Earth and Planetary Science Letters 419 (2015) 63–70

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Physical and chemical stratigraphy suggest small or absent glacioeustatic variation during formation of the Paradox Basin cyclothems

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ARTICLE INFO

Article history:
Received 6 September 2014
Received in revised form 11 February 2015
Accepted 5 March 2015
Available online 24 March 2015
Editor: G.M. Henderson

Keywords:
carbonate cycles
late Paleozoic ice age
carbon isotopes
meteoric diagenesis

ABSTRACT

The Paradox Basin cyclothems previously have been interpreted as Milankovitch style glacial–interglacial cycles from the Late Paleozoic Ice Age, but an unambiguous test for a glacioeustatic origin has not been conducted. A high resolution coupled chemical and physical stratigraphic analysis of two outcrop sections and three core segments provides new evidence that supports either minor sea level change of several meters or an autocyclic mechanism for parasequence formation. High amplitude sea level change is ruled out by the scale of thin top-negative isotopic meteoric diagenesis trends associated with parasequence tops and subaerial exposure fabrics. Isotopic gradients from shelf (light) to basin (heavy) indicate that parasequences are deposited diachronously, with isotopes of more distal sections recording increased basin restriction. These results support the idea that the late Pennsylvanian was a prolonged period of relatively static eustasy, agreeing with recent studies in the western USA. The methods provide a new set of tools and context for extracting environmental information from cyclic upward shallowing carbonate parasequences.

1. Introduction

Ice sheets intermittently covered the south pole for nearly 70 million years (330 ma to 260 ma) during the late Paleozoic ice age (LPIA) (Veevers and Powell, 1987). In the LPIA tropics, ubiquitous cyclic sedimentary basins recorded the onset, dynamics, and eventual demise of this icehouse period. These records provide a basis for understanding the climate, vegetation, and glacial dynamics of a long term warming trend during an icehouse interval, which may be relevant to understanding and predicting the consequences of modern climate change (Stocker et al., 2013). The sedimentary record is fundamentally complex, incorporating information about climate, tectonics, and biology as well as the internal forcings of the sedimentary system, all recorded through the physics and chemistry of sediment transport. Comprehensive basin- and global-scale studies of the physical and chemical stratigraphy allow one to deconvolve this record into each of its components. These components have been used to reconstruct a rich history of the LPIA (Montañez and Poulsen, 2013), but further research on the sensitivity of the sedimentary system to the unique boundary conditions of that time can improve estimates of associated ice volume and eustatic changes.

Throughout Euramerica, LPIA sedimentary basins are comprised of cyclic stacks of meter-scale upward-shallowing parasequences (cyclothems). These parasequences are bounded by flooding surfaces, and the facies within often exhibit a progression from low to high energy sedimentary facies. Variations in sea level or climate, as a result of predictable orbitally driven ice volume changes, may be responsible for forming many of these cyclothems (Wanless and Shepard, 1936; Ross and Ross, 1985; Heckel, 1994). However, sea-level change estimates from different LPIA basins and authors vary by up to 150 m (Rygel et al., 2008). This variability could arise from the noise introduced by the sedimentary system, or it could indicate that the cycles are not generated by a single, global sea level signal.

The relationship between cyclothems and glacioeustasy is complicated because ordered sedimentary cycles may form from either random or periodic inputs. Sediment supply, accommodation space, biological productivity, and prevailing atmospheric forces all vary periodically with glacial–interglacial change and may be recorded as ordered sedimentary cycles. Since sedimentary transport is ultimately responsible for the stratigraphic record, all environmental inputs are filtered through the physical thresholds of

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http://dx.doi.org/10.1016/j.epsl.2015.03.017

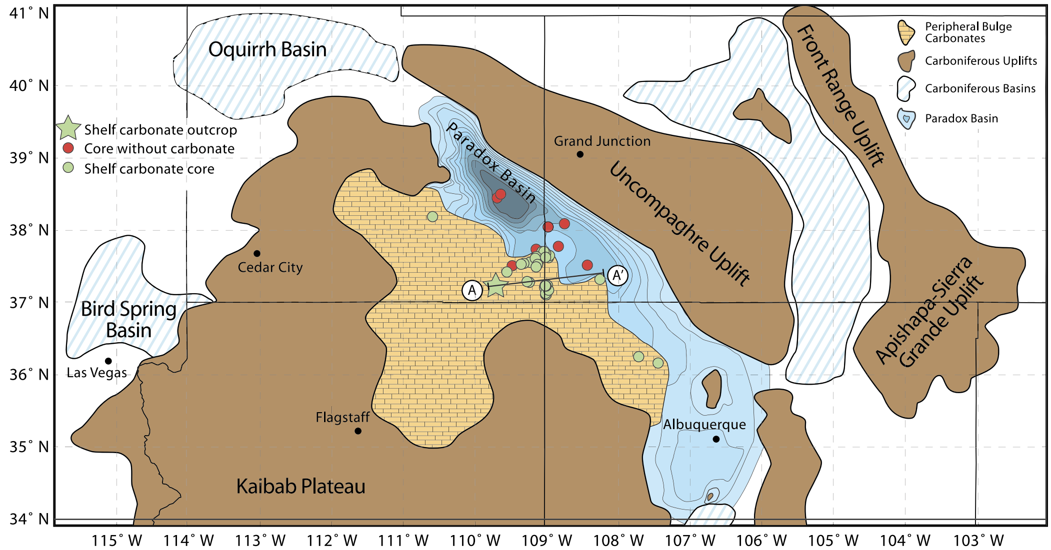

Fig. 1. Pennsylvanian Isopach map of the Paradox Basin region with core and outcrop study locations. Isopachs are 150 m intervals from Peterson and Ohlen (1963). The orange region represents the extent of carbonate facies during the Desert Creek and Ismay sequences based on labeled cores from the USGS Core Research Center and from Peterson and Ohlen (1963). Basin and Uplift locations adapted from Barbeau (2003). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

transport mechanisms. This sedimentary process may obscure periodic forcings in the resulting stratigraphy, or generate patterned stratigraphy where no periodic forcing exists (Jerolmack and Paola, 2010). The extensive cyclic sediments and the potentially large environmental forcing of the late Paleozoic icehouse make it the ideal place to study the relationship between sea level change and carbonate parasequences.

1.1. The Paradox Basin

The Paradox Basin (Fig. 1) is a foreland basin formed by flexure adjacent to the Uncompahgre uplift that is filled with cyclic marine sediments and evaporites from the Pennsylvanian subperiod (Barbeau, 2003). Stacked upward-shallowing carbonate parasequences exist along the margins of the basin, and the interior sediments are salt and sapropel interbeds (Hite and Buckner, 1981). Peterson and Hite (1969) identified 29 salt–sapropel basinal cycles that are thought to correlate to major carbonate sequences developed on the peripheral bulge. The correspondence of these lithologically distinct cycles implies that a single mechanism is responsible for cyclicity on the shelf and in the basin. These carbonate sequences are separated by regionally extensive black sapropel shales that are easily identified in analog core logs due to their contrasting gamma ray signal with carbonates and evaporites. Each of these roughly 30 m thick (4th order) sequences is comprised of 4–6 meter-scale (5th order) upward-shallowing parasequences. This relationship is illustrated in Fig. 2A. Since these parasequences lack a significant fluvio-deltaic siliciclastic component, it is unlikely that the parasequences were generated by cyclic wet to dry climate changes as discussed in Cecil (2003), although the larger scale sequences may be partially controlled by regional climate.

Goldhammer et al. (1991) used the spectral properties of the thickness distribution of these meter-scale cycles to argue that a hierarchical stacking of these sequences may have been generated by the modulation of obliquity (41 ka) and long term eccentricity (413 ka). However, since non-random stratigraphy does not provide unambiguous origin for the cycles, it is necessary to seek new independent evidence of a causal mechanism that will support or reject the idea that glacioeustasy is responsible for the generation of cyclothems in the Paradox Basin. Only a successful positive test that glacioeustasy is responsible for the parasequences can allow the use of the Milankovitch model to understand the frequency and amplitude of ice volume change in the Pennsylvanian. During the modern icehouse, large sea level drops of up to 120 m exposed the Bahama bank, and meteoric waters significantly altered the carbon and oxygen isotopes of the carbonates (Swart and Eberli, 2005). Top–down early meteoric diagenesis can be preserved in the isotopes of ancient carbonates (Allan and Matthews, 1982), and this signature would be expected for carbonate platforms that were exposed during sea level fall. Oxygen isotopes in carbonate phases are subjected to isotopic exchange with subsurface fluids, and may not reliably preserve ancient primary or early diagenetic signals (Jacobsen and Kaufman, 1999). Carbon isotopes, on the other hand, are generally more resistant to diagenetic changes and often are used as a proxy for the isotopic composition of the dissolved inorganic carbon (DIC) of ancient seawater. However, early diagenesis during exposure to CO_2 rich meteoric fluids has high potential for preservation if the sediments are not eroded away during exposure. These altered sediments may be targeted by proximity to exposure surfaces and through physical evidence of dissolution and recrystallization, and the correspondence of anomalously light carbon isotopes and these physical features could indicate meteoric diagenesis.

Coupled high resolution chemical and physical stratigraphic data from two shelf carbonate outcrops and three basinward cores are presented below. Small (<5 meter) scale meteoric diagenesis associated with some cycle caps might indicate that if sea level were changing, the amplitude is small. Additionally, very heavy carbon isotopes in the basin-ward cores suggest increased restriction of the basin and diachronous deposition of parasequences from the peripheral bulge to the basin interior. Carbonate buildup in the shallow seaways connecting the Paradox Basin to the global ocean is the simplest mechanism to explain the observed geochemistry, and the diachronous depositional cycles without requiring large changes in global sea level.

2. Methods

In the field, the sediments of the Honaker Trail and Paradox formations were classified into ten lithofacies based on environ-

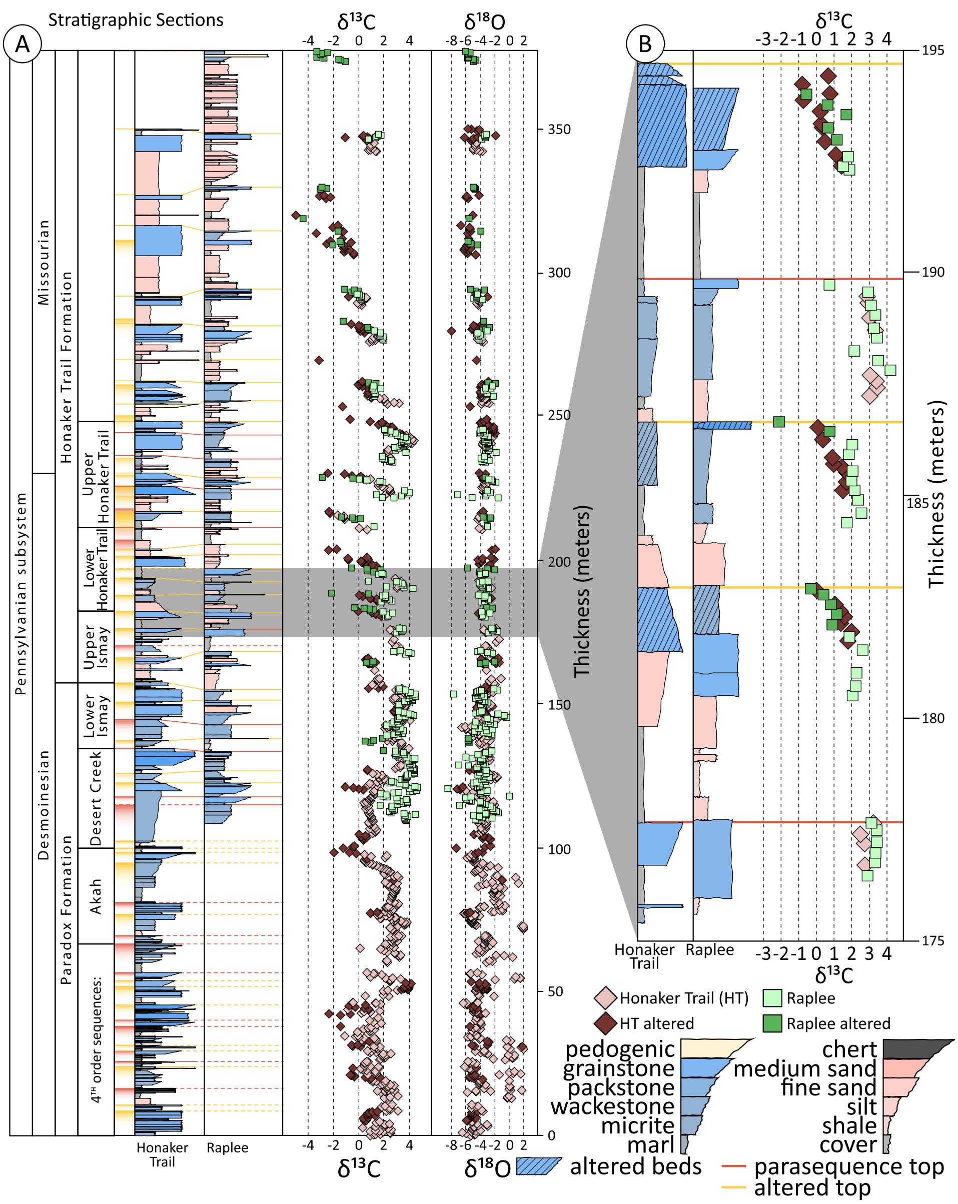

Fig. 2. (A) Honaker Trail and Raplee sections with corresponding $\delta^{13}C$ and $\delta^{18}O$ of carbonate. Parasequence tops are marked in red or orange. Orange parasequence tops correspond to parasequences with strata that have physical evidence of dissolution or recrystallization. Red parasequences lack obvious physical signs of diagenesis, and were identified by flooding surfaces and facies progressions. Dark green or dark red sample symbols mark samples collected from beds that were identified in the field with potential diagenetic features. The 4th order sequences from Goldhammer et al. (1991) are labeled on the left. (B) Select parasequences from the Honaker Trail and Raplee syncline that exhibit top-negative isotopic $\delta^{13}C$ trends associated with exposure such as brecciation, root traces, and dissolution features. Parasequences from the Honaker Trail section have been slightly stretched (1 m) so that the tops in each section align. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mentally sensitive sedimentary structures and the Dunham classification scheme for carbonate sediments (Dunham, 1962). Parasequences were identified as a sedimentary sequence that shallow upwards and is bounded by flooding surfaces. 55 upward-shallowing parasequences between 0.9 and 28.4 m thick were identified in a 350 m section measured along the Honaker Trail (Fig. 4). At a second shorter outcrop section, the Raplee syncline east of Mexican Hat, 33 parasequences were identified. Where these sections overlap, only 3 parasequences were not identified in both sections, and in all three cases the interval in the other section is covered and has no outcropping strata. Additionally, three core segments at the USGS Core Research Center in Denver, CO were described and sampled for isotopic analysis. These cores segments span the Ismay sequence, as identified by the basal Gothic Shale.

Nearly 3000 carbonate samples, from roughly every 20–30 cm in each section and core studied, have been analyzed for $\delta^{13}C$ and $\delta^{18}O$. These samples were slabbed and polished to selectively microdrill micrite for isotopic analysis. All carbonate powders were heated to 110 °C to remove water. Samples were then placed in individual borosilicate reaction viles and reacted at 72 °C with 5 drops of H_3PO_4 before the CO_2 analyte was sent to the IRMS. Measured precision is ±0.1‰ for carbon and ±0.2‰ for oxygen. The samples were analyzed with either a Thermo DeltaPlus continuous flow IRMS or a Sercon IRMS coupled with a GasBench II sampling device. An additional subset of samples were analyzed in the University of Michigan Stable Isotope Laboratory on a Finnigan MAT 251 triple collector isotope ratio mass spectrometer with a Kiel I preparation device. $\delta^{18}O$ and $\delta^{13}C$ data are reported in the

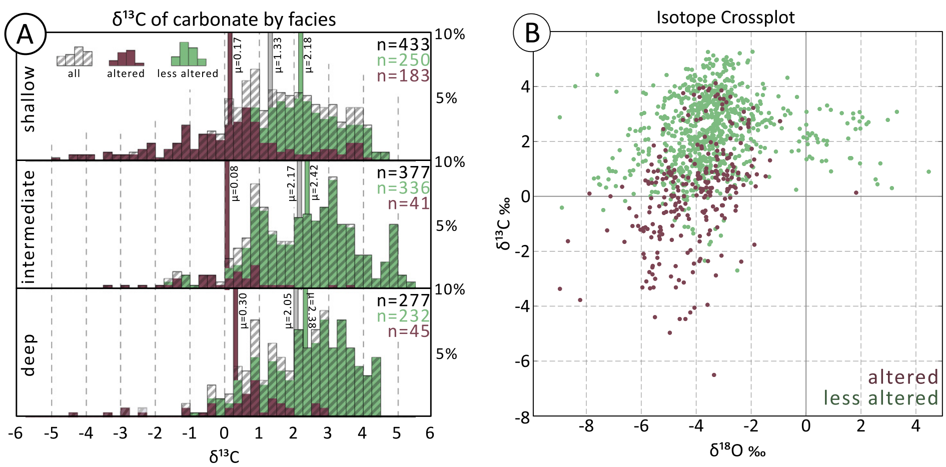

Fig. 3. (A) Histograms of δ^{13}C for shallow, intermediate, and deep facies from sections at Honaker Trail and the Raplee syncline. Beds identified in the field with physical characteristics indicative of dissolution or recrystallization are plotted in red, the entire outcrop dataset is plotted in grey stripes, and the unaltered beds are plotted in green. Vertical bars indicate the mean value (μ) of each corresponding dataset. (B) Carbon and oxygen isotopes for all samples in this study. Red samples are from beds identified in the field with physical evidence of alteration, and green samples are from stratigraphic beds lacking these features. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

standard delta notation relative to the Vienna Pee Dee Belemnite (VPBD) standard.

3. Results

Grammer et al. (1996) and Goldhammer et al. (1991) have described the facies in the Paradox basin in great detail. Deep, low energy environments favor the accumulation of silt and mud, often have thin planar bedding, and lack bioturbation. More energetic wackestones and packestones contain abundant skeletal material, bioturbation, scours, low silt and mud fraction, and fossil assemblages composed of: bryozoa, brachiopods, crinoids, rugose corals, and fusilinids. These features indicate a normal marine depositional environment, perhaps between storm wave base and fair weather wave base. Cross-bedded, mud-free grainstones formed as high energy shoals above fair weather wave base where wave energy abraded skeletal remains, winnowed away carbonate muds, and coated grains with layers of micrite. Coralline (*Chaetetes* and *Syringapora*) and stromatolitic patch reefs formed in the shallow low energy areas protected by these roaming carbonate shoals. Cryptalgal laminites, often laterally transitioning into mud chip breccias and mudcracks, are partially dolomitized and represent deposition very near or in the intertidal zone (peritidal).

These facies are organized in meter-scale upward-shallowing carbonate parasequences that have been grouped into 4th order sequences bounded by regionally extensive black shales (Fig. 2). These black shales can be traced into the basin through core records and gamma ray logs and correspond to sequence bounding units on salt–sapropel cycles (Peterson and Hite, 1969). Of the meter scale 5th order parasequences observed in outcrop along the San Juan River, 16 parasequences are capped by unequivocal exposure surfaces, evidenced by root fossils or desiccation cracks. In each of these exposure sequences, the cap facies often contain stylolites, fossilized root traces, calcite filled popcorn to fist sized vugs, or pervasive fabric destructive recrystallization. Carbon isotopes in the lower portions of these exposure-topped parasequences are between 2‰ and 4‰, the same range as other Pennsylvanian records (Saltzman, 2003). Up section, the carbon isotopes monotonically decline to values as low as −5‰ approaching the exposure surface (Fig. 2), and there is a stronger positive covariance between δ^{13}C and δ^{18}O in these samples (Fig. 3B). Within tens of centimeters above the exposure surface, carbon isotopes abruptly return to the positive values of +2 to +4‰.

Of the 1087 outcrop samples analyzed, there are more light carbon isotopes in shallow facies (Fig. 3A). However, when physical evidence of exposure, such as dissolution features, heavy recrystallization, dolomitization, root horizons, or mud cracks is used to filter the dataset for potential diagenesis, the carbon isotopic values of shallow, intermediate, and deep facies have similar distributions (Fig. 3A). Since the isotopic value of the unaltered sediments is not changing rapidly in time, the lack of a gradient from shallow to deep facies indicates that there were no large vertical (water depth) or lateral gradients in the δ^{13}C of the Paradox basin.

All of the sedimentary lithofacies present in outcrop along the peripheral bulge are also present in 3 cores spanning a 120 km transect (Fig. 1) towards the basin interior. However, wackestones are more abundant in sections closer to the basin interior, while grainstone and packestone are more abundant on the edge of the basin. 5th order parasequences cannot be reliably traced into these cores, but the large scale sequences, such as the Lower Ismay interval, are easily identified by the corresponding basin-spanning black shales. During the Lower Ismay interval, the δ^{13}C of carbonate in outcrop along the shelf edge is between +2 and +4‰, which is in line with values reported by Saltzman (2003) from other locations along the Panthalassic margin. Approaching the foredeep, the δ^{13}C of carbonate increases to values of +5 to +6‰ (Fig. 4).

4. Discussion

4.1. Diachronous deposition

The carbon isotopic data from these sections is difficult to explain with synchronous deposition of cycles and sustained isotopic gradients in the Paradox basin. In modern carbonate environments, lateral gradients in the isotopic composition of dissolved inorganic carbon result from two mechanisms. In the Bahamas, waters on the carbonate platform are continually scavenged of light carbon by grasses and algae, and in many places the mixing time is relatively slow compare to the residence time, resulting in sustained isotope gradients across the shelf (Broecker and Takahashi, 1966). This gradient is further enhanced because aragonite, which is heavier than calcite, dominates inner shelf deposition while the outer shelf and slope environments have more calcitic plankton. The combined effect accounts for isotopic gradients of 1–2‰, with heavier sediments deposited on the platform. Since this mechanism results in heavier nearshore deposition, it cannot

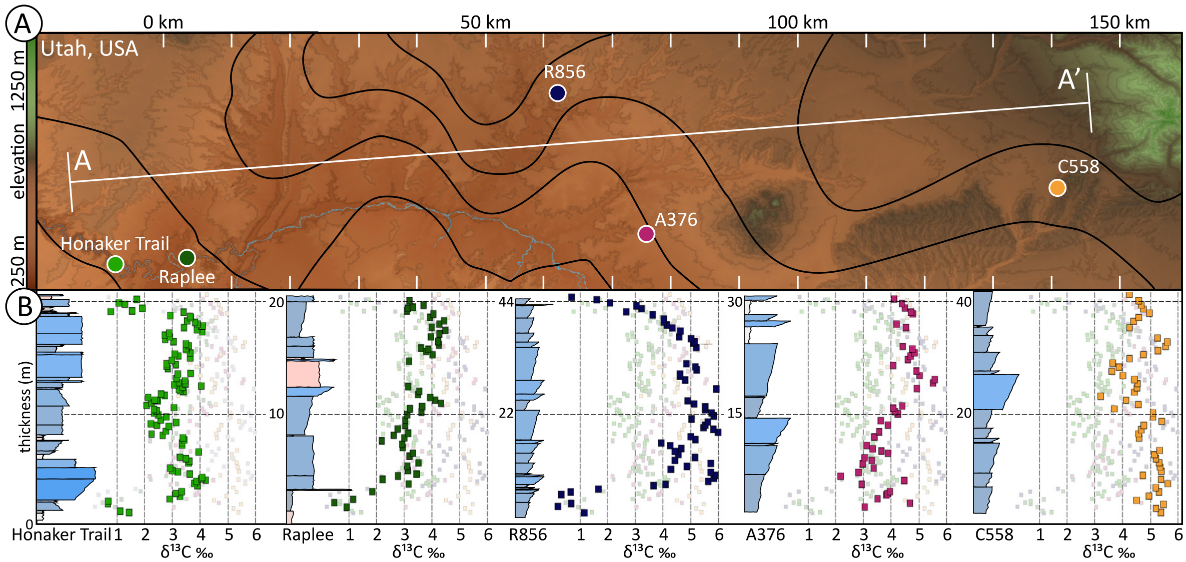

Fig. 4. (A) Map inset of the Paradox Basin focused on the stratigraphic sections and cores highlighted for the lateral transect. Bold lines are Pennsylvanian–Permian isopach contours of 150 m adapted from Peterson and Ohlen (1963). The base map is a digital elevation model, with grey 50 m elevation contours. (B) Side by side comparison of the stratigraphy (facies legend in Fig. 2) and carbon isotopes of the Ismay Sequence δ^{13}C along transect A–A′. Each plot contains the carbon isotopes from all 5 sections (gray), and the highlighted color data corresponds to the adjacent stratigraphy.

explain the distal enrichment observed in the Paradox Basin. Alternatively, in the Florida Bay, river water discharged from the Everglades is loaded with isotopically light remineralized organic which overwhelms the marine water chemistry and results in isotopically lighter carbonates deposited nearshore (Patterson and Walter, 1994). The resulting lateral gradient in carbon isotopes could explain the lighter carbon isotopes deposited nearshore, but it cannot account for carbon isotopes further into the basin that are heavier than Pennsylvanian δ^{13}C from the rest of Laurentia (+3 to +4‰, Saltzman, 2003). The carbon isotopes from the two nearshore sections, Honaker trail and Raplee, are consistent with these Laurentia values, but the Ismay sequence in the most basinward cores is enriched up to +6‰, which is significantly heavier than any other open ocean carbonates deposited along the Panthalassic margin. It is also evident from the overlying Cutler formation that fluvial input to the Paradox Basin came from the Uncompaghre uplift in the northeast. Therefore, the most significant river input would be on the wrong side of the basin to explain the observed gradient. Furthermore, a lateral gradient of carbon isotopes would be preserved as offsets in the isotopes by facies from a single location. Marls and wackestones, deposited distally from carbonate tidal flats should be heavier than grainstones and packestones deposited nearshore. Fig. 3 illustrates the distribution of carbon isotopes grouped by depositional environment for the Honaker trail and Raplee outcrop sections. For this figure, peritidal breccias and grainstones are considered shallow, packestones are intermediate, and subtidal marls, mudstones and wackestones are deep. The mean values for all three depth ranges are between 2.18 and 2.42‰, and the distributions are consistent enough to conclude that there are no facies dependent trends in the data. Since none of these mechanisms for maintaining lateral isotopic gradients fully explain the observations presented here, it is worth considering the possibility that parasequences in this basin were deposited diachronously. The carbonate platform could prograde from the foreland bulge towards the basin interior, and the chemistry of the carbonates would then track changes in basin seawater over this time period. Therefore, the enrichment in ^{13}C observed in the basinward sediments may be related to the same process driving the progradation of the carbonate tidal flats.

The Paradox is an intracratonic basin that may be highly sensitive to changes in shape or depth of shallow seaways that connect it to the Panthalassic ocean through a series of basins (see Fig. 1). The Oquirrh basin is immediately to the northwest and the San Juan Basin is to the southeast. The seaway connecting the Paradox to the Oquirrh is narrow (<50 km) and the entire preserved Pennsylvanian accumulation in this region is less than 150 m, whereas the connection to the San Juan basin may be up to 100 km wide and underwent greater subsidence during the deposition of the Honaker Trail and Paradox formations. Since the δ^{13}C of the carbonates along the basin margins matches the late Pennsylvanian Panthalassic ocean, these sediments were most likely deposited during a stage where the flux of waters into and out of the basin was high enough to keep the nutrients and dissolved inorganic carbonate composition in equilibrium with Panthalassia.

4.2. Basin restriction

The presence of salt–sapropel cycles in the foredeep indicates a second state where the water in the basin is stratified or restricted enough for evaporite deposition. Marine evaporites today only occur in shallow environments such as sabkhas and lagoons. In deep, mostly land-locked basins, such as the Red Sea, salinities do not reach levels high enough for evaporites since any salt transported from the surface into the deep waters of these basins is carried out by countercurrents (Brongersma-Sanders, 1971). However, evaporite deposition in deep basins is well known in the geologic record, with examples such as the Messinian salinity crisis of the Mediterranean Ocean (Ryan, 1973; Hsü et al., 1977). The salts of the Paradox are located in the region of the basin with the greatest subsidence and accommodation space, and the edges of the basin, where the shallowest environments occur, do not have evaporites. The deep water evaporite model of Schmalz (1969) reconciles the thick distribution of cyclic evaporites in the deepest part of the Paradox Basin. Deep water evaporites only form if there exists a trap to keep dense deep water brines from escaping the basin, such as a shallow exit seaway in a mostly land-locked basin. When surface evaporation exceeds runoff, high salinity can lead to the precipitation of gypsum in the surface, and crystal settling drives the transport of $CaSO_4$ into the deep. The gypsum will dissolve in the undersaturated deep waters leading to an increase in salinity. If these deep waters can escape the basin and mix with the open ocean, then the basin will remain undersat-

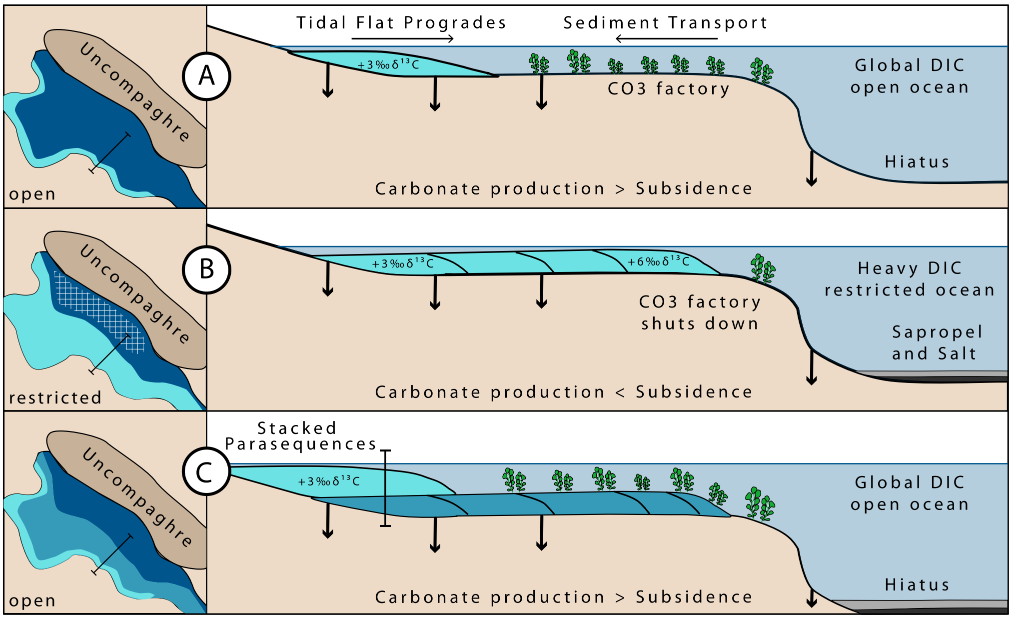

Fig. 5. Three stages of the Paradox basin autocyclic model. In stage (A) the ocean is well connected to Panthalassia and the carbonate factory is very active. Carbonate is transported landward and trapped. In stage (B) the tidal flat has prograded over the productive carbonate factory, and restricted the flow through the shallow seaway connecting the basin to the open ocean. The restricted waters result in isotopically heavier carbonate deposition and eventually salt precipitation in the basin. With the carbonate factory turned off at the end of stage (B), subsidence is greater than sedimentation and the tidal flat is flooded. In stage (C), the carbonate factory has the nutrients, light, and time to re-establish itself on top of the old flooded tidal flats, and carbonate once again is transported landward to get trapped in prograding tidal flats. Model is adapted from Ginsburg (1971).

urated. However, a shallow obstruction connecting the basin to the open ocean may amplify the halocline and lead to a vertically stratified water column. If the export of organic matter from the surface productivity continues, the stratified bottom waters will eventually become oxygen limited, and the burial of organic matter in sapropels will occur. With less remineralized organic matter cycling back into the surface waters, the DIC will become heavier through time. Eventually, the lack of new upwelling nutrients will kill off the surface productivity, and the ever increasing salinity will lead to the deep water precipitation of gypsum (Fig. 5B). The entire system will reset as soon as the oceanic conduits open back up, from the shallowing of the basin interior through rapid salt deposition, or glacioeustatic sea level rise, or as the connecting seaways sufficiently deepen through continued flexural and/or thermal subsidence (Fig. 5C). Slight changes in relative sea level of the basin openings, especially if the geometry is wide and shallow, can significantly alter the interior circulation of the basin and drive the cyclicity of both the deep basin evaporites and the carbonate rich periphery. Glacioeustasy and carbonate build up are two mechanisms that could periodically alter the sea level in these regions. If glacioeustasy is responsible for the basin restriction, there should be physical and geochemical evidence of deep, penetrative meteoric diagenesis at the fore bulge.

4.3. Meteoric diagenesis

Isotopically light δ^{13}C of some parasequences tops that get gradually heavier with depth is evidence of early meteoric diagenesis, but the depth of each diagenetic event at the Honaker Trail and Raplee outcrops suggests minor or no sea level change. When sea level falls and carbonate platforms are exposed, meteoric fluids (undersaturated in carbonate and charged with atmospheric CO_2 or respired CO_2 from organic material) are driven through the platform by gravity (Thrailkill, 1965, 1968; Matthews, 1974; Bögli and Schmid, 1980). The freshwater saturated (phreatic) region of the platform experiences extensive dissolution and often is characterized by the development of large solution cavities and openings, which eventually collapse. The mixing of undersaturated meteoric fluids and super saturated marine fluids along the fringes of the freshwater lens can result in the precipitation of new calcite that contains a mixture of carbon and oxygen from both the marine and meteoric systems. Carbon and oxygen from the meteoric system will have a unique isotopic signature derived from a combination of atmospheric values, dissolved marine carbonate, and CO_2 generated by the decay of marine and terrestrial organic matter and the respiration of nearby roots from living plants. Organic matter is light in carbon (−25‰) due to kinetic fractionation during photosynthesis, and dissolved atmospheric CO_2 is on the order of 10‰ lighter than seawater CO_2 due to the kinetics of exchange between atmosphere and water (Hayes, 2001). Marine values normally will be heavier than both of these light reservoirs, so dissolution and reprecipitation of carbonate in a karst system should drive marine carbonates to lighter values. The thickness of meteorically altered, isotopically light carbonate is indicative of the vertical extent of the phreatic zone. The depth of diagenesis in the phreatic zone is a function of the permeability of the vadose cap, and the flux of CO_2 charged meteoric waters through the rock. In dry conditions with low permeability sediments, the freshwater to marine isotopic transition will be shallow and sharp near mean sea level. Wet environments with permeable sediments may develop a deep meteoric profiles extending well below mean sea level in locations away from the coastline. Throughout the Pleistocene, the Great Bahama Bank has been exposed to rainwater during the sea level draw down associated with each stadial, and the isotopic values of bulk carbonate in the upper parts of the platform are much lighter than the carbonate precipitated from seawater on and around the bank today (Swart and Eberli, 2005). Clino core is on the shelf edge of the Bahama Bank in 10 m of water and the freshwater lens during the 120 m sea level drop of the last glacial maximum has been interpreted to be at least 100 m deep based on the downcore isotopic profile. The 100 m thick top-negative carbon isotope anomaly completely overprints at least 7 glacioeustatic parasequences within this interval that have been identified in the physical stratigraphy and are thought to correspond to Pleistocene glacial–interglacial cycles. Isotopic depletion with similar vertical scale from the Middle Carboniferous has been identified in Kazakhstan (Katz et al., 2013) and Nevada (Bishop et al., 2009). The meteoric isotopic profile from the Late Mississippian in Arrow Canyon, Nevada goes from +3‰ to −7‰, and penetrates 60 m below the exposure surface.

The isotopic profiles of meteoric diagenesis in the Paradox basin are never more than a few meters deep, and stacked parasequences record independent meteoric events without overprinting underlying parasequences. The parasequences illustrated on the right of Fig. 2B are good examples of these observations. The expectation based on the diagenesis during the Pleistocene is that high amplitude sea level change in the Paradox Basin cycles would result in a single large top negative isotopic anomaly that completely overprints the parasequences below. The mixing zone between the freshwater lens and seawater in coastal carbonate environments is a significant site for the development of porosity and permeability (Back et al., 1986), and repeated cycles of sea level change would subject the lithologic column over of the entire range of sea level change to these dissolving forces. The mixing zone in coastal carbonates of the Yucatan peninsula within 1 km of the coastline is between 2 and 4 m deep, and the δ^{13}C of the water above the mixing zone is between −12‰ and −7‰ (Stoessell et al., 1989). This mixing zone gets deeper further inland, and the shape ultimately is controlled by the amount of freshwater entering the system, the distance from the shoreline, and the permeability of the rock (Budd and Vacher, 1991). Therefore, unless the Paradox basin cycle tops, which are often coarse ooilites or coated grainstones, were impermeable to meteoric water, then these shallow meteoric diagenesis profiles cannot be generated by high amplitude sea level change. In fact, sea level change is not a requirement to explain the exposure sequences or negative isotopic profiles. In the case of no sea level change, exposure surfaces are generated by storm events that accumulate sediment above the mean sea level, and these local highs develop shallow freshwater lenses. Furthermore, low amplitude periodic sea level change should generate highly ordered parasequence thicknesses. Since the parasequence thicknesses in the Paradox basin are unpredictable and random (Lehrmann and Goldhammer, 1999), the most elegant model for their origin is one controlled entirely by intrinsic sedimentary processes.

4.4. Autocyclic depositional model

Ginsburg (1971) proposed a sedimentation model for generating regressive carbonate cycles based on observations in the Bahamas, Persian Gulf, and Florida that is completely controlled by the trapping of carbonate near the shore. In this model, carbonate that is produced over extensive open platforms is collected in intertidal lagoons (Fig. 5A). These nearshore traps prograde and decrease the carbonate production area, and eventually subsidence outpaces the sediment production, resulting in transgression (Fig. 5B). In the Paradox basin, carbonate banks are present in core extending into the shallow seaways connecting to the ocean (see Fig. 1). If the carbonate accumulating in these seaways is tied to the diachronous progradation observed in the shelf to basin transect, then there is a single mechanism that simultaneously explains the paradoxical alternations of sapropel–evaporite in the deep basin, the cyclic nature of carbonates on the peripheral bulge, the elevated δ^{13}C of the basinward sections, and the lack of deep meteoric diagenesis in any of the carbonates.

5. Conclusions

Isotopic evidence from three cores and two outcrop sections indicates that carbonate parasequences were deposited diachronously from the forebulge into the foredeep of the Paradox Basin. Heavier isotopes in the carbonates from the basin interior are evidence of the increasing anoxic bottom waters associated with stratification and restriction of the basin. Shallow meteoric diagenesis profiles associated with root filled exposure surfaces in some of the parasequences at the forebulge indicate that sea level change associated with the exposure was minor or nonexistent. Additionally, the lack of order in the parasequence thicknesses supports the idea that the stochastic sedimentary system, as opposed to environmental factors, imparted the greatest control on the formation of cycles in the Paradox Basin. Previous studies in the western United States, relying solely on physical stratigraphy, have found that the late Pennsylvanian is a time period of glacial minimum and relatively static eustasy (Bishop et al., 2010), which is consistent with the results presented here. Furthermore, this study demonstrates that laterally extensive coupled physical and chemical stratigraphy can be used to extract environmental information from cyclic upward-shallowing carbonate parasequences, and indicates that local sedimentary and regional basinal processes can significantly contribute to the apparent cyclicity in the stratigraphic record.

Author contributions

Field work was conducted by B.C.D. and A.C.M. B.C.D. wrote the manuscript and drafted figures, with input from A.C.M.

Acknowledgements

B.C.D. was supported by Princeton University Department of Geosciences Scott Fund and an ExxonMobil Research and Engineering Company science grant. A.C.M. was supported by a Sloan Foundation research fellowship and Princeton University. The ideas presented here benefited from discussions with David Barbeau, David Jones, and Anne-Sofie Ahm. Lily Adler, Yuem Park, and new Tom Birren provided assistance in the field. We thank the Utah BLM for providing access to the Honaker Trail and Raplee locations, and the USGS Core Research Center helped us to access and sample a number of cores from the Paradox Basin. Alison Campion, Collin Edwards, Natalie Saenz, Yuem Park, Julia Wilcots, Leah Nelson, Katherine McLellan, Anna Erkalova and Josh Zoellmer helped prepare samples for isotopic analysis at Princeton University.

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