^{13}C and ± 0.08 ‰ (one standard deviation) for δ^{18}O based analyses of NBS-19 and an internal laboratory standard analyzed during this study.

3.3. Statistical analysis

We used statistical tests for correlation and comparisons of population means. To test for systematic differences in carbon isotopic distributions as a function of position relative to shoreline, grain type, and facies association we performed a series of One-Way ANOVA tests. ANOVA analysis is used to test for differences in means of two or more groups of data. If the *p*-value of an ANOVA analysis is less than 0.05, then we can reject the null hypothesis that the groups have equal means. But, the ANOVA test does not tell us which groups are distinct, for that information we included the Tukey HSD post hoc *t*-test to determine which datasets are significantly different from each other. All ANOVA tests were completed using the IBM SPSS Statistics 22 package (IBM Corp., 2021).

To test for correlation between carbon isotopic trends and sea level change, we deployed the statistical approach outlined in Quinton et al. (2023) and Quinton and Rygel (2023). A Spearman's Rank Correlation analysis is used to test for correlation of carbon isotopic values and meterage within the transgressive systems tract (TST) and highstand systems tract (HST) of a High Frequency Sequence (HFS). A HFS passes this test, and therefore records statistically significant correlation between δ^{13}C and sequence stratigraphic framework, if there was a strong correlation (Spearmen Rank Correlation Coefficient $r_s > 0.5$ or < -0.5) and the *p*-value is <0.05 for both system tracts. For those HFSs with significant scatter in δ^{13}C values, we deployed the modified statistical approach from Quinton and Rygel (2023) for noisy data sets. The Gaussian correlation test for noisy data was performed in R using the RoCoCo - R Package from Bodenhofer et al. (2013).

4. Results

4.1. Facies analysis and sequence stratigraphic framework

Using previous work (primarily Bebout and Kerans, 1993 and Rush and Kerans, 2010) and our own observations, we developed a 12-fold facies association scheme that captures the full spectrum of environments from shelf to basin and interpreted our sections using this framework. Each facies association is designated with a letter and a unique color in Fig. 3 (relative positions) and Fig. 4 (idealized portrayal and brief description); a key for symbology is provided in Fig. 5. Although measured sections were calibrated to important sequence surfaces and marker beds identified in previous studies, facies analysis allowed for (in some cases) parasequence-level correlation with previous studies. Summary measured sections with our observations, interpretations, and correlations are provided in Figs. 6–11 and more detailed sections are provided in the supplementary materials.

Whenever possible, we used existing sequence stratigraphic frameworks and tied out sections to them. For the Walnut Canyon section, sequence boundaries, maximum flooding surfaces, and in many cases parasequences were precisely located using the detailed photomosaic and tracing provided by Rush and Kerans (2010); their Fig. 6). Their placements were based on facies changes and stratal geometries along the ~500 m-wide-exposure along the east wall of the canyon just inside of the park boundary. At Walnut Canyon (and any other location that parasequences were identified) we used their nomenclature, where parasequences are numbered with their associated HFS and the sequence in which they appear (ex. the first parasequence in HFS G26 is P G26.1 and the second parasequence is P G26.1).

Sequence boundaries for the Permian Reef Trail sections (Toe of Slope, Slope, and Shelf Crest) were based on the measured sections and correlation panels provided in Bebout and Kerans (1993) and the chapters therein. Maximum flooding surfaces were not identified by these authors and we used our sections to place the MFS at the base of the deepest water deposits within each sequence. Parasequences were not recognized in the Toe of Slope nor Slope sections in previous publications or in this study. Shallowing-upward cycles were recognized in

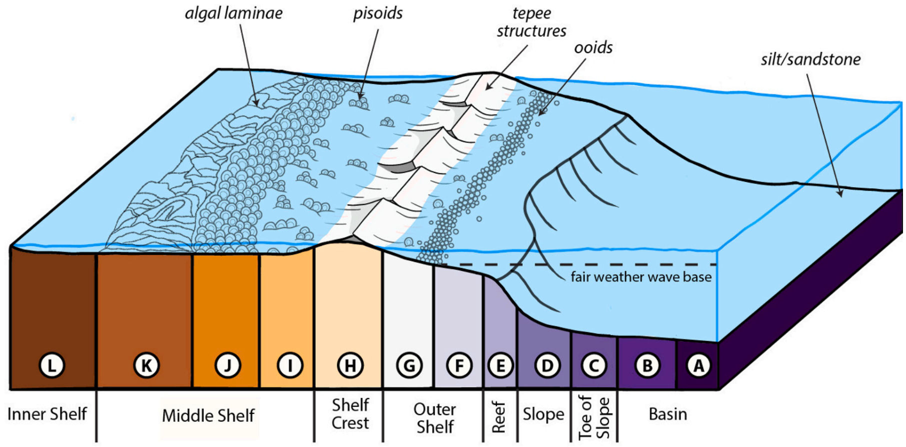

Fig. 3. Depositional environments for the Delaware Basin modified from Tinker (1998) and Rush and Kerans (2010). Facies associations used in this study (identified by color and letter) are modified from those used in Rush and Kerans (2010) and Bebout and Kerans (1993).

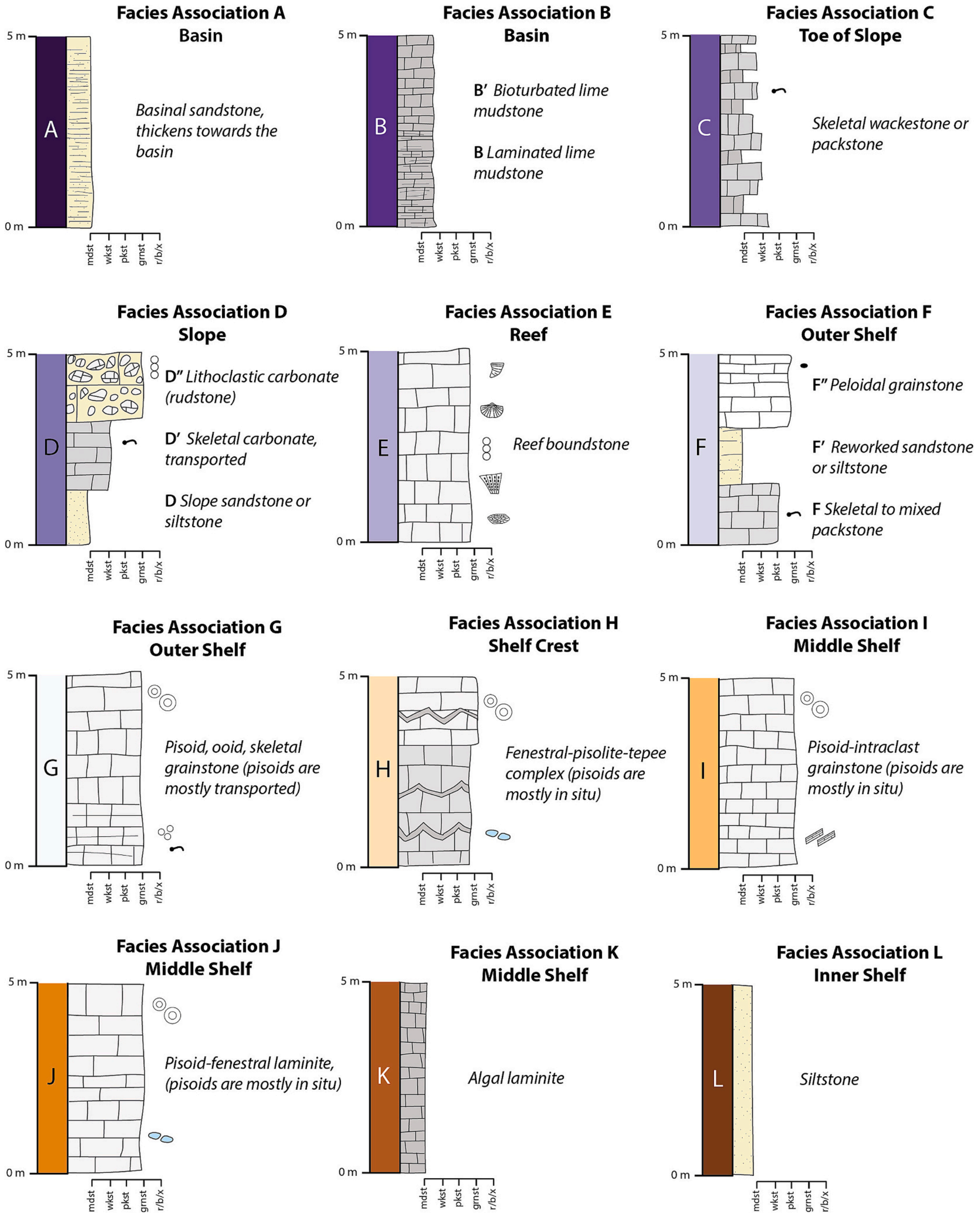

Fig. 4. Descriptions of facies associations, modified from Bebout and Kerans (1993) and Rush and Kerans (2010).

the Shelf Crest section; although detailed bed-by-bed correlation was not possible given the nature of the outcrop, our parasequence calls largely follow their cycles.

To our knowledge, there was no sequence stratigraphic framework previously established for the Williams Ranch Road section. The HFS G27 sequence boundary is placed at the base of the siltstone following Tinker (1998) and the HFS G29 sequence boundary was placed at the boundary between the Lamar Limestone Member and the Reef Trail Member following Kerans et al. (2017). The placement of the HFS G28 sequence boundary is approximate and positioned at the contact between a packaged of thin bedded skeletal lime mudstone and an overlying thinly laminated cherty lime mudstone.

4.2. *Petrographic analysis*

Thin sections were used to supplement field descriptions and to document any systematic relationships between lithology, dolomitization, and different generations of cement. Petrographic analysis aided in our facies interpretations where field-based observations were not sufficient (e.g. identification of peloidal grainstones which in the field can be mistaken for lime mudstone). Staining with Alizarin Red indicated that of the 49 carbonate samples, 15 samples exhibited little to no dolomitization and two exhibited complete dolomitization, but the original fabric was still intact. The remaining 32 samples had partial dolomitization, much of it was fabric selective in individual samples, but there were no systematic patterns in whether the cements, mud, or grains were dolomitized. Only three samples exhibited notable staining indicating the presence of ferrous iron; none of them showed any

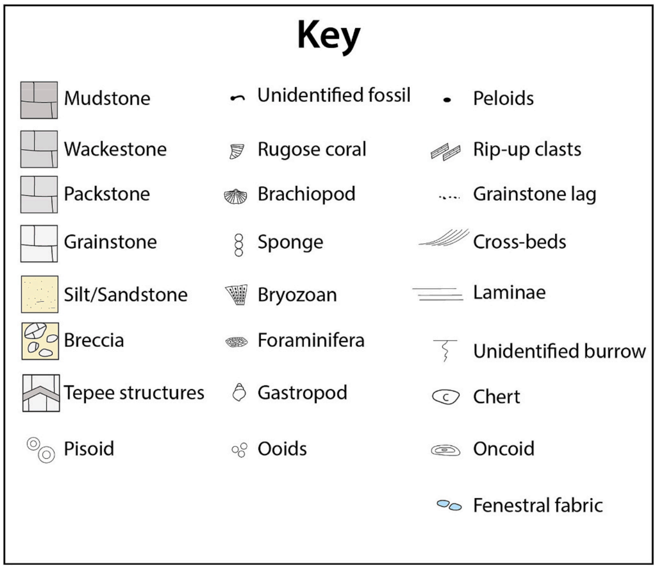

Fig. 5. Lithology and symbol key for measured sections.

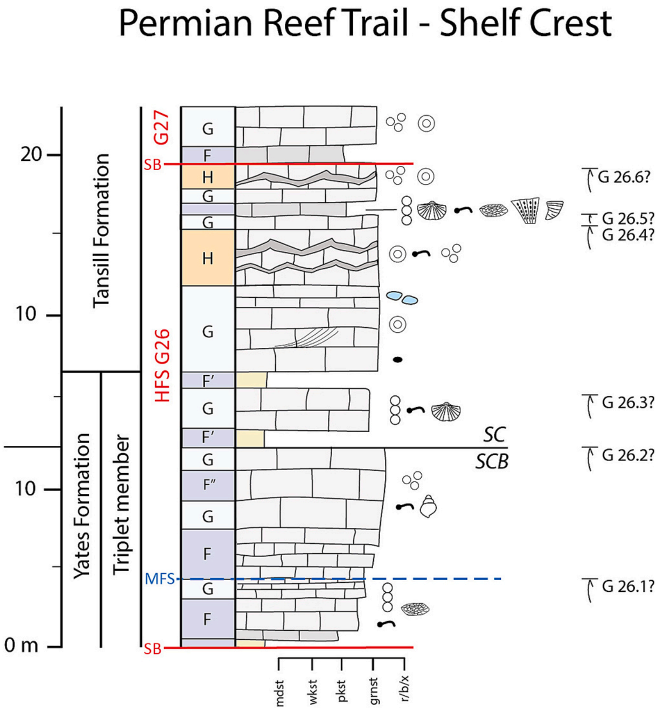

Fig. 6. Summary measured section for Permian Reef Trail- Shelf Crest. Sedimentological and facies association interpretations are from this study. Sequence stratigraphic boundaries and parasequence placements are modified from Kerans and Harris (1993).

systematic patterns in its distribution. Petrographic descriptions are provided in Table S1 in the supplemental materials file.

4.3. Carbon isotopes

We present 493 new carbonate carbon and oxygen isotopic values for a shelf to basin transect of the Delaware Basin in Fig. 12 (a complete data table with all reported values is included in the supplementary materials file, Table S2). Values reported herein average 4.4 ‰, which matches values previously reported for the Delaware Basin (Korte et al., 2005; Jin et al., 2012; Smith et al., 2020) and for the Capitanian elsewhere (Bond

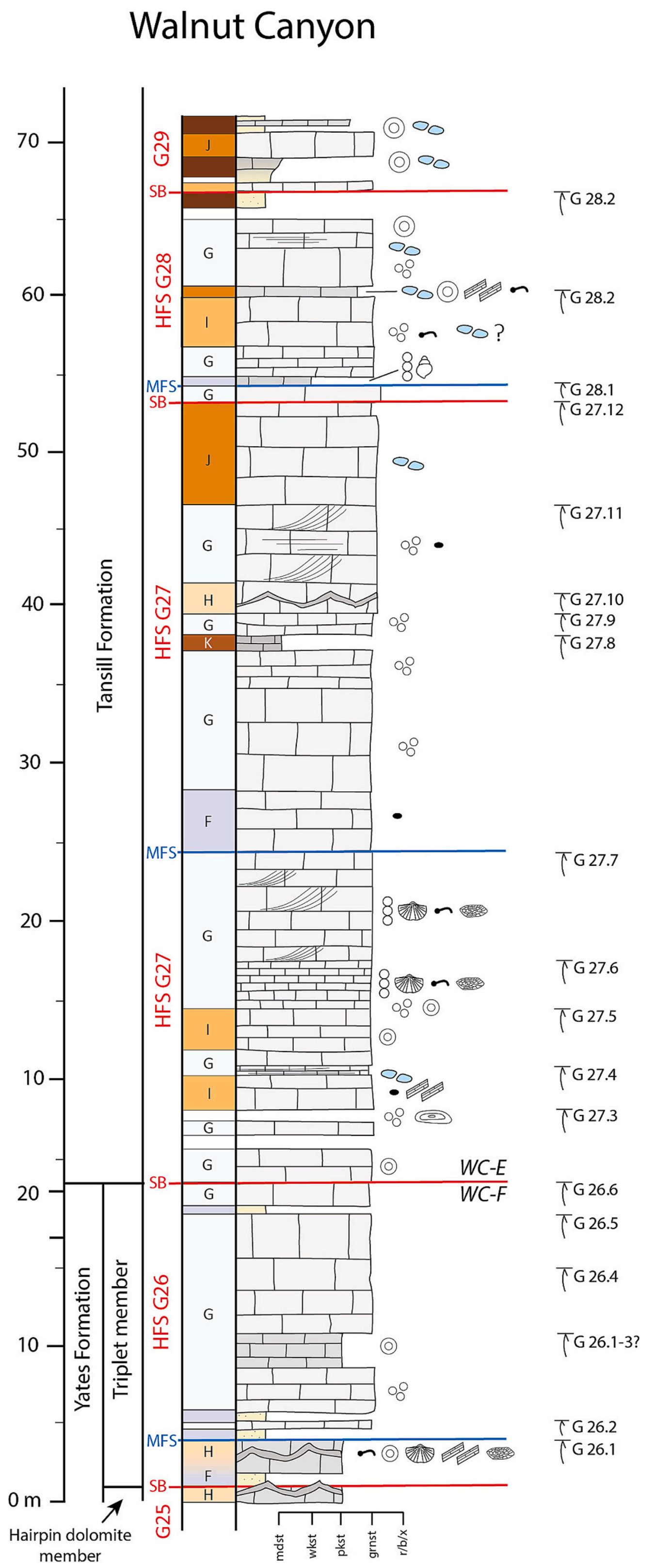

Fig. 7. Summary measured section for Walnut Canyon. Note that this composite section is composed of Rush and Kerans (2010) closely spaced sections E and F. Sedimentological and facies association interpretations are from this study. Sequence stratigraphic boundaries and parasequence placement are modified from Rush and Kerans (2010).

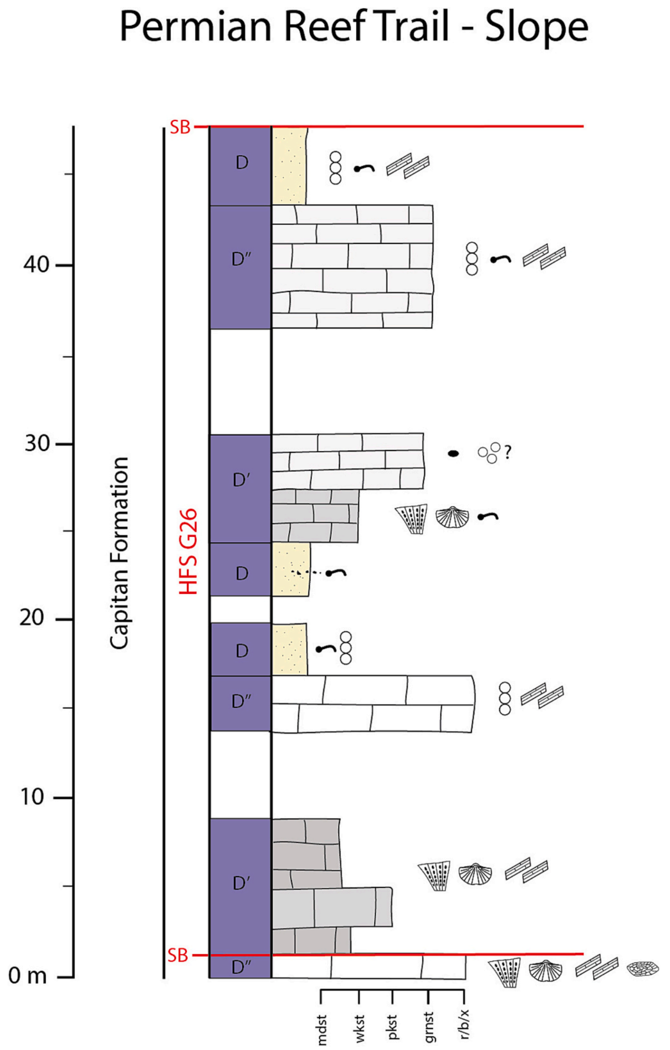

Fig. 8. Summary measured section for Permian Reef Trail - Slope. Sedimentological and facies association interpretations are from this study. Sequence stratigraphic boundaries are modified from Mruk and Bebout (1993).

et al., 2010; Tierney, 2010; Isozaki et al., 2011; Cao et al., 2018; Arefifard et al., 2022). We observe a general trend of decreased δ^{13}C variability and an increase in values from ~4 ‰ to ~4.6 ‰ through the Capitanian. This result is consistent with the trend towards increasing values documented in other basins (Bond et al., 2010; Tierney, 2010; Isozaki et al., 2011).

Results from all statistical tests are reported in Tables 1 and 2. The only ANOVA tests that returned statistically significant correlations (p-values <0.05) were those comparing carbon and oxygen isotopic values by facies association and comparisons of the carbon and oxygen isotopic values of HFS G26, G27, and G28. Additionally, the ANOVA test comparing oxygen isotopic values from the Walnut Canyon, PRT- Toe of Slope, and Williams Ranch Road sections (our shelf to basin transect) returned a p-value <0.05. None of the high frequency sequences analyzed passed the test for statistically significant correlation with δ^{13}C.

5. Discussion

5.1. Do the carbon isotopic values represent primary ocean water chemistry of the Delaware Basin?

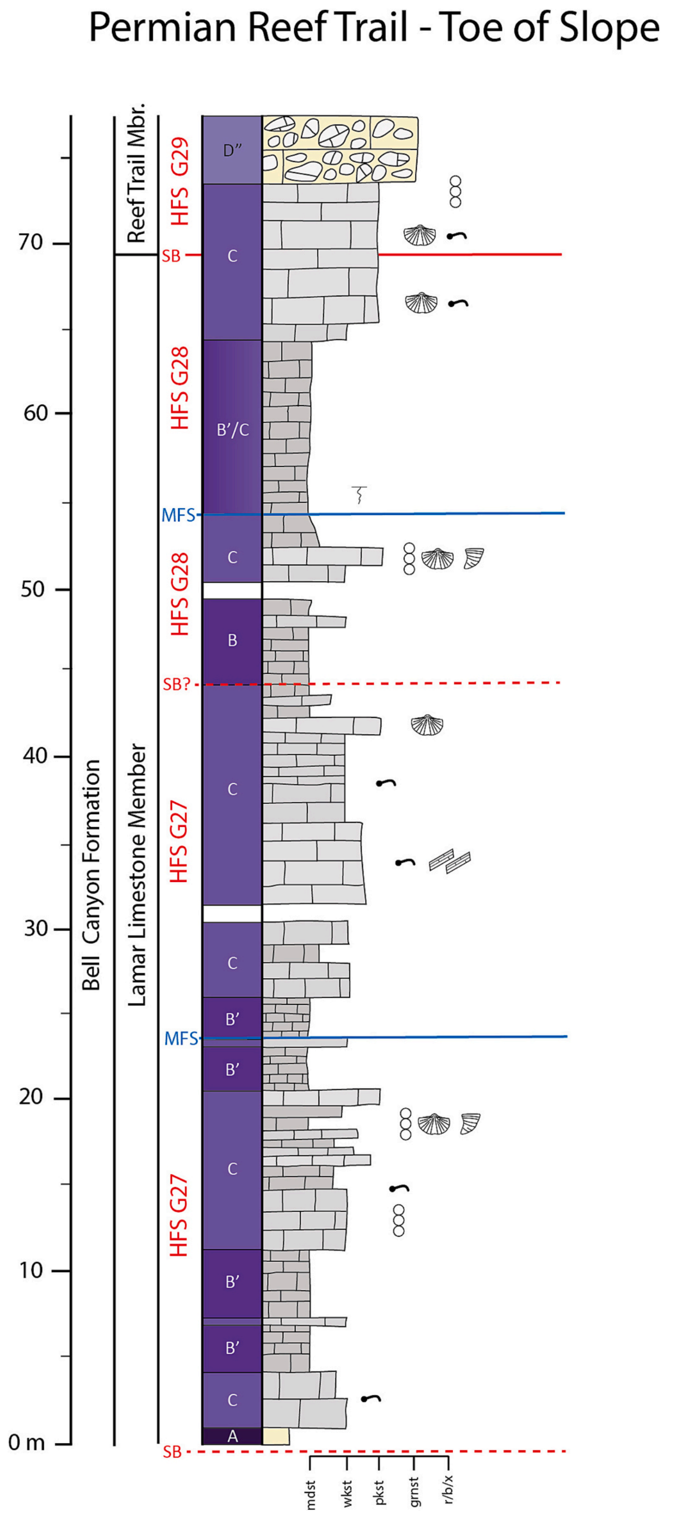

Fig. 9. Summary measured section for Permian Reef Trail - Toe of Slope. Sedimentological and facies association interpretations are from this study. Sequence boundaries are modified from Brown and Loucks (1993), maximum flooding surfaces (MFS) are positioned based on facies association stacking patterns. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The carbon isotopic results from this study are interpreted to reflect primary values and trends of ocean water chemistry within the Delaware Basin. We argue that this is the best interpretation for the following reasons: 1) our values are similar to those reported from other coeval basins, 2) the diagenetic history of these rocks is well constrained by

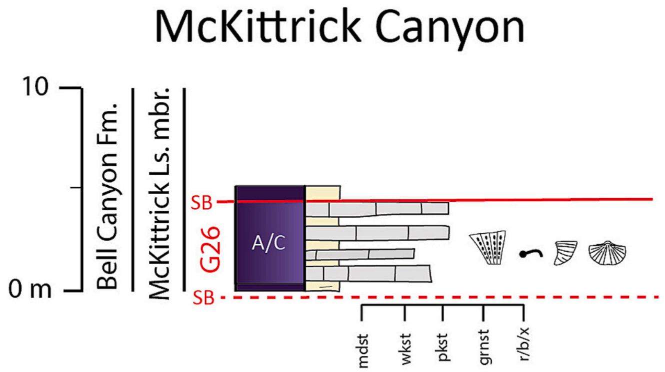

Fig. 10. Summary measured section for McKittrick Canyon. Sedimentological and facies association interpretations are from this study. Sequence boundaries are modified from Bebout and Kerans (1993) and chapters therein.

previous geochemical and petrographic studies and our values fall outside of identified diagenetic ranges, 3) our targeted sampling of slabs and petrographic analysis supports the interpretation that diagenetic phases record lower δ^{13}C and δ^{18}O values than the bulk of our data, and 4) co-variation in carbon and oxygen isotopic values is easily explained by primary processes operating in a restricted basin. We discuss each of these reasons in more detail below.

Our results are best interpreted as primary because the values and trends are similar to those reported elsewhere for the Capitanian (e.g. Bond et al., 2010; Tierney, 2010; Isozaki et al., 2011; Cao et al., 2018; Arefifard et al., 2022). It is unlikely that diagenetic processes will result in alteration to similar values and trends in geographically widespread basins. The one exception is what Smith and Swart (2022) refer to as a global diagenetic event, where a global fall in sea level can result in diagenetic alteration of exposed basins. The result is a systematic decrease in δ^{13}C values across geographically widespread basins. However, in such a scenario we would except to observe a correlation between carbon isotopic values and sea level change in our dataset. However, we found no such evidence (section 3.3 and discussed in detail in section 5.2.4). Based on these results, we argue that a global diagenetic event does not explain the similar trends across basins. Instead, the similarity of values and trends across basins suggests that data from the Delaware Basin records primary environmental processes.

Furthermore, the lack of diagenetic overprinting is supported by the well-constrained diagenetic history of the Delaware Basin (Given and Lohmann, 1985, 1986; Mutti and Simo, 1993; Melim and Scholle, 2002; Chafetz et al., 2008; Bishop et al., 2014; Present et al., 2019; Smith et al., 2020). These studies established the range of carbon and oxygen isotopic values for altered versus primary phases using a variety of petrographic and geochemical measures. These ranges are indicated in Fig. 13 along with geochemical data from this study. Syndepositional alteration and cementation is argued to have occurred in a low water to rock marine sourced fluid so the carbon isotopic values of these phases should reflect a primary marine signal (Given and Lohmann, 1985; Mutti and Simo, 1993). Post-depositional cements in the basin are depleted with respect to ^{13}C (carbon isotopic values <0.5 ‰), and ^{18}O (oxygen isotopic values <-6.8 ‰) (Mutti and Simo, 1993). The values we report are generally much higher than cement values and much more closely match those reported from intact, unaltered aragonite cements from tepee structures on the platform (Chafetz et al., 2008). Our results also generally fall within the range of values Smith et al. (2020) interpreted as primary using Mn/Sr values and petrographic analysis to screen δ^{13}C data in the Delaware Basin. In short, our results are not consistent with identified diagenetic end members but instead match those of carbonates interpreted as primary in the basin.

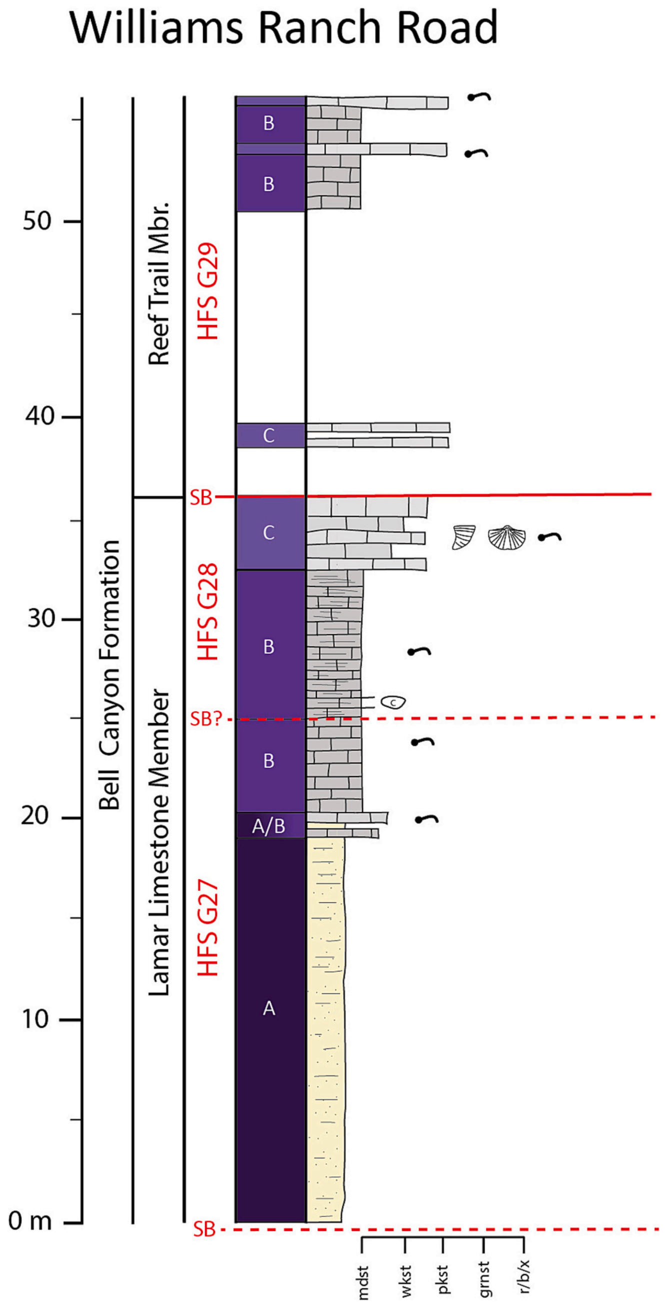

Fig. 11. Summary measured section for Willams Ranch Road. Lithostratigraphy from Fall (2010).

Results from selective drilling of slabs and petrographic analysis as part of this study provide additional constraints on diagenetic end members and support the interpretation that our δ^{13}C values are primary. Given the extensive diagenetic work already completed on the basin (e.g. Given and Lohmann, 1985, 1986; Mutti and Simo, 1993; Melim and Scholle, 2002; Chafetz et al., 2008; Bishop et al., 2014; Present et al., 2019; Smith et al., 2020) we primarily relied on those studies as a framework for constraining diagenesis. Targeted drilling of slabs supports findings of these previous studies that post-depositional phases (e.g. spar and even recrystallized mud) do record low δ^{13}C and δ^{18}O values compared to unaltered phases. The fact that the bulk of our data fall outside of this range indicates that the δ^{13}C values from this study are primary. Secondly, we found no systematic relationship between grain type (coarse vs. fine) and carbon isotopic values as might be expected if the samples were influenced by diagenetic fluids (Table 1, *p*-value = 0.056). The higher permeability and porosity of coarse-grained lithologies generally make them more susceptible to diagenetic alteration than their fine-grained counterparts (Hayes et al., 1989). Finally,

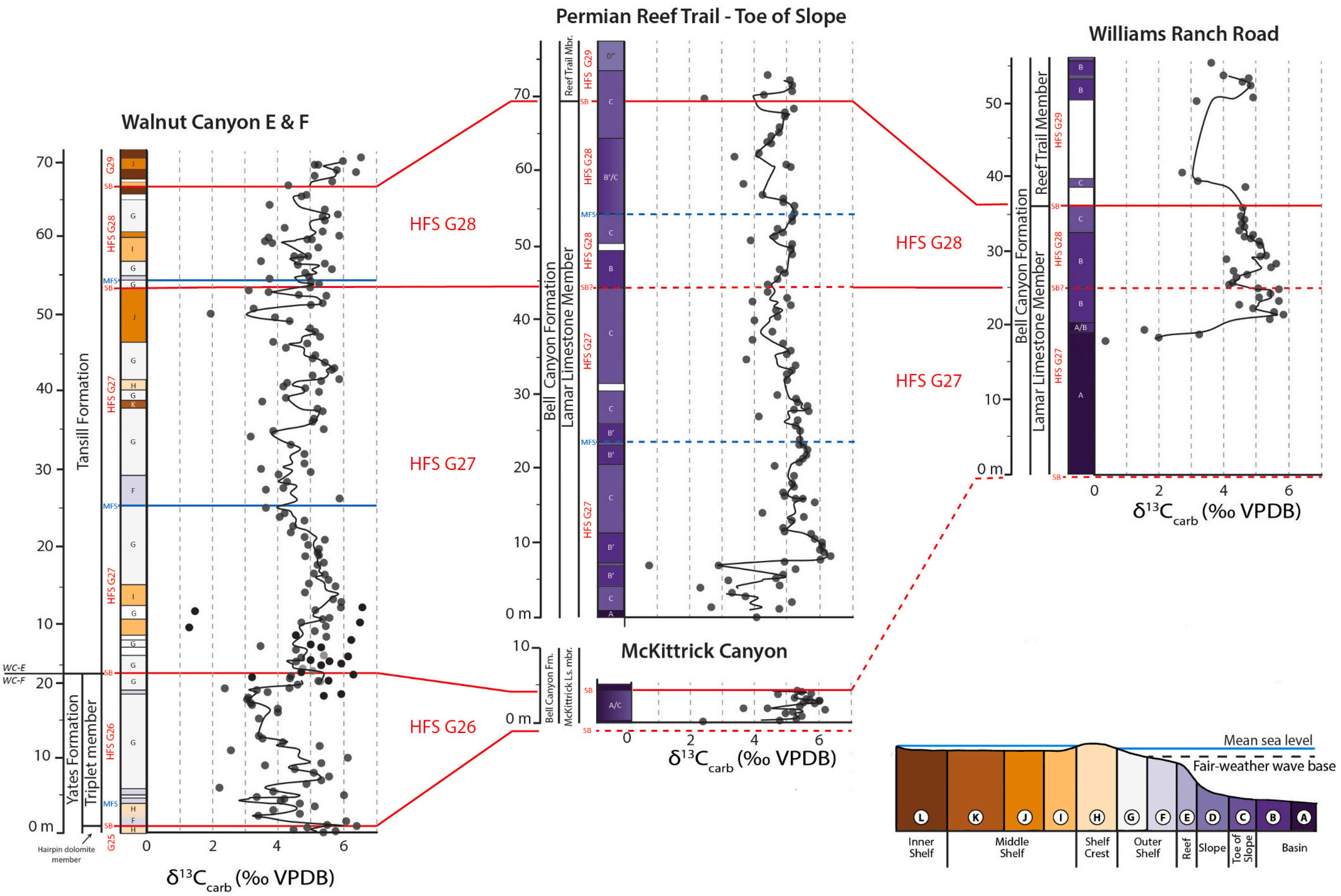

Fig. 12. Sequence stratigraphic correlation and carbon isotopic trends from this study. Three point moving averages for the carbon isotopic values are plotted as a black line. Sequence boundaries are indicated with horizontal red lines and maximum flooding surfaces with horizontal blue lines. The study sections are arranged so that the most proximal section (Walnut Canyon) is on the left and the most distal study section (Williams Ranch Road) is on the right. Facies associations are color coded and identified with a letter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dolomitization was minor in our geochemical samples (Table S2 in supplementary material file, 17 out of 493 geochemical samples).

It should be noted that we do observe statistically significant correlation between carbon and oxygen isotopic values (Fig. 13). In the past, covariation in carbon and oxygen isotopic values was used as an indication for digenetic influence (Allan and Matthews, 1982; Marshall, 1992). However, recent work on the well constrained diagenetic history of the Great Bahama Banks has demonstrated that correlation between carbon and oxygen isotopic values is not a definitive mark of alteration (Swart and Oehlert, 2018). Furthermore, there are completely feasible, non-diagenetic reasons why carbon and oxygen isotopic values might co-vary:

1. Basin restriction and lack of mixing with the open ocean could lead to the isotopic evolution of the basin as net evaporation drives oxygen isotopic values higher and organic carbon burial drives carbon isotopic values higher (a process that has been invoked in the Delaware Basin by Smith et al. (2020)).
2. An influx of meteoric water (with low $\delta^{18}O$ and $\delta^{13}C$) could shift the carbon and oxygen isotopic value of the water in a basin.
3. If observed globally, enhanced organic carbon burial could led to global cooling. The enhanced organic carbon burial would result in increasing $\delta^{13}C$ values and the cooling temperatures would cause $\delta^{18}O$ values to increase.

In all these cases, co-varying carbon and oxygen isotopic values would be a direct result of primary processes operating in the basin, not an indication of diagenesis.

In summary, we argue that our results are best interpreted as primary because the values and trends match those observed elsewhere and fall within the range of $\delta^{13}C$ values previously interpreted as primary in the Delaware Basin (Given and Lohmann, 1985; Chafetz et al., 2008; Smith et al., 2020). It should be noted that the presence of some diagenetic influence on our results cannot be completely ruled out and some of the values we report that fall on the lower end of the carbon and oxygen isotopic values (Fig. 13) could reflect the incorporation of diagenetic end members. But, for all the reasons discussed above, we argue that any digenetic influence is minor and interpret our data accordingly.

5.2. Do observations from the Delaware Basin match those from modern shallow carbonate settings?

In the last three decades there have been several important studies focused on documenting carbon isotopic patterns in the modern shallow water carbonate settings of the Great Bahama Banks. These studies have increased our awareness and understanding of the processes influencing $\delta^{13}C$ values in shallow marine settings (e.g. Patterson and Walter, 1994; Swart and Eberli, 2005; Swart, 2008; Geyman and Maloof, 2019, 2021; Geyman et al., 2022). The question is, how well do these modern carbonate settings serve as analogues for the ancient epicontinental basins of the Paleozoic? We attempt to answer this question by testing hypotheses about carbon isotopic variability from the GBB:

1) *Are there spatial gradients in $\delta^{13}C$ values*

Table 1
ANOVA test results including interpretation of returned *p*-values and post hoc Tukey HSD *t*-test results. All analyses were completed using the IBM SPSS Statistics 22 package. Those p-values that indicate (<0.05) statistical significance are presented in bold.

ANOVA Test Results		
Data Type	*p*-value	Result
Carbon isotopic values of facies associations	**<0.001**	F and D are identified as having statistically significant differences in carbon isotopic values.
Oxygen isotopic values of facies associations	**<0.001**	Oxygen isotopic values for facies associations C, D, and B are statistically distinct from G, F, H, I, and J.
Carbon isotopic values of coarse grained vs. find grained lithologies	0.056	No statistically significant difference in carbon isotopic values between coarse grained and fined grained lithologies.
Carbon isotopic values of HFS G26, G27, and G28	**<0.001**	Carbon isotopic values for HFS G26 are statistically distinct.
Oxygen isotopic values of HFS G26, G27, and G28	**<0.001**	Oxygen isotopic values for HFS G28 are statistically distinct.
Lateral Variation Test	0.083	No statistically significant difference between Shelf Crest and Walnut Canyon.
Carbon isotopic values by allochem type	0.072	No statistically significant difference in carbon isotopic values of allochem types.
Carbon isotopic values by allochem type for HFS G26	0.096	No statistically significant difference in carbon isotopic values of allochem types for HFS G26
Carbon isotopic values by allochem type for HFS G27	0.185	No statistically significant difference in carbon isotopic values of allochem types for HFS G27
Carbon isotopic values by allochem type for HFS G28	0.817	No statistically significant difference in carbon isotopic values of allochem types for HFS G28
Carbon isotopic values along a basin transect	0.094	No statistically significant difference in carbon isotopic values of HFS 27–29 for Walnut Canyon, Toe of Slope, and Willams Ranch Road.
Carbon isotopic values along a basin transect for HFS G26	0.342	No statistically significant difference in carbon isotopic values for HFS G26 for Walnut Canyon and Slope.
Carbon isotopic values along a basin transect for HFS G27	0.071	No statistically significant difference in carbon isotopic values for HFS G27 for Walnut Canyon, TOS, and Willams Ranch Road.
Carbon isotopic values along a basin transect for HFS G28	0.862	No statistically significant difference in carbon isotopic values for HFS G28 for Walnut Canyon, TOS, and Willams Ranch Road.
Oxygen isotopic values along a basin transect	**<0.001**	Walnut Canyon oxygen isotopic values are statistically distinct from those in the Toe of Slope and Willams Ranch Road.

2) *Do carbon isotopic values vary as a function of allochem type?*
3) *Do carbon isotopic values vary as a function of environment (facies association)?*
4) *Is there a relationship between carbon isotopes and sea level?*
5) *Are there parasequence-level patterns in carbon isotope curves?*

5.2.1. *Are there spatial gradients in carbon isotopic values?*

The work of Patterson and Walter (1994) on the Great Bahama Banks and Florida Bay established that shallow carbonate settings can record significant spatial gradients in $\delta^{13}C$ values. Specifically, they observed up to 4 ‰ variations in the carbon isotopic value of dissolved inorganic carbon (DIC) due to a combination of freshwater input, terrestrial organic carbon, photosynthesis, and non-equilibrium conditions with the atmosphere. These spatial gradients in $\delta^{13}C$ occur as both depth gradients (distance from shoreline) and lateral gradients (along shoreline). These findings have been further corroborated by detailed sampling of water and sediments in the Great Bahama Banks by Geyman and Maloof (2021). In fact, Geyman and Maloof (2019) argue that the diurnal carbon engine might result in significant gradients between the shallow water carbonates of the platform and deeper water settings of the basin and open ocean. In the shallow shelf where photosynthesis is at its highest, carbonate precipitation is stimulated by decreased CO_2 levels in the water during peak photosynthesis. As such, the carbonate sediments in these shallow shelf settings have elevated $\delta^{13}C$ values because they reflect the chemistry of the water during the day when photosynthesis reaches its peak, not the average $\delta^{13}C$ value of DIC. As a result, depth gradients of up to “a couple of” per mil can develop across a basin (Geyman and Maloof, 2019). The presence of these spatial gradients in $\delta^{13}C$ is not unique to modern carbonate settings. Multiple studies document the presence of depth gradients in the $\delta^{13}C$ values from ancient carbonate basins (e.g. Holmden et al., 1998; Panchuk et al., 2005; Fanton and Holmden, 2007; Saltzman and Edwards, 2017; Quinton et al., 2021; Quinton et al., 2023), however there has been less work testing for the presence of lateral gradients in ancient carbonate platforms.

We tested for the presence of lateral gradients in carbon isotopic values in the Delaware Basin by comparing carbon isotopic values for the same interval of time (HFS G26) from the Walnut Canyon and the PRT - Shelf Crest sections (Fig. 14). These locations were separated by ~40 km along the carbonate platform. As illustrated with the facies association distribution curves in Fig. 14, the PRT - Shelf Crest represents average deposition in slightly deeper outer shelf position than the Walnut Canyon section. Despite a 0.44 ‰ difference in average values between these two sections, results from an ANOVA test indicate that there is no statistically significant difference in the carbon isotopic distribution between these two sections (*p*-value = 0.083). Thus, we found no evidence supporting significant and sustained lateral variation in carbon isotopic values for this portion of the Delaware Basin. We acknowledge that our test is by no means exhaustive, and it is possible that lateral gradients existed in other parts of the basin.

Depth gradients have been previously documented in ancient carbonate basins, though the nature of the gradient has varied as the carbon isotopic value of terrestrial organic carbon changes relative to that of marine organic carbon (Quinton et al., 2021; Quinton and Rygel, 2023). In fact, previous studies have argued that a depth gradient existed in the Delaware Basin and that the magnitude of the difference in $\delta^{13}C$ values between shallow and deep-water settings changed over time due to increased basin restriction and/or water column stratification (Smith et al., 2020).

In this study, we compare carbon isotopic values for three sections along a basin transect for multiple high frequency sequences to test for depth gradients in $\delta^{13}C$ values (Fig. 12). Our results indicate that there is no statistically significant difference in carbon isotopic distributions for the platform, toe of slope, and basin (ANOVA *p*-value = 0.094). Because it is possible that a depth gradient in carbon isotopic values existed for some intervals and not others, we compared carbon isotopic distributions of the platform, toe of slope, and the basin for different time slices represented by HFS G26, G27, and G28 (Fig. 15). Once again, we found no evidence for statistically significant differences during deposition of G26 (ANOVA *p*-value = 0.342), G27 (ANOVA, *p*-value = 0.071), and G28 (ANOVA, *p*-value = 0.862).

Our results do not support the existence of depth gradients during the middle-late Capitanian of the Delaware Basin. We attribute the differences in our findings from those of Smith et al. (2020) as a consequence of: 1) the larger number of $\delta^{13}C$ samples in this study, 2) our inclusion of three positions in the basin (rather than two), and 3) our use of sequence stratigraphic surfaces to more tightly constrain our correlations. It should also be noted that the most significant evidence for the existence of spatial gradients in $\delta^{13}C$ values that Smith et al. (2020) documented came from the upper Tansill Formation and the Reef Trail Member of the Bell Canyon Formation (HFS G29), an interval we do not have enough

Table 2
Test results from Spearman Rank Correlation and Gaussian Rank Correlation analysis. For Spearman Rank Correlation the r_s value indicates the strength and direction of correlation. The number of analyses is indicated by the n value.

Sequence Stratigraphic Correlation Results							
Section	Sequence	Systems Tract	Spearman Rank Correlation (r_s)	Spearman *p*-value	Gaussian for noisy data *p*-value	n	Passes or Fails Test
Walnut Canyon	HFS G26	TST		Insufficient data		4	Fails
		HST	−0.0277	0.131	0.287	31	
	HFS G27	TST	−0.180	0.294	0.289	36	Fails
		HST	0.079	0.593	0.882	48	
	HFS G28	TST		Insufficient data		3	Fails
		HST	0.197	0.345	0.412	25	
Toe of Slope	HFS G27	TST	0.421	**0.005**		43	Fails
		HST	**−0.532**	**0.004**		27	
	HFS G28	TST	0.385	0.175		14	Fails
		HST	−0.100	0.693		18	

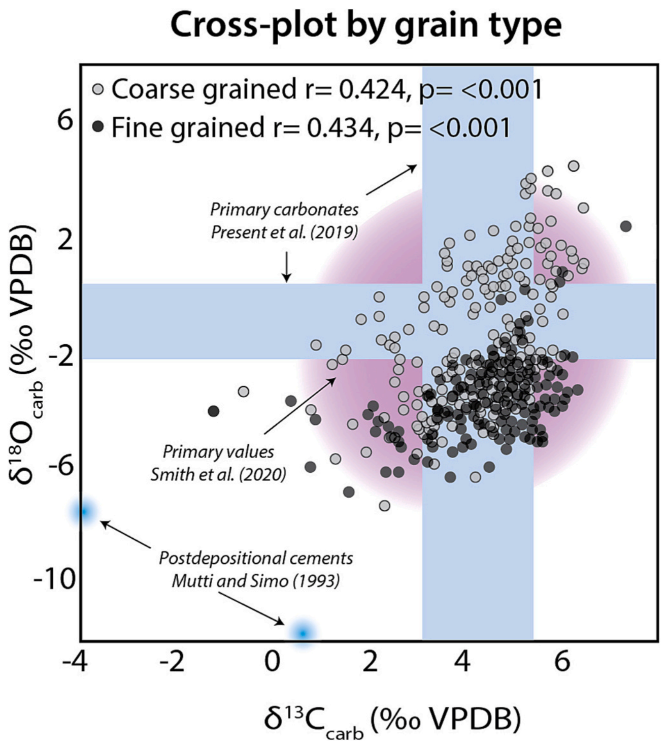

Fig. 13. Carbon and oxygen isotopic cross plot for the Delaware Basin. Results from a Pearson test of correlation between oxygen and carbon isotopic values are reported in the top left corner for coarse grained lithologies and fine grained lithologies. The *r* value is the correlation coefficient and represents the strength and direction of the relationship between oxygen and carbon isotopic values and *p* represents the significance of that correlation (where *p*-value <0.05 indicates a statistically significant correlation). The blue bars indicate the range of primary marine carbonates for the late Permian from Present et al. (2019) after Given and Lohmann (1986) and Korte et al. (2005). The purple zone represents the range of interpreted primary values based on petrographic and Mn/Sr screen from Smith et al. (2020). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

data in to perform our statistical test. As such, we cannot rule out the possibility that depth gradients developed at the very end of the Capitanian.

5.2.2. *Do carbon isotopic values vary as a function of allochem type?*

Recent work on modern sediments in the Great Bahama Banks demonstrates that significant differences in δ^{13}C values exist in the sediments that form in shallow water carbonate settings (Geyman and Maloof, 2021). Ooids and other coated grains have systematically higher δ^{13}C values than carbonate mud, and skeletal material from corals, gastropods, and bivalves have values that are systematically lower than either ooids or carbonate mud (Geyman and Maloof, 2021). The result is up to 10 ‰ variability in δ^{13}C values from sediment on the Great Bahama Banks. These systematic differences in δ^{13}C values have been attributed to a combination of vital effects, development of microenvironmental conditions, and differences in carbonate mineralogy. The existence of carbonate component controlled δ^{13}C variability has significant implications for the generation and interpretation of carbon isotopic records from shallow carbonate settings because it could create noise that obscures important perturbations in the carbon cycle or create artificial fluctuations caused by shifting facies patterns that are unrelated to the carbon cycle.

To test for systematic δ^{13}C differences as a function of component type, we compared carbon isotopic distributions of mud and different allochem types in samples from the Delaware Basin (Fig. 16). For every geochemical sample we documented the dominant allochem in the sample. When it was not possible to identify a dominant allochem, the sample was classified as mixed. For carbonate mud and wackestone samples, the mud was sampled. For packstone and grainstone samples those with ooids, pisoids, skeletal, and mixed samples had a sufficient number of analyses to perform statistical tests. We found no statistically significant differences in the δ^{13}C values of these grain types (ANOVA, *p*-value $= 0.072$). These results are not surprising as sediments undergo physical and chemical changes as they lithify (Geyman and Maloof, 2021). If original δ^{13}C differences among grain types did exist, it is possible that abrasion, homogenization, and even syndepositional and postdepositional diagenesis could obscure that signal. Furthermore, it is possible that sample powders analyzed in this study do not uniquely represent the dominant allochem but instead incorporated a small amount of other grains. For example, in packstones some mud is likely incorporated into the sample powder and therefore contributed to the measured δ^{13}C values. This could also help to obscure small scale δ^{13}C differences among grains and is the nature of bulk sampling. Microdrilling of sample slabs could allow targeting of single grains and reduce homogenization when testing for grain specific δ^{13}C values. Regardless, these results support the practice of bulk rock sampling for carbon isotopic records when paired with detailed sedimentological observations, that way any variability related to grain type that does exist can be constrained prior to interpreting δ^{13}C trends.

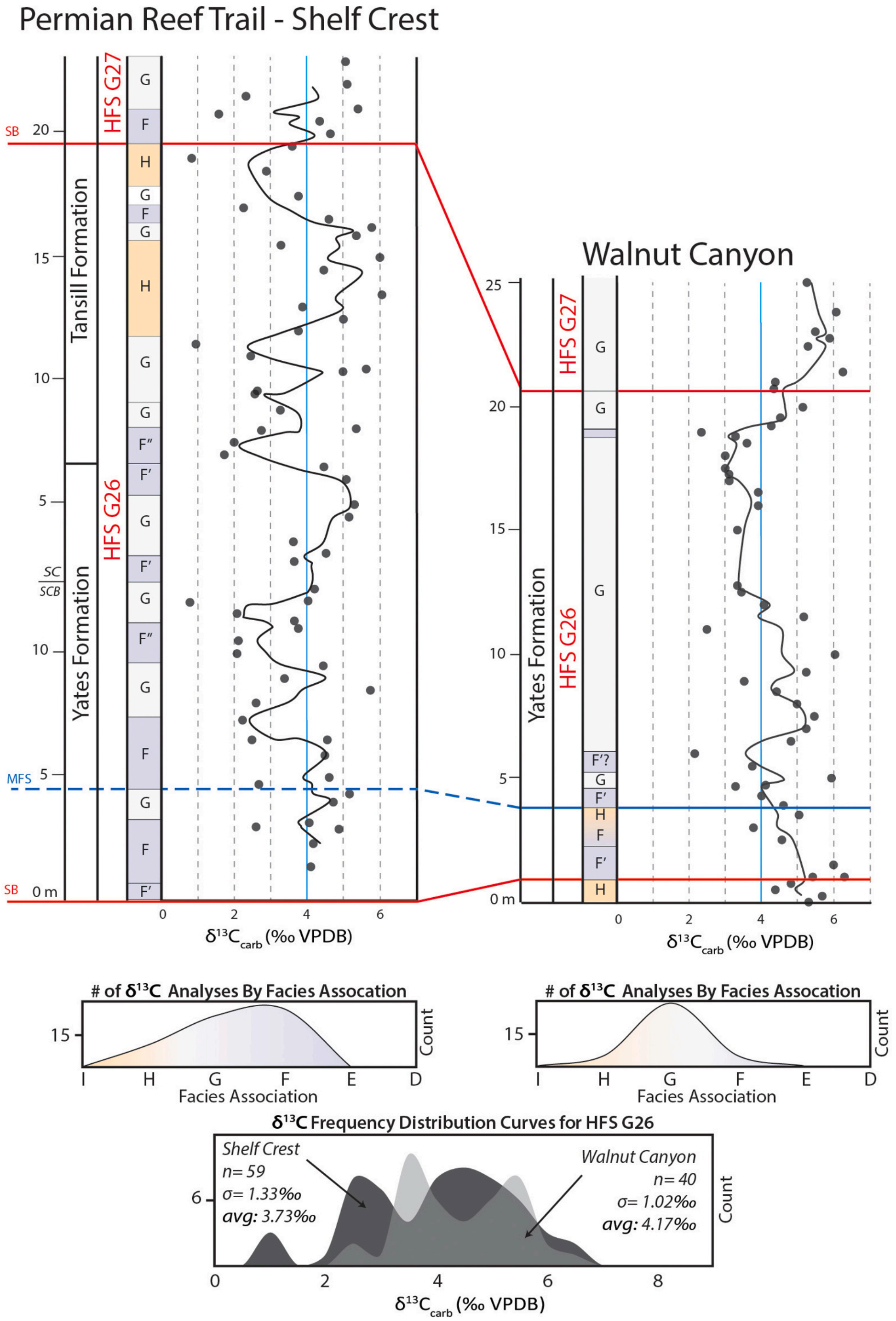

Fig. 14. Carbon isotopic records for Permian Reef Trail - Shelf Crest and Walnut Canyon to test for lateral gradients in $\delta^{13}C$ values along the Delaware Basin shoreline. Three point moving averages for the carbon isotopic values are plotted as a black line. Correlation between the sections is based on the position of sequence boundaries. The number of carbon isotopic analyses for each facies association (*n*) is plotted as frequency curves for each section. All carbon isotopic values are binned and plotted as frequency curves for both study sections. The count refers to the frequency at which a carbon isotopic value occurs within each dataset.

5.2.3. *Is there evidence that geochemistry varied as a function of environment (facies association)?*

If systematic variations in the carbon isotopic value of DIC (Patterson and Walter, 1994) and grain type exists (Geyman and Maloof, 2021), we might expect these combined effects to result in systematic differences in the $\delta^{13}C$ value of facies associations. Geyman and Maloof (2021) argued for systematic differences in the carbon isotopic values of facies based on observed grain type variations in $\delta^{13}C$ for the Great Bahama Banks. While we did not detect grain type carbon isotopic variability nor systematic $\delta^{13}C$ spatial gradients in the Delaware Basin, it is possible these two factors combined might result in resolvable systematic differences in carbon isotopic values.

To test for systematic geochemical differences among the facies associations in the Delaware Basin we compared the carbon and oxygen isotopic distributions for facies associations that had at least 15 analyses (Fig. 17). Oxygen isotopic data was included in this analysis to help us distinguish among possible diagenetic and environmental interpretations for the patterns observed. For carbon isotopic values, we

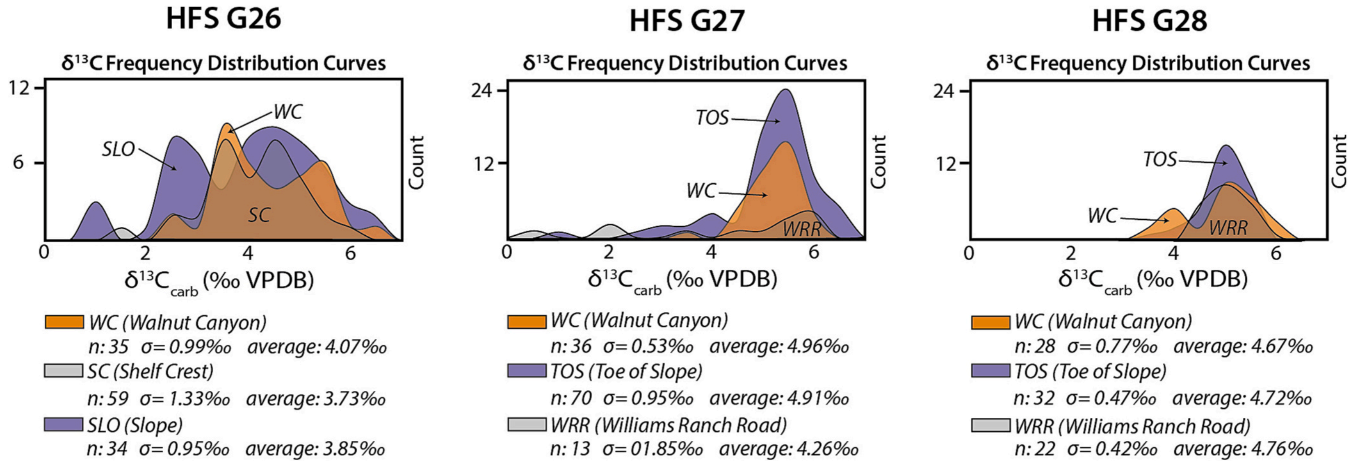

Fig. 15. Frequency distribution curves for carbon isotopic values for high frequency sequences (HFS) G26, G27, and G28 are plotted for three sections representing a depth transect of the basin. The *n* value indicates the number of analyses from each study section for a given HFS and count refers to the frequency at which a carbon isotopic value occurs within each of these datasets.

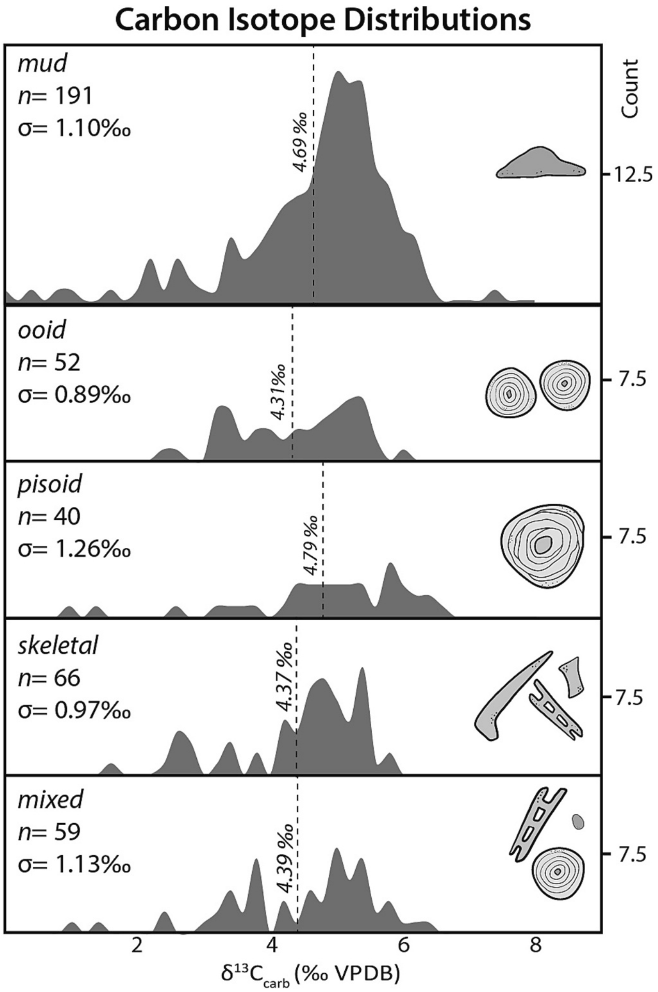

Fig. 16. Frequency distribution curves for carbon isotopic values by the dominant carbonate component in the sample. For carbonate mud and wackestone samples, mud was analyzed. For packstone and grainstone samples, if it was not possible to identify a dominant allochem the analysis was listed as mixed. Average carbon isotopic value for each distribution is identified with a dotted line. The *n* value indicates the number of analyses for each carbonate component and count refers to the frequency at which a carbon isotopic value occurs within each of these datasets.

found that Facies Associations F (outer shelf) and D (slope) had statistically distinct $\delta^{13}C$ distributions with averages $\sim$1 ‰ different from those of the other facies associations (ANOVA p-value <0.001). We also documented a statistically significant difference in the $\delta^{18}O$ distributions among the facies associations with slope to basin associations (B, C, and D) recording systematically lower $\delta^{18}O$ values than those of the platform facies associations (F, G, H, I, and J). These results are summarized in Fig. 17. There are two possible explanations for these systematic differences: non-uniform diagenetic processes or primary environmental differences in the basin.

5.2.3.1. Non-uniform diagenetic processes. One possible explanation for systematic differences in facies associations is that some environments in the basin experienced different diagenetic processes that imparted distinct carbon and oxygen isotopic signals. As previously discussed, we interpret our carbon isotopic record as generally reflecting primary sea water chemistry. But, it is possible some samples have been influenced by diagenetic processes.

Movement of diagenetic fluids along pre-existing syndepositional fracture networks that exist on the margin of the platform could produce zoned diagenetic effects. The platform routinely experienced brittle failure and developed networks of faults and fractures during HFS G26–29 (Hunt et al., 2003; Rush and Kerans, 2010). These faults and fractures could act as conduits for diagenetic fluids like those associated with the Castile Formation (evaporatively enriched in ^{18}O) or those associated with later stages of burial (Melim and Scholle, 2002). Because Facies Association F and D are closest to the areas where these fracture networks form on the sea floor, they might have been affected by diagenetic processes not experienced as readily by the rest of the platform and basin. However, that explanation fails to consider that the features and faults cut through multiple units and facies associations - not just those that represent the outer shelf during brittle failure. For example, the fracture and faulting network for this interval of time was mapped out at Walnut Canyon by Rush and Kerans (2010) and all the facies associations for our Walnut Canyon section are equal distance to existing fractures and faults. As such, if those fractures acted as conduits for diagenetic fluids, they should affect all of the facies associations in our Walnut Canyon section equally. For this reason, we do not think this explanation is a viable option to explain the systematic carbon isotopic differences of Facies Associations F and D.

A simple meteoric diagenesis model cannot explain the observed patterns in carbon and oxygen isotopic values of the facies associations as we would expect low $\delta^{18}O$ and $\delta^{13}C$ values on the entire platform or in facies associations closest to shore. But perhaps we can invoke the more

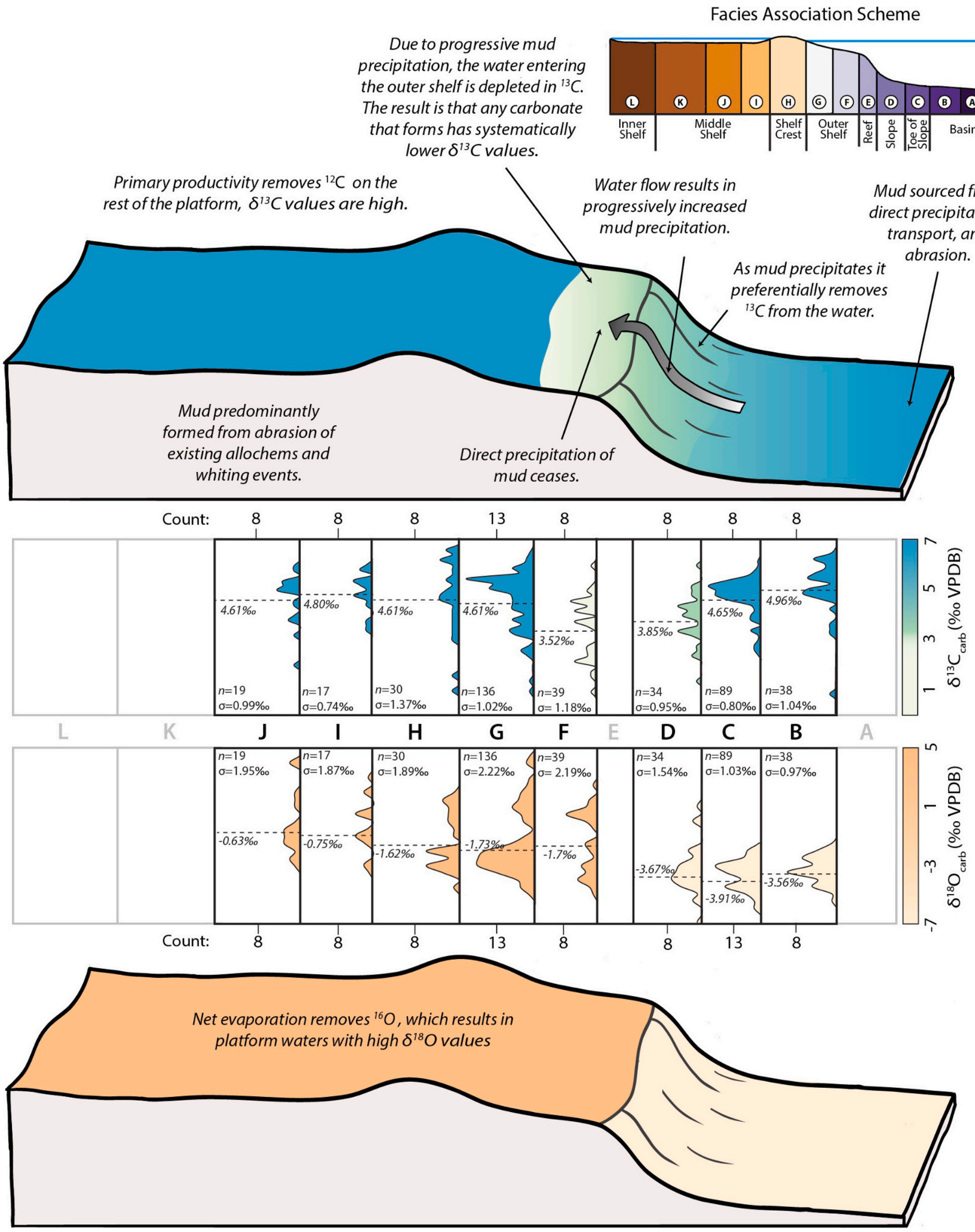

Fig. 17. Frequency distribution curves for carbon and oxygen isotopic values plotted by facies association. The *n* value indicates the number of analyses for each facies association and count refers to the frequency at which a carbon isotopic value occurs within each of these datasets. The average for each distribution is identified with a dotted line and the color of the frequency curve. Schematic diagrams illustrating possible interpretations of the carbon and oxygen isotopic distributions are included. The carbon isotopic explanation invokes the Geyman et al. (2022) model for mud formation as upwelling water along the slope leads to progressive mud formation.

complicated diagenetic scenario proposed by Given and Lohmann (1986) based on an observed increase in the $\delta^{13}C$ values of meteoric cements in a downslope direction. They argue that this progressive increase in $\delta^{13}C$ values is the result of an evolving meteoric fluid as it travels down depositional dip from the platform top to the basin. The meteoric fluid starts with low $\delta^{13}C$ values (due to oxidation or organic carbon), as the fluid starts to interact with existing rocks in outer shelf it dissolves some of the metastable carbonate phases. As these are marine rocks, they preferentially release ^{13}C into the fluid. The result is that the $\delta^{13}C$ value of the water progressively increases downslope (Given and Lohmann, 1986).

Application of this model to our data set poses some possible issues. The first is that Given and Lohmann (1986) were looking specifically at sparry calcite they identified as meteoric cement. Their cements recorded much lower carbon and oxygen isotopic values (0.3 ‰ to −5.5 ‰ for $\delta^{13}C$ and − 12.8 ‰ to −8.0 ‰ for $\delta^{18}O$) than ours and they occur in the range of what is expected for post-depositional cements (Mutti and Simo, 1993). It is possible that some of this diagenetic signal contributed to the bulk rock $\delta^{13}C$ values for Facies Association F and D. The result would be systematically lower values in these two facies associations. It should be noted that this interpretation still doesn't account for the fact that the $\delta^{18}O$ values for F and D are distinct in that Facies Association F, with higher values, matches the platform and Facies Association D, with lower values, matches the basin. If this model of an evolving meteoric fluid moving down slope along depositional dip is correct, we would expect Facies Association F to have the lowest $\delta^{18}O$ values as it should reflect those meteoric fluids before they undergo significant fluid and rock interactions. Furthermore, when sampling we avoided any cement and samples were examined under a microscope to minimize any possible inclusion of sparry meteoric cements. Moreover, it is unlikely that these two facies associations are the only ones that happened to preferentially incorporate some diagenetic phases when it is well documented that other platform facies associations were impacted by post-depositional processes which imparted low carbon and oxygen isotopic values (Mutti and Simo, 1993). For these reasons, we do not favor a diagenetic interpretation but cannot rule it out.

5.2.3.2. Primary environmental differences. Instead, we favor an explanation for the geochemical patterns among facies associations that invokes primary processes operating in different environments within the Delaware Basin. We attribute the systematically higher δ^{18}O values in all the platform facies associations as the result of evaporative enrichment of ^{18}O in this warm shallow water body. This model agrees with previous authors' interpretations of the high oxygen isotopic values from the Delaware Basin (Given and Lohmann, 1985; Korte et al., 2005). While the absolute δ^{18}O values are not necessarily primary, if the system started with high initial values and was not completely reset by diagenesis, the offset between basin and platform could be preserved.

The systematically lower δ^{13}C values of Facies Associations F and D can be explained by a reservoir effect due to progressive updip mud formation on the slope (Fig. 17). Geyman et al. (2022) recently documented compelling evidence from the Great Bahama Banks that the primary source of carbonate mud is direct precipitation from upwelling waters along the bank margins. In these settings supersaturated waters interact with very fine-grained suspended carbonate sediment that act as condensation nuclei and promote the precipitation of carbonate mud. The result is progressively increasing mud formation up the slope of the platform margin. Using the model for mud formation proposed in Geyman et al. (2022), we argue that as this mud forms it is possible that the δ^{13}C value of the upwelling water mass progressively decreases. Early-formed mud in the middle of the slope will preferentially incorporate the heavier ^{13}C isotope. This will leave the remaining water depleted in ^{13}C. This process will continue as the upwelling water moves further up the slope. The result is a water mass reaching the platform margin that has a lower δ^{13}C value than what it started with. While later-formed mud will still preferentially incorporate ^{13}C, its δ^{13}C value will record the ^{13}C depleted reservoir that it formed in. This process would result in mud with progressively decreasing δ^{13}C values up the slope.

The process of δ^{13}C evolution due to mud production along the slope could explain the systematically lower values in Facies Associations F and D when compared to the rest of the facies associations. Facies Association C occurs at the toe of the slope and contains early-formed mud that best reflects the average δ^{13}C of the water mass in the basin. Facies Association D was deposited on the slope and includes a) *in situ* mud from direct precipitation, b) allochems that were transported downslope, and c) mud that was transported downslope. Consequently, δ^{13}C values of Facies Association D reflect a combination of transported mud and allochems with high carbon isotopic values as well as *in situ* mud with lower carbon isotopic values. Facies Association F was deposited in the outer shelf at the edge of the platform and records the limit of direct mud precipitation via upwelling waters. This is also where the carbon isotopic composition of the water mass would be the most depleted in ^{13}C. Consequently, Facies Association F will have the lowest δ^{13}C values in mud formed via direct precipitation. Sediments of Facies Association F also include transported grains and average δ^{13}C values record mixing of *in situ* mud from direct precipitation as well as transported mud and allochems. Lastly, Facies Association G was deposited in a relatively high energy environment between the shelf crest (Facies Association H) and the edge of the outer shelf (Facies Association F) and contains largely platform-derived sediments with little mud. Thus, its carbon isotopic composition is comparable with and representative of values from the shelf crest and middle shelf.

While this interpretation is consistent with our data, additional testing is needed to confirm what could be an interesting effect on the carbon isotope geochemistry of slope settings on carbonate platforms. Such a geochemical phenomenon has not been documented in the Great Bahama Banks, but the Geyman et al. (2022) study that proposed the model for direct carbonate mud precipitation along the slope, only collected mud samples from the platform itself and previous studies assumed that mud precipitation dominantly took place well within the platform. For the Delaware Basin, microsampling of mud from traceable units along a transect from the outer shelf to the toe of slope paired with petrographic and/or geochemical constraints on diagenetic alteration would allow for a test of whether the δ^{13}C differences in Facies Associations F and D reflect the isotopic evolution of a water mass due to mud precipitation or post-deposition diagenetic overprinting. Further geochemical testing might also provide independent support for the proposed different types of mud (e.g. mud that formed through abrasion vs. that formed from direct precipitation).

5.2.4. *Is there a relationship between carbon isotopes and sea level?*

It is possible that sea level change could influence the nature of δ^{13}C trends in shallow marine settings. This possibility rests on the fact that sea level controls many of the processes that influence carbon isotopic values (e.g. proximity to shoreline, basin restriction and mixing, surface area for primary productivity, degree of subaerial exposure, relative percentage and type of carbonate sediments forming, and more). Quinton and Rygel (2023) provide a summary of the processes linking sea level and carbon isotopic trends and outline the various models that have been proposed for how that relationship manifests in ancient and modern shallow water carbonate settings. In the GBB, Swart and Eberli (2005) and Swart (2008) argue that sea level and carbon isotopes are linked based on sea level's influence on the type, abundance, and transportation of carbonate sediments.

To test for a possible link between sea level and carbon isotopes, we use the sequence stratigraphic framework for these rocks as an indicator of sea level and deploy a simple series of correlation tests outlined in Quinton et al. (2023) and Quinton and Rygel (2023). This method allows us to identify sequences where sea level change was a potentially significant driver of documented δ^{13}C trends. We found no evidence that there was a statistically significant relationship between sequence stratigraphic framework and carbon isotopic patterns in HFS G26, G27, or G28 (Table 2). Visual examination of the δ^{13}C trends for each High Frequency Sequence in Fig. 12 supports this interpretation. There are no apparent trends related to the sequence stratigraphic framework. These results indicate that sea level change at the sequence level did not influence carbon isotopic trends in a systematic and resolvable way in the Delaware Basin during the late Capitanian.

5.2.5. *Are there parasequence-level patterns in carbon isotope curves?*

It has also been suggested that sea level might influence δ^{13}C trends at a smaller scale. For example, Geyman and Maloof (2021) argued that since carbonate grains in the Great Bahama Banks exhibited systematic differences in average δ^{13}C values, we might expect to observe trends at the parasequence level as the dominant grain type changes with facies. Using the average values of different grain types, Geyman and Maloof (2021) modeled how different facies stacking patterns might influence the carbon isotopic trends of hypothetical parasequences in the Great Bahama Banks.

We tested for the presence of parasequence-level δ^{13}C trends in the platform of the Delaware Basin. Since we observed systematic differences in the carbon isotopic values of Facies Association F and G, we might expect a parasequence recording a transition from F to G to also display decreasing δ^{13}C values. We do not observe any systematic patterns in carbon isotopes that can be tied to parasquences (Fig. 18). This result is not surprising because we did not observe systematic differences in δ^{13}C values of carbonate grain types like Geyman and Maloof

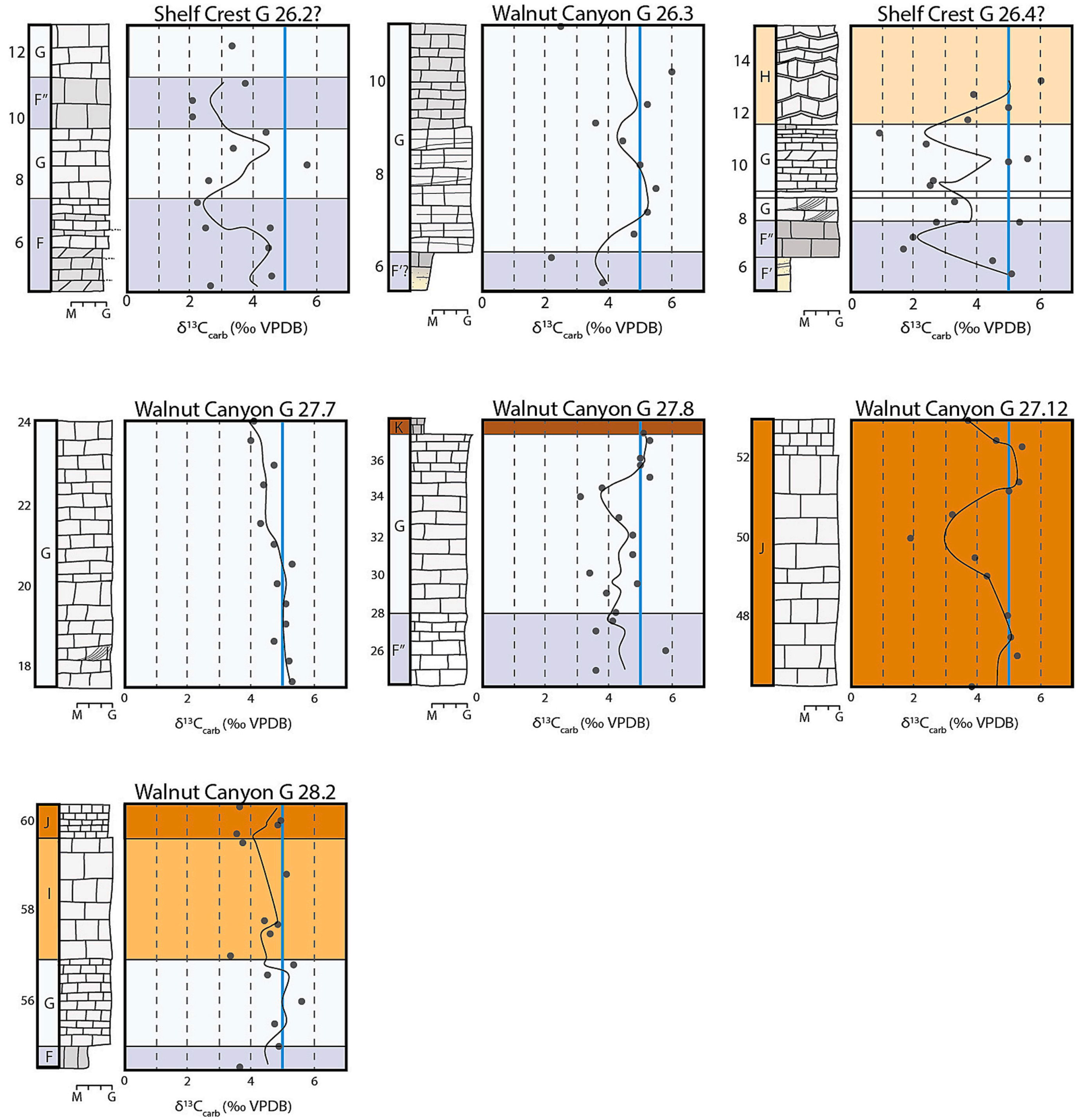
Shelf Crest G 26.2?
Walnut Canyon G 26.3
Shelf Crest G 26.4?
Walnut Canyon G 27.7
Walnut Canyon G 27.8
Walnut Canyon G 27.12
Walnut Canyon G 28.2

Fig. 18. Carbon isotopic values plotted for parasequences from Shelf Crest and Walnut Canyon. Facies associations are color coded and indicated with a letter. Parasequence numbering is based on Rush and Kerans (2010). These shallowing upwards trends might be expected to record recurring patterns in carbon isotopic values due to sea level's influence on processes that influence $\delta^{13}C$ values and/or because of stacking patterns in facies associations.

(2021) did in the Great Bahama Banks sediments. The lack of recurring and systematic patterns in carbon isotopes within parasequences is likely due to the fact that any observed differences in grain type, facies, and/or facies associations are small and there are numerous factors impacting the carbon isotopic values.

5.3. How analogous are the Permian Reef Complex and the Great Bahama Banks?

Our results indicate that many of the hypotheses about sources of $\delta^{13}C$ variability in the GBB do not manifest in the carbon isotopic record of the Delaware Basin. The dissimilarity could come from homogenization of any $\delta^{13}C$ variability - a point also raised by Geyman and Maloof (2021). But our finding begs the question, how much do these two basins have in common? They both have a well-developed steep rimmed platform geometry of similar size and topography (Tinker, 1998; Miall, 2019) and both record significant sea level fluctuations during an icehouse climate (Gardner, 1992). But there are also some important differences. The first is that the GBB is not a true epicontinental basin but instead occupies a position on transitional oceanic-continental crust at the margin of the Gulf of Mexico and the Atlantic Ocean. As a result, the GBB has multiple outlets (e.g. Straits of Florida, Old BHM Channel, Santaren Channel, NW Providence Channel) for the flow of open ocean water, though the steep nature of the platform does limit mixing with the shallow waters of the platform (Reijmer et al., 2009). In contrast, the Delaware Basin was a true epicontinental basin and its connection with the open ocean was limited to either the narrow Hovey and/or Diablo Channels (Hill, 1999). As a result of this narrow outlet for the flow of open ocean water, Capitanian carbonates in the basin (Artesia Group) record periodic restriction that culminated in the extensive evaporite deposits of overlying Castile and Salado Formations when that outlet closed. The restricted shallow water carbonate environments of Delaware Basin are different than those observed in the GBB. Most notably in the types of lithologies present (e.g. the abundant tepee structures and pisoids in the Delaware Basin vs. the ooid dominated shoals of the GBB) and the salinity of the water (the mesosaline to hypersaline platform waters of the Delaware Basin vs. the mesosaline platform waters of the GBB) (Melim and Scholle, 2002; Reijmer et al., 2009). The nature of the extreme restriction in the Delaware Basin may have overwhelmed any systematic δ^{13}C variability related to grain type or environment. Lastly, the Permian biosphere was markedly different from that which occupies the area around the GBB in the modern. As such, vital effects and organic carbon sources likely influenced the δ^{13}C of carbonate sediments in different ways.

In short, our results suggest that the GBB might not be the best analogue for the Delaware Basin, but there are still some important lessons that we can take away from this comparison:

1. Just like in the Great Bahama Banks there are observable δ^{13}C differences in carbonates across the basin. Those in the Delaware Basin are related to facies associations. It is only when geochemical records are paired with detailed sedimentological observations (both field and petrographic) that we can test for these sources of variability and therefore be confident in the interpretation of observed trends as reflecting perturbations to the carbon cycle.
2. Even if δ^{13}C differences exist among carbonate grain types; abrasion, homogenization, as well as syndepositional and postdepositional diagenesis can significantly obscure those geochemical differences in ancient carbonates.
3. The model of mud formation due to direct precipitation along the bank margin of the GBB (Geyman et al., 2022) is consistent with our results from the Delaware Basin.

5.4. *Carbon cycling in the Delaware Basin and the late Permian*

Our high-resolution carbon isotopic record along a platform to basin transect is the first of its kind to be generated from the Delaware Basin. The most significant observation from this dataset is that δ^{13}C values increase and variability decreases through the middle to late Capitanian. We interpret this change to reflect increased basin restriction and development of dysoxic to anoxic conditions in the Delaware Basin. The development of low oxygen conditions reduced recycling of organic carbon into the water column, which resulted in a net burial of organic carbon enriched in ^{12}C. Decreased communication with the open ocean through a narrow channel reduced the replenishment of ^{12}C to the system, driving the δ^{13}C values of the basin higher. This interpretation supports previous work suggesting increased restriction in the Delaware Basin during the Capitanian (Given and Lohmann, 1985; Jin et al., 2012; Smith et al., 2020).

Similarly high and increasing δ^{13}C values have also been documented from Croatia, Japan, East Greenland, China, and Svalbard (Bond et al., 2010; Tierney, 2010; Isozaki et al., 2011; Cao et al., 2018). The fact that similar trends are observed in multiple basins suggests that the Capitanian increase in δ^{13}C values likely reflects increased organic carbon burial in the many semi-restricted basins that existed at this time. High δ^{13}C values have also been recorded in paleo-atoll carbonates from the middle of the Panthalassa ocean (Isozaki et al., 2007). Given the palaeoceanographic setting of this paleo-atoll (e.g. free from terrestrial input and basin restriction), its carbon isotopic record is interpreted to reflect open ocean chemistry for the Capitanian (Isozaki et al., 2011). The fact that increasing δ^{13}C values have been documented for the open ocean suggests that the increased organic carbon burial in restricted basins like the Delaware Basin was sufficient to cause a global perturbation to the carbon cycle. Multiple causal mechanisms for the organic carbon burial have been proposed (ocean anoxia, changes in ocean circulation, sea level fall induced basin restriction) and many have been linked to extinction in the Capitanian (Isozaki et al., 2011; Cao et al., 2018; Smith et al., 2020). However, the question of what caused the perturbation of the carbon cycle, the timing of the perturbation, and how it is linked to biodiversity changes is unresolved (Fielding et al., 2023). This is due, in part, to the lack of high-resolution geochemical data sets tied to sedimentological observations that can be paired with global biodiversity data. The carbon isotopic record presented here provides an appropriate sedimentological-geochemical dataset for the Delaware Basin and represents a first step in generating the data needed to understand the relationship between the late Permian carbon cycle and extinction. But, more work in other basins must be done.

6. Conclusions

We present the first high resolution carbon isotopic record paired with detailed sedimentological and sequence stratigraphic framework for a platform to basin transect of Capitanian carbonates of the Delaware Basin. We were able to test for proposed systematic sources of δ^{13}C variability based on studies of the Great Bahama Banks. We show that Capitanian carbonates of the Delaware Basin:

1. Do not record resolvable depth or lateral gradients in δ^{13}C values
2. Do not have δ^{13}C values that vary with grain type
3. Do record statistically significant differences in the δ^{13}C distributions between facies associations. Specifically, slope and outer shelf deposits of Facies Associations D and F record systematically lower δ^{13}C values than both the platform and basin facies associations. We attribute this difference in δ^{13}C values to water mass depletion of ^{13}C driven by the direct precipitation of mud in upwelling waters.
4. Do not record variations in carbon isotopic values driven by changes in sea level
5. Lack the type of systematic δ^{13}C variability seen in the Great Bahama Banks because of homogenization and environmental differences between the basins.
6. Highlight the importance of generating high-resolution carbon isotopic records that are directly tied to a detailed sedimentological and sequence stratigraphic framework.
7. Have many important differences from the carbonates of the Great Bahama Banks
8. Record a global perturbation to the carbon cycle during the Capitanian that was driven by increased organic carbon burial and anoxia in restricted basins like the Delaware Basin.

CRediT authorship contribution statement

Page C. Quinton: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Michael C. Rygel:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Anah Bogdan:** Writing – review & editing, Investigation. **Lauryn Higgins:** Writing – review & editing, Investigation. **Ty Paddock:** Writing – review & editing, Investigation. **Caroline Winstead:** Writing – review & editing, Investigation. **Chelsea Wright:** Writing – review & editing, Investigation.

Declaration of competing interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.palaeo.2024.112560.

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