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

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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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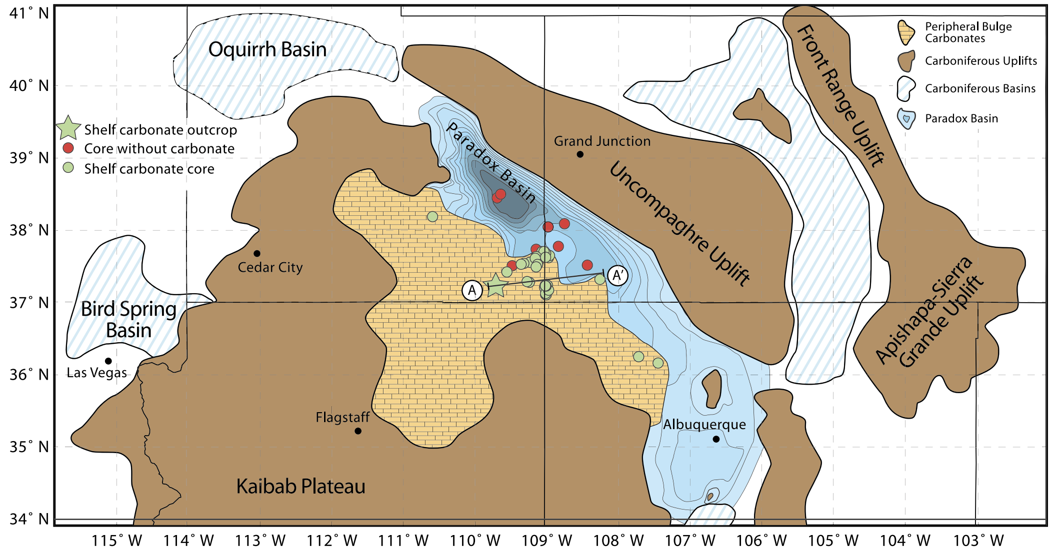

Fig. 1. Pennsylvanian Isopach map of the Paradox Basin region with core and outcrop study locations. Isopachs are 150 m intervals from Peterson and Ohlen (1963). The orange region represents the extent of carbonate facies during the Desert Creek and Ismay sequences based on labeled cores from the USGS 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-