

Dynamic Late Ordovician climate responses: The cascading effects of expanding continental ice?

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ABSTRACT

The interplay between astronomical forcing, continental ice volume, and biotic immigration is well studied in the Cenozoic, and documentation of such connections in the Paleozoic is rapidly increasing. Herein, we present analyses from late Katian subtropical marine deposits, revealing a transition from obliquity- ($\sim 33.8 \pm 0.46$ k.y.) and precession- ($\sim 17\text{--}22$ k.y.) dominated sedimentation to a regime dominated by obliquity and short eccentricity ($\sim 93\text{--}125$ k.y.). We term this shift the late Katian transition. Transition from precession- to short eccentricity-dominated sedimentary cycles suggests expansion of ice sheets over Gondwana. This shift precedes a major episode of faunal immigration in Laurentia, which may have been facilitated by this climatic transition.

INTRODUCTION

The late Katian Age of the Ordovician Period represents a pivotal transition in Earth's history, bridging the remarkable expansion of life during the Great Ordovician Biodiversification Event (Stigall et al., 2019) and one of the most taxonomically severe mass extinctions in the Phanerozoic, the Late Ordovician Mass Extinction (Raup and Sepkoski, 1982) (Fig. 1). Furthermore, the late Katian featured multiple episodes of climatic cooling and warming (Männik et al., 2025) coupled with widespread faunal immigration (Stigall, 2023). Understanding the late Katian is therefore critical for unraveling the complex interplay between Earth system components and understanding their influence on ecological, evolutionary, and paleobiogeographic patterns. This work provides new insights into these dynamics of biotic trends, global climate fluctuations, continental ice volumes, and astronomically influenced variability in Paleozoic strata.

Geologic Setting

This study focuses on upper Katian strata of southern Ohio, United States, situated within the northern Cincinnati arch structural-depositional province (Brett et al., 2020). These mixed carbonate-clastic deposits have been minimally altered by tectonic deformation and late diagenesis (Brett et al., 2020). During the Katian, this area was covered by a subtropical ($20^{\circ}\text{--}23^{\circ}\text{S}$) epeiric sea at the distal edge of the Taconic foreland basin (Brett et al., 2020). The region comprised a northward-dipping ramp with water depths ranging from above normal wave base to below storm wave base (Brett et al., 2020). Many previous authors have identified and traced unconformity-bounded sequences within the Cincinnati arch (e.g., Holland and Patzkowsky, 1998; Brett et al., 2020). These studies have identified a link between local deposition and eustatic sea-level variability evidenced by the geographic extent of depositional sequences greatly exceeding the flexural wavelength of the lithosphere (Holland and Patzkowsky, 1998). The notion that the sea-level fluctuations that produced type Cincinnati depositional sequences were glacioeustatic has been tested empirically for the Kope Formation (Elrick et al., 2013). Elrick et al. (2013)

demonstrated that $\delta^{18}\text{O}_{\text{apatite}}$ measurements from conodont elements are isotopically heavier in shallower facies and isotopically lighter in deeper facies, suggesting that $\sim 40\text{--}100$ k.y. glacioeustatic cycles played a dominant role in their genesis.

Offshore deposits in the type Cincinnati, such as the Kope and Waynesville formations, have been interpreted as having formed through alternating deposition of authigenic bioclastic carbonates and allogenic siliciclastics. In this scenario, rising sea level sequesters siliciclastic material in newly formed accommodation space near shore. This results in siliciclastic starvation in offshore environments and allows for accumulation of authigenic carbonate bioclasts dominated by brachiopod, bryozoan, and echinoderm sclerites. This mechanism for offshore shell bed genesis is termed the episodic starvation model (Brett et al., 2008; Dattilo et al., 2008, 2012; McLaughlin et al., 2008).

Study Interval

This study targets the Fort Ancient and Clarksville Members of the Waynesville Formation, which comprise a third-order depositional sequence, termed “C5” (Cincinnati 5) (Brett et al., 2020). The C5 sequence contains three fourth-order sequences (C5A, C5B, and C5C), the first two within the Fort Ancient Member and the third within the Clarksville Member (Brett et al., 2020). For further discussion of sequence architecture, see the Supplemental Material¹ and Brett et al. (2020). The base of the C5 sequence represents the boundary between the globally recognized *Amorphognathus superbus* and *Amorphognathus ordovicicus* North Atlantic province conodont zones (Bergström and MacKenzie, 2005). Independent numerical age constraints

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¹Supplemental Material. Data, R script for analyses, photos of drill core, supplementary figures, discussion of stratigraphic architecture, and extended methods. Please visit <https://doi.org/10.1130/GEOL.S.31955877> to access the supplemental material; contact editing@geosociety.org with any questions.

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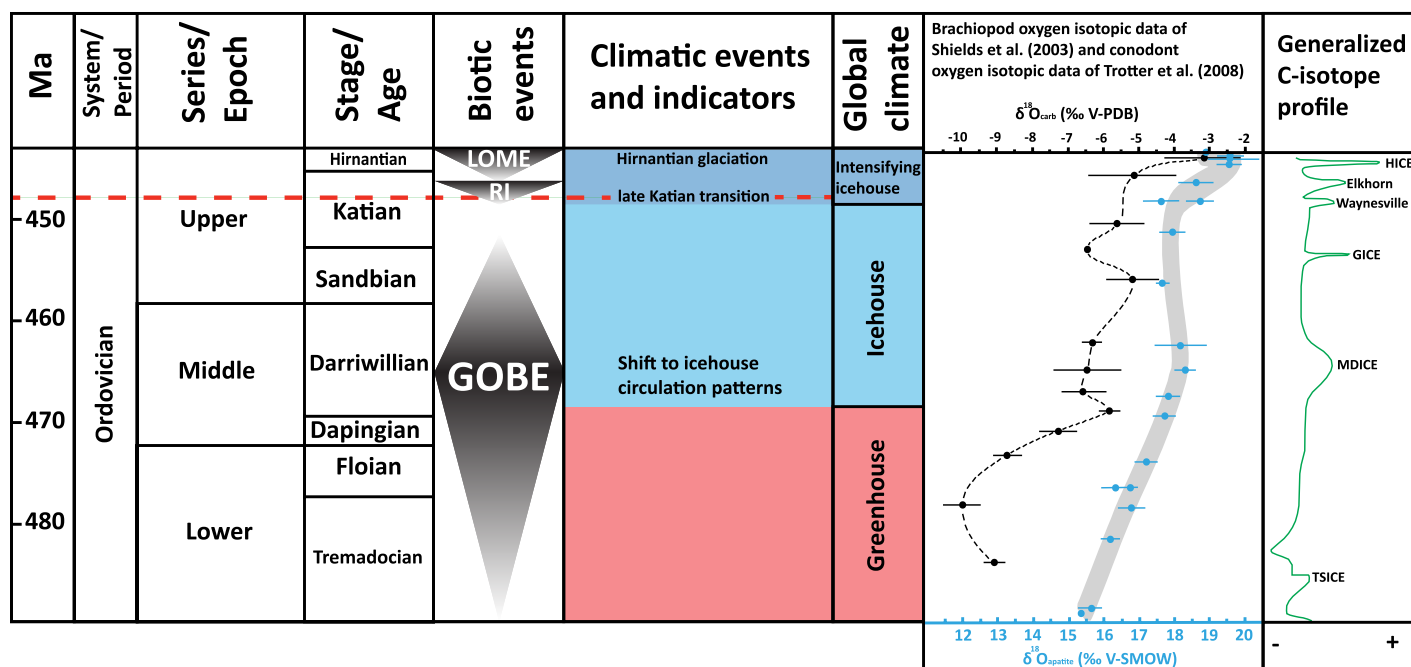


Figure 1. Ordovician time scale with biotic events, climatic events, and oxygen isotope trends. Oxygen isotope figure is modified from Trotter et al. (2008); conodont data are indicated in blue, and brachiopod data are indicated in black. carb—carbonate. Error bars for Ordovician brachiopod data are ± 1 sigma, all other data are shown at ± 2 sigma; errors for some means were unavailable. Gray band represents the primary first-order temporal trend of Ordovician $\delta^{18}\text{O}_{\text{apatite}}$ determined by Trotter et al. (2008). Carbon isotopic profile is modified from Algeo et al. (2016). For shift to icehouse circulation patterns, see Rasmussen et al. (2016). LOME—Late Ordovician Mass Extinction; RI—Richmondian Invasion; GOBE—Great Ordovician Biodiversification Event; V-PDB—Vienna Pee Dee belemnite; V-SMOW—Vienna standard mean ocean water.

for these strata are limited, but radiometric dates from bentonites in the Utica Shale of New York (United States) place the base of the Edenian North American regional stage at ca. 451 Ma (Sell et al., 2013). Ling et al. (2019) placed the base of the Hirnantian at 443.14 ± 0.24 Ma based on radiometric dates derived from bentonites in SW China, indicating that our study interval lies within this ~ 8 m.y. span.

MATERIALS AND METHODS

A Core Labs gamma ray spectrometer was used to collect bulk gamma ray data through the C5 sequence in the Fairborn core (drilling location: 39.7784°N , 83.9651°W ; Fig. 2). These deposits contain very little organic matter to sorb radioisotopes (e.g., ^{238}U). Consequently, gamma ray production is dominated by radioisotopes within allogenic terrigenous material (e.g., ^{40}K and ^{232}Th), making gamma ray spectroscopy an ideal methodology for quantifying variations in siliciclastic influx. Analyses were conducted in the R packages “astrochron” (Meyers, 2014) and “Waverider” (Arts, 2023); see the code in the Supplemental Material for additional details. The dataset was assessed using a locally weighted regression spectral background estimate (LOWSPEC) (Meyers, 2012) and a continuous wavelet transform (CWT) using a Morlet wavelet to test for the presence of candidate orbitals (sedimentary cycles prospectively influenced by orbital forcing). Candidate orbital selection criteria follow

Meyers (2012). Average spectral misfit analysis (ASM) (Meyers and Sageman, 2007) was conducted using the candidate orbitals detected via LOWSPEC and CWT. ASM was also used to compare the observed sedimentary cycles to an auto-regressive $1[\text{AR}(1)]$ red noise model using 100,000 Monte Carlo simulations. ASM was paired with TimeOpt (Meyers, 2014), an optimization-based approach that accounts for uncertainties in both time scales and astronomical response using precession and eccentricity as target parameters. TimeOpt uses precession and eccentricity as target parameters so that both amplitude modulation and cycle bundling can be evaluated during optimization. Astronomical target frequencies appropriate for the Late Ordovician (459 Ma) were estimated using the function “calcPeriods” (Meyers, 2014), with average secular frequencies (g , s) derived from Laskar et al. (2004) and a Late Ordovician (459 Ma) precession constant (k) calculated from Waltham (2015). Although these parameters carry inherent uncertainty, the resulting target frequencies are broadly consistent with other Ordovician estimates (Zhong et al., 2020). A Monte Carlo astrochronologic test was then conducted using the functions “timeOptSim” and “timeOptSimPwrLaw” (Meyers, 2014) to evaluate the null hypothesis that variability in clastic abundance arises solely from stochastic processes.

To test the impacts of variable sedimentation rate on orbital signal preservation, we used the function “timeOptTemplate” (Meyers, 2019),

which extends the TimeOpt framework to accommodate sedimentation rate changes. Four scenarios were tested: (1) gamma ray intensity positively correlates with sedimentation rate, (2) gamma ray intensity inversely correlates with sedimentation rate, (3) sedimentation rate increases linearly upward, and (4) sedimentation rate decreases linearly upward. Astronomical tuning in which the presumed obliquity cycle was tracked in the CWT was then conducted. Obliquity was selected for tuning due to its persistent expression throughout the studied interval and because eccentricity and precession (but not obliquity) were used as targets in TimeOpt, and we sought to assess obliquity independently (cf. Muller and MacDonald, 2002).

Visual inspection of the gamma ray log and the CWT indicated a shift in cycle period from shorter sedimentary cycles in the lower sequence C5 to longer sedimentary cycles in the upper sequence C5 (Fig. 3A). To assess the visually identified change quantitatively, the total gamma dataset was split at 76.5 m depth, the approximate position of the putative change in sedimentary cycle period, and both a CWT and LOWSPEC analysis were conducted on the two parts of the dataset separately.

RESULTS

LOWSPEC analysis revealed candidate orbitals at ~ 2.7 m, ~ 1.2 m, ~ 0.61 m, ~ 0.53 m. The periodogram and CWT indicate short eccentricity is recorded from 2.08 to 3.33 m, obliquity

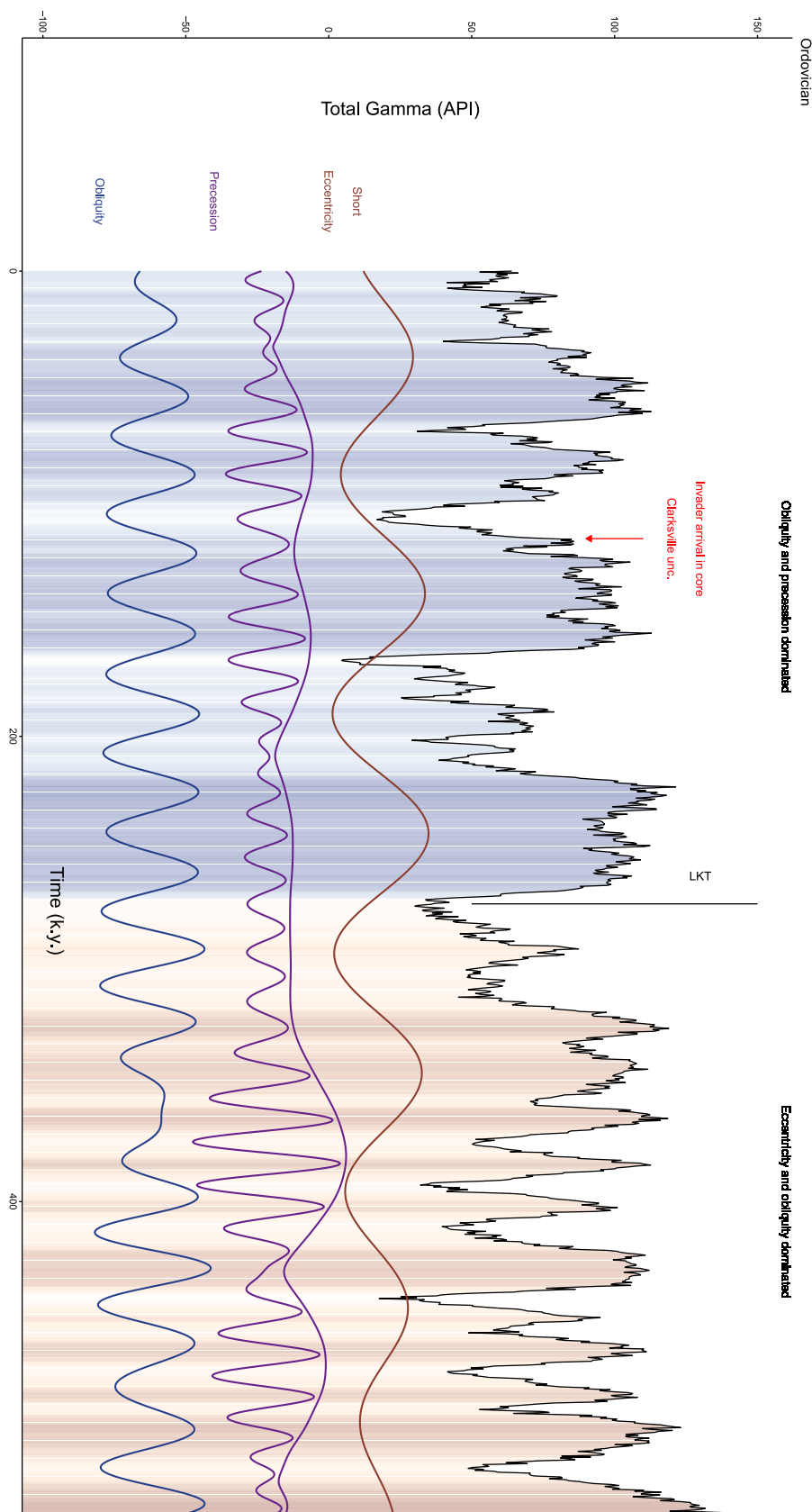


Figure 2. Obliquity tuned total gamma (American Petroleum Institute) data with bandpass-filtered precession, obliquity, and short eccentricity signals. Time in the figure is referring to the duration of the study interval indicated by the obliquity tuned data. “Clarksville unc.” refers to a minor unconformity at the base of the Clarksville Member of the Waynesville Formation. Note antiphased Hilbert transform of bandpass-filtered precession and bandpass-filtered short eccentricity. LKT—late Katian transition.

is recorded from 0.88 to 1.38 m, and precession is recorded from 0.49 to 0.68 m (Fig. 3A).

ASM indicates that sedimentary cycle bundling matches the expected bundling pattern for Ordovician orbital frequencies (Zhong et al., 2020), with an ASM of 0.0007 cycles/k.y. at an average sedimentation rate of ~ 3.13 cm/k.y. Additionally, comparison of the detected candidate orbitals to an AR(1) red noise model yielded a p -value of 0.00005. TimeOpt yields an optimal sedimentation rate of 2.97 cm/k.y. with an $r^2_{\text{opt}} = 0.127$ (opt—optimal). The Monte Carlo astrochronologic tests resulted in p -values of 0.079 for timeOptSim and 0.083 for timeOptSimPwrLaw, allowing for rejection of the null hypothesis at $\sim 91\%$ – 92% confidence, depending on the noise model considered.

All four “timeOptTemplate” models yielded results broadly consistent with the constant-rate case, with mean sedimentation rates of 3.02, 2.96, 2.96, and 2.96 cm/k.y., and r^2_{opt} values of 0.14, 0.13, 0.15, and 0.12, respectively. This indicates that variable sedimentation rates do not substantially improve the overall solution.

When the data set is manually tuned to the ~ 33 k.y. Late Ordovician obliquity cycle, power is preserved, and in some cases concentrated, at the periods of precession and short eccentricity (Fig. 3B). This “minimal tuning” approach (Muller and MacDonald, 2002) thus provides an independent line of evidence that lithologic variability in the Waynesville Formation reflects astronomically controlled climate cycles. The antiphased relationship between the bandpass-filtered eccentricity signal and the amplitude of the bandpass-filtered precession signal (isolated via Hilbert transform) suggests that eccentricity maxima correspond to carbonate-rich intervals (low total gamma values) (Fig. 2). This is consistent with eccentricity maxima causing more intense seasonality and warmer summers, resulting in ice sheet retreat and, consequently, transgression (Imbrie et al., 1984). Furthermore, the CWT shows that spectral power of the precession signal increases and decreases with a ~ 93 – 125 k.y. periodicity, corresponding to the short-eccentricity modulator. Finally, the CWT for the lower portion of the study interval (76.5–84.2 m depth) indicates a dominance of ~ 0.88 – 1.38 m and ~ 0.49 – 0.68 m cycles, which are interpreted as obliquity and precession. In contrast, the CWT for the upper portion of the study interval (67.5–76.5 m) reveals increased influence of an ~ 2.08 – 3.33 m cycle, interpreted as short eccentricity, at the expense of the ~ 0.49 – 0.68 m precession cycle.

DISCUSSION

Global Cooling and the Late Katian Transition

The transfer of spectral power from precession to short eccentricity is interpreted to represent a

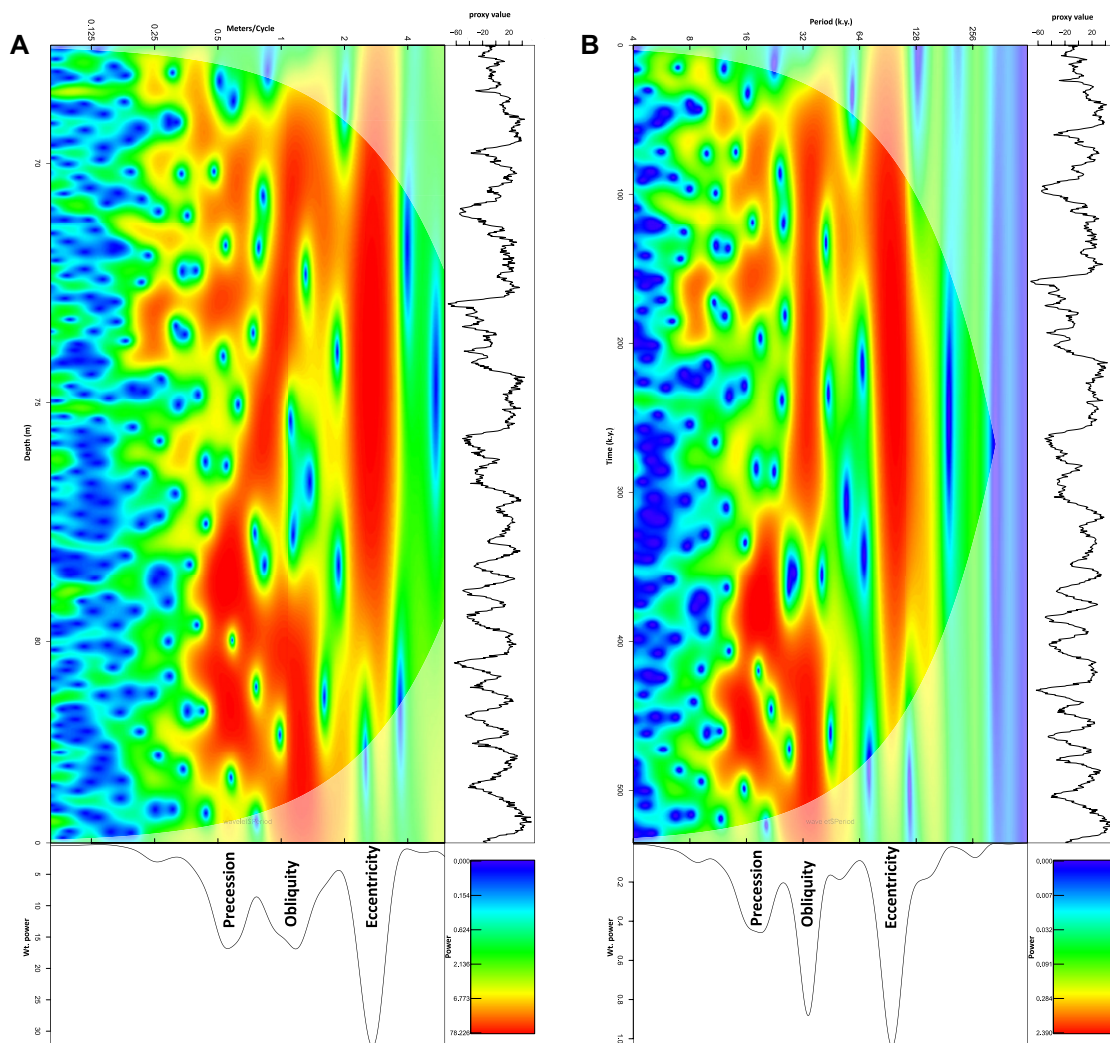


Figure 3. (A) Continuous wavelet transform (CWT) of untuned (depth domain) total gamma values (American Petroleum Institute [API]) data on the right side of the log in both A and B. Note persistent obliquity, strong precession in lower C5, and strong eccentricity in upper C5. (B) CWT of obliquity-tuned (time domain) total gamma (API) data. Time in panel B is referring to the duration of the study interval as calculated from the obliquity tuned data. Wt. power—wavelet transform spectral power (power is the square of amplitude and is what is being displayed in A and B).

shift from smaller ice sheets in the southern hemisphere to larger ice sheets, a shift we term the late Katian transition (LKT). The LKT shares similarities with the mid-Pleistocene transition (MPT), which marked a change from glacial cycles dominated by ~ 41 k.y. obliquity to those influenced by ~ 100 k.y. short eccentricity, but an in-depth comparison of the two is beyond the scope of this work. We propose a plausible model for the LKT climatic shift: This shift to stronger ~ 100 k.y. eccentricity influence in the marine record following the LKT suggests that terrestrial ice margins were replaced by marine-based ice sheet margins along the shoreline of Gondwana. Ice sheets with terrestrial margins are more susceptible to summer melting due to the lower albedo of the adjacent terrigenous material. Ice sheet expansion and development of a marine-based margin would result in weaker control of summer melting on ice sheet ablation and a shift to calving as the primary ablation mechanism, as is the case in East Antarctica today (Raymo et al., 2006). Following the development of a marine-based ice sheet margin, only the most extreme precession-driven insolation maxima (modulated by short eccentricity)

would produce substantial ice loss and sea-level change. This would result in strongly dampening the precession signal in the marine record while simultaneously enhancing expression of short eccentricity (Raymo et al., 2006).

Stratigraphic Evidence for Glacioeustasy

The LKT hypothesis is lent further credence by the presence of subaerial unconformities following this transition, which are distributed across at least two paleocontinents, suggesting eustatic regression. One such erosion surface, the mid-Richmondian unconformity (MRU) (Aucoin and Brett, 2016), separates our study interval from the overlying C6 (Cincinnatian 6) sequence and completely truncates our study interval in up-ramp sections in northern Kentucky (United States). The MRU is correlated with a subaerial unconformity in the Saunja Formation of Estonia and Latvia (Aucoin and Brett, 2016). This unconformity is in turn correlated to a paleokarst surface in the Slandrom Limestone of Sweden (Calner et al., 2010). These Baltoscandian paleokarst surfaces are developed just above the globally recognized *Amorphogna-*

thus ordovicicus North Atlantic conodont zone boundary, which also occurs at the base of our study interval.

Furthermore, channels of late Richmondian age in south-central Tennessee (United States) have been interpreted as incised valley fills cut as much as 30 m into the underlying strata (Wilson, 1949; Holland and Patzkowsky, 1998). These incised valleys occur in a similar stratigraphic position to the MRU in Kentucky. The channel fills contain Katian fauna, which do not persist into the Hirnantian Stage (Wilson, 1949), precluding the possibility that these channels were incised during the later Hirnantian glaciation. Past studies in the Nashville dome have noted that the magnitude of sea-level change at this boundary is particularly difficult to explain outside the context of glacioeustasy (Holland and Patzkowsky, 1998).

Despite mounting stratigraphic evidence for glaciation, tentative Katian glacial deposits have only been documented in Niger and Libya (Cherns and Wheelley, 2007; Legrand, 2011). However, Katian glacial deposits may have been eliminated by subglacial and/or sub-

aerial erosion during the Hirnantian. Alternatively, they may still exist but lie undiscovered in the terranes that comprised Gondwana.

Paleontological Significance

The strata analyzed in this study record a biotic immigration event termed the Clarks-ville Phase (Aucoin and Brett, 2016). This is the first major pulse of a larger series of biotic immigration events termed the Richmondian Invasion, during which a suite of novel taxa spread across eastern Laurentia (Stigall, 2023). The temporal coincidence of widespread biotic immigration with the climatic changes documented herein suggests a potential linkage. Past studies of the Late Ordovician have also suggested Milankovitch forcing of biotic turnover (Crampton et al., 2018), and a more thorough investigation of the LKT's impact on the biosphere is warranted.

CONCLUSIONS

Available cyclostratigraphic and sequence stratigraphic data strongly suggest that astronomically forced climatic cycles influenced sedimentation patterns during the late Katian, likely through modulation of continental ice volume over the paleocontinent of Gondwana. Furthermore, we document a shift to increased influence of short eccentricity on sedimentation patterns, which we term the late Katian transition and link to an increase in continental ice volume in the Southern Hemisphere. Finally, we suggest that intensifying glaciation and the associated changes in global climate may have facilitated and/or driven the suite of biotic invasions collectively known as the Richmondian Invasion, a possibility that warrants further investigation.

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