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Astronomical calibration of the Jurassic–Cretaceous transition links cooling, calcification events, and Boreal–Tethyan carbon-cycle decoupling

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Abstract

The Jurassic–Cretaceous transition is one of the least constrained intervals of the Mesozoic timescale, limiting robust assessment of the timing and relationships among climate change, carbon-cycle perturbations, and marine biotic evolution. Here we establish a high-resolution astrochronological framework for the Tithonian–Berriasian Sulaiy Formation of central Saudi Arabia by integrating astronomical tuning with calcareous nannofossil biostratigraphy, ⁸⁷Sr/⁸⁶Sr isotope stratigraphy, and carbonate $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ records. Astronomical calibration identifies 15 stable 405-kyr eccentricity cycles within the Tithonian and 14 within the Berriasian, providing a continuous chronology spanning ~149.2–137.8 Ma. The resulting timescale demonstrates that enhanced obliquity forcing between ~146.1 and 140.2 Ma coincided with the principal interval of late Tithonian–early Berriasian cooling. The integrated chronology refines the timing of Boreal–Tethyan carbon-isotope decoupling, and the erected Tithonian–Berriasian climato-chronostratigraphic scheme provides a robust temporal framework for linking orbital forcing, climate, carbon cycle, and carbonate production across the Jurassic–Cretaceous transition.

Highlights

- Astrochronology for a cored Tithonian–Berriasian carbonate succession, dated to ~149.8–137.8 Ma, with an age of ~143.1 Ma for the Jurassic – Cretaceous boundary.
- Enhanced obliquity forcing observed in the SW Neo-Tethys site between 146.6 and 140.2 Ma (Late Tithonian-Middle Berriasian)
- Tithonian-Early Berriasian nannofossil calcification events I and II occurred during ~2.4 Myr eccentricity maxima.
- Boreal–Tethyan carbon cycle decoupling dated to 147–140 Ma.

Introduction

The Jurassic–Cretaceous (J–K) transition is a period of major changes in Earth’s systems, including climate, carbon cycle, sea level, oceanography, and life. To understand the possible relationships between these events, a reliable, global, high-resolution time framework is essential, which, however, currently does not exist, making this interval the least constrained of the Mesozoic timescale ¹. This has significant consequences, for instance for our understanding of a proposed mass extinction event at this boundary ^{2,3}, which, due to the lack of clear evidence for synchronous, dramatic environmental shifts or catastrophic events, led other authors to propose that this period represents a time of normal rates of background extinction and faunal turnover ⁴. Unlike other major Period boundary intervals, the J–K transition lacks a clear, synchronous biotic turnover and is characterised by faunal and floral provincialism, notably between Boreal and Tethyan realms ^{4–8}. Despite recent advances in biostratigraphy, magnetostratigraphy, and chemostratigraphy of the J–K boundary interval ^{5,6,8–13} it remains poorly constrained due to: 1) limited outcrops and biostratigraphic calibration, 2) scarcity of independently dated horizons, 3) uncertainties in magnetostratigraphic characterisation, and 4) a poorly preserved stable 405-kyr eccentricity signal along the Tethyan margins ¹⁴. These limitations are reflected in major age discrepancies: the

current Geologic Time Scale places the J–K boundary at 143.1 ± 0.6 Ma¹⁵, whereas U–Pb ages from Argentina, Mexico and Siberia suggest a younger boundary at ~ 141.8 – 140.7 Ma^{16–18}. Modern time scales increasingly rely on the recognition of orbitally driven Milankovitch cycles in the sedimentary record (GTS 2020). The principal cyclicities reported for the Tithonian–Berriasian interval include precession (~ 18.4 and 22.1 ka), obliquity (~ 38.1 ka), short eccentricity (~ 95 – 120 ka), and the stable long eccentricity cycle (~ 405 ka), which provides the most reliable metronome for deep-time age calibration¹⁹.

The Late Tithonian–Berriasian represents a fundamental reorganization of pelagic carbonate production and marine ecosystems. Following the decline of siliceous sedimentation, calcareous nannoplankton underwent rapid diversification, accompanied by the proliferation of heavily calcified nannoliths, particularly nannoconids, resulting in a marked increase in pelagic carbonate accumulation throughout the Tethys, Atlantic, and Pacific oceans^{20,21}. This interval has been linked to relatively cool and predominantly arid climatic conditions, reduced terrigenous input, increasingly oligotrophic surface waters, low atmospheric CO₂, high seawater carbonate saturation and low Mg/Ca ratios, all of which favoured enhanced calcification²¹. The onset of this major increase in nannofossil carbonate production, originally referred to as the Kuenen Event and later formalized as the first Nannofossil Calcification Events (NCE), marks a major turning point in the evolution of the global carbonate factory^{22–26}. Understanding the timing and expression of these calcification events in different basins therefore provides important insights into the links between climate, ocean chemistry and pelagic carbonate production across the Jurassic–Cretaceous transition. The Arabian Plate takes a central palaeogeographical position during the J–K transition period, with its location around the equator, facing the open southern Neo-Tethys Ocean (**Fig. 1a**) and the development of a thick Early Cretaceous carbonate shelf^{27,28}. The most complete Arabian

rock succession of this time interval is located inboard in central Saudi Arabia, where it outcrops as the Sulaiy Formation, forming a 400 km long escarpment (**Fig. 1b**; Wolpert et al., 2015). The position of the J–K boundary in this Formation is currently poorly constrained, having been assigned to the middle part of the formation²⁹ and, erroneously, based on misinterpreted carbon isotope data, to the base of the formation³⁰ Motivated by its suitable paleogeographic location and well-developed carbonate succession, a shallow well was drilled through this formation, recovering 205 m of well-preserved core and accompanying geophysical downhole logs. We integrate gamma-ray cyclostratigraphy, calcareous nannofossil biostratigraphy, $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{13}\text{C}$, and $\delta^{18}\text{O}$ isotope stratigraphy to establish an astronomically calibrated timescale for the Tithonian–Berriasian of central Saudi Arabia to provide better constraints for the J–K boundary climato-chronostratigraphic framework; and to discuss the impact of the proposed framework on the Boreal–Tethys decoupling.

Geological setting

During the latest Jurassic–earliest Cretaceous, the Arabian Plate formed a broad carbonate platform along the passive southern margin of the Neo-Tethys Ocean, occupying low northern paleolatitudes ($\sim 20\text{--}25^\circ\text{N}$) within the subtropical Tethyan realm, near the transition to the subtropical arid belt (**Fig. 1a**). Following deposition of the evaporitic Hith Formation (Late Jurassic), a marine transgression re-established open-marine conditions and initiated deposition of the Sulaiy Formation on a low-gradient carbonate ramp²⁸. The transition from the warm and arid conditions of the Hith evaporites to the less arid conditions of the Sulaiy Formation has significant paleoclimatological implications³¹.

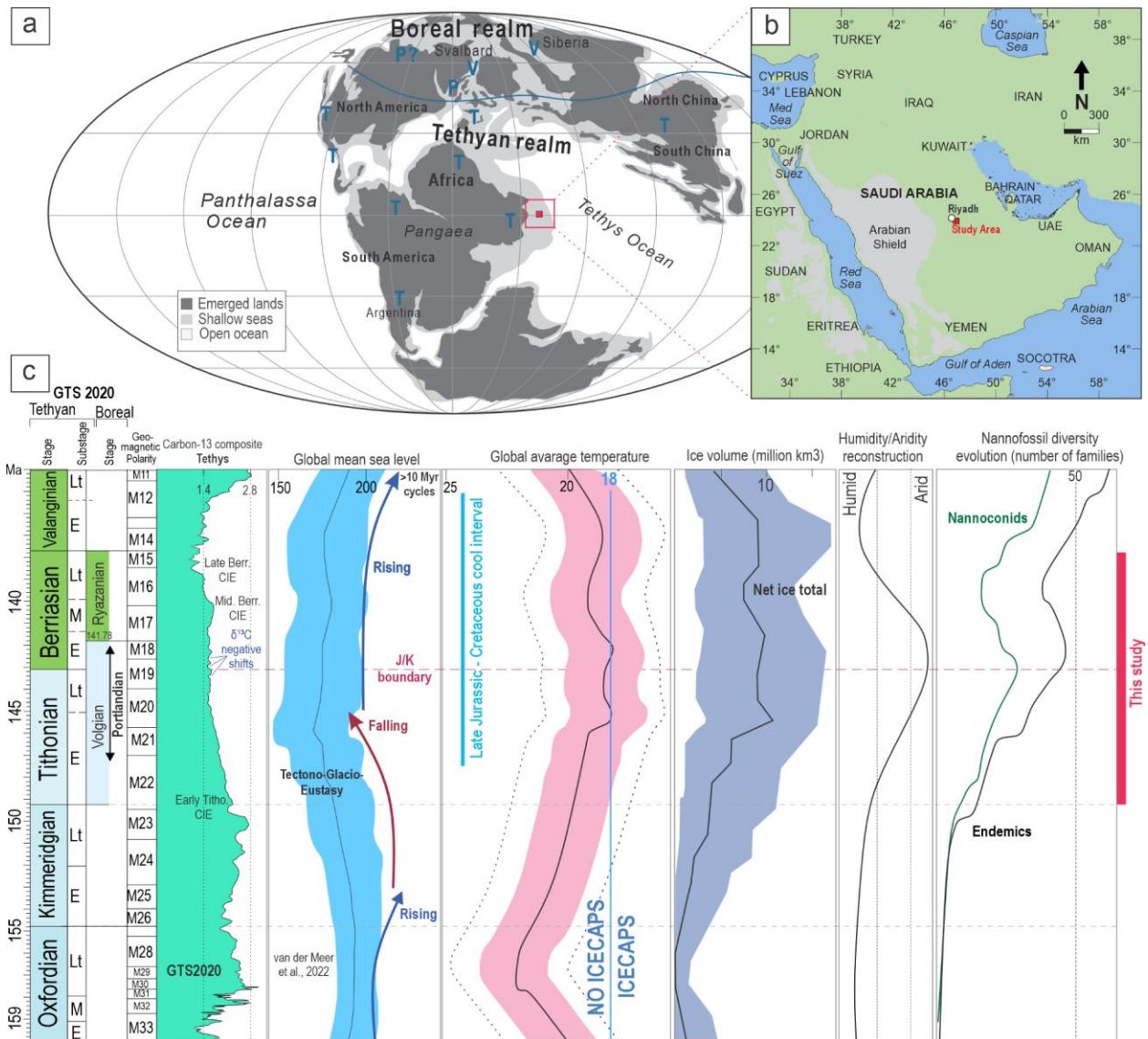


Figure 1. (a) Jurassic-Cretaceous transition paleogeographic reconstruction⁵ and the location of the study area in the southern Tethyan margin. T: Tithonian. V: Volgian. P: Portlandian. (b) Present-day map of the Arabian Peninsula and the Location of the Bh-02 core in central Saudi Arabia (near Riyadh). (c) chronostratigraphic nomenclature around the Jurassic-Cretaceous boundary, climate and sea level proxies and biodiversity^{15,32,33}. The regional stage terminology follows historical stratigraphic usage and is not strictly equivalent to the standard Tithonian–Berriasian stages of the International Chronostratigraphic Chart (ICS). In the British succession, the Portlandian encompasses part of the Tithonian and extends into the lower Berriasian. Similarly, in the Boreal realm, the Volgian–Ryazanian succession does not coincide exactly with the Tithonian–Berriasian boundary, as the upper Volgian extends into the lower Berriasian and the Volgian–Ryazanian boundary occurs within the lower Berriasian.

Biostratigraphic constraints obtained from the literature on these formations are summarized

in the Supplementary Information. The formation crops out in a crescent-shaped belt parallel to

the Arabian Shield and is dominated by muddy facies (mudstones and wackestones), and more grainy, bioturbated, tempestite-influenced wackestones to packstones deposited across offshore-to-shoal environments of a low-gradient carbonate ramp²⁸. The tempestite interpretation is based on thin event beds, sharp basal contacts, and coarse bioclastic accumulations, indicating episodic storm reworking above the storm wave base²⁸. These facies are organized into hierarchical shallowing-upward cycles, with individual cycles typically 2–5 m thick and grouped into larger cycle sets of 8–12 m thickness²⁸. The succession is arranged within a transgressive–regressive framework and contains regionally recognized maximum flooding surfaces, including the Upper Tithonian–Lower Berriasian flooding interval with no evidence for significant hiatuses³¹.

The studied Tithonian–Berriasian interval coincides with the Tithonian–early Barremian Cool Interval (TEBCI; ³³, a phase of progressive cooling within the Mesozoic greenhouse (**Fig. 1c**). Proxy records indicate maximum cooling during the latest Tithonian–earliest Berriasian, marked by increased ice volume, lower global temperatures, and a eustatic sea-level fall following the Early Tithonian transgression and associated carbon-isotope excursion^{34–36} (**Fig. 1c**). Although the extent of Mesozoic continental ice remains debated, growing evidence supports the development of substantial polar ice masses, potentially reaching up to one-third of present-day ice volume and driving orbitally controlled eustatic fluctuations^{37,38}. In the northwestern Tethys, this interval corresponds to peak aridity, with reduced weathering, diminished clastic input, oligotrophic conditions, and weakened hydrological cycling^{6,12} (**Fig. 1c**). Coincident with these environmental changes, calcareous nannoplankton underwent a major diversification pulse across the J–K transition, particularly among nannoliths, contributing to the marked increase in global nannofossil diversity during the latest Tithonian–Berriasian^{24,25}

Results and Discussion

Calcareous nannofossils biostratigraphy and Paleoecology

The J–K boundary in core BH-02 is placed at the first occurrence (FO) of *Nannoconus wintereri*^{8,13}. The FO of *Zeugrhabdotus embergeri* is recorded at 173.0 m (± 1.6 m), followed by the FO of *Conusphaera mexicana minor* at 169.7 m (± 0.5 m), which marks the upper boundary of NJT14. The FO of *Conusphaera mexicana mexicana* occurs higher in the section at 158.0 m (± 0.9 m) and coincides with an early Tithonian increase in nannolith abundance (Fig. 2). The interval between 181 and 146 m is dominated by Jurassic-affinity taxa, including *Watznaueria*, *Cyclagelosphaera*, abundant *Zeugrhabdotus*, and rare *Crepidolithus*.

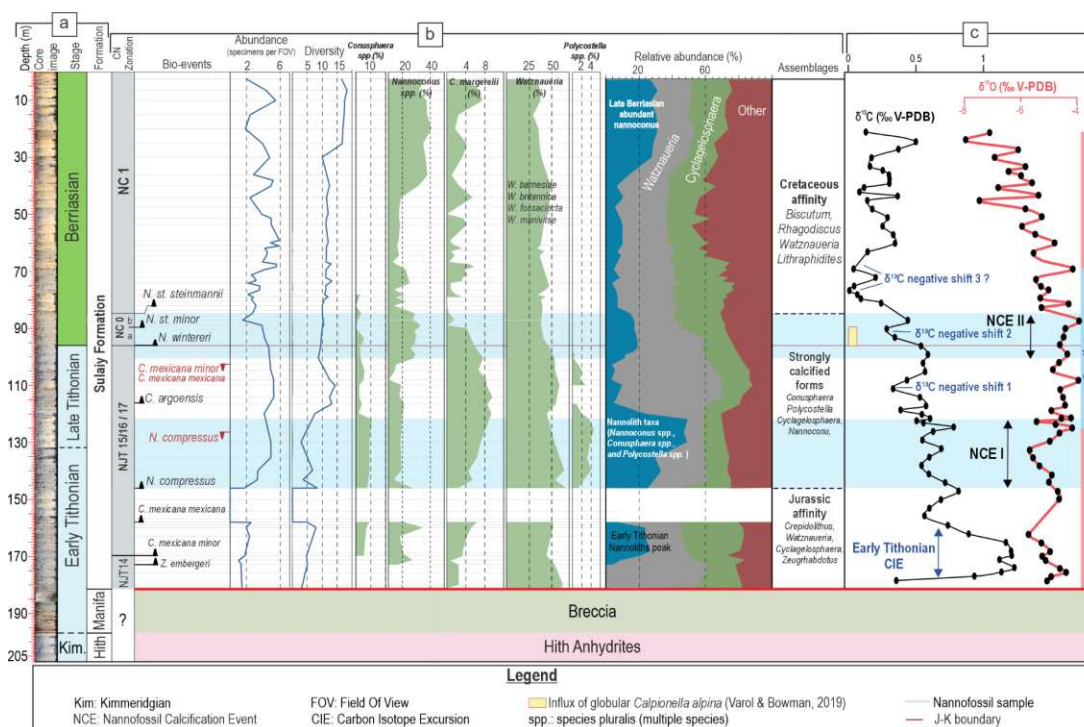


Figure 2. Integrated calcareous nannofossil biostratigraphy and counting with the stable isotope ($\delta^{13}\text{C}$ – $\delta^{18}\text{O}$) profiles in the BH-02 core. (a) Depth (in meters) and the image of the BH-02 core with the formations: Hith Formation: 205.13 m to 197 m, the Manifa Formation: 197 m to 181.5 m, and the rest is attributed to the Sulaiy Formation. (b) Stratigraphic distribution pattern of calcareous nannofossil species in the Tithonian to Berriasian interval of the Bh-02 core, with focus on the most important carbonate producers in the Tithonian (*Conusphaera* spp., *Polycostella* spp., *Nannoconus* spp., *Watznaueria* spp.). Three assemblages are distinguished: the Jurassic affinity assemblage, the strongly calcified forms, and the Cretaceous affinity assemblage. (c) Carbon and oxygen isotope curve and the positions of three negative carbon-isotope excursions near the J–K boundary³⁹. The cool and warm conditions are inferred from our $\delta^{18}\text{O}$ curve.

Because *Microstaurus chiastius* and *Nannoconus globulus minor* are absent, the NJT15–NJT17 biozones could not be differentiated and are therefore treated as a single interval. The FO of *Nannoconus wintereri* at 96.0 m (± 0.1 m) marks the base of the NC0 Zone and approximates the J–K boundary. The NC0 interval extends upward to the FO of *Nannoconus steinmannii steinmannii* at 84.6 m (± 0.3 m). In comparison, the FO of *Nannoconus steinmannii minor* at 89.5 m (± 0.3 m) defines the subdivision between the NC0a and NC0b subzones. Quantitative analyses indicate that a few dominant taxa (*Watznaueria* spp., *Cyclagelosphaera* spp., *Conusphaera* spp., *Polycostella* spp., and *Nannoconus* spp.) account for approximately 50–70% of the total assemblage. *Watznaueria* and *Cyclagelosphaera* dominate throughout the interval, peaking in the Late Tithonian, while *Cyclagelosphaera margerelii* contributes about 1–9% of the assemblage and declines toward the Berriasian.

Nannofossil calcification events

The Late Jurassic–earliest Cretaceous marks a major reorganization of the global pelagic carbonate factory, driven by the diversification and ecological expansion of heavily calcified calcareous nannoplankton²³. The first increase in pelagic nannofossil calcite production was identified as the Kuenen Event⁴⁰ and later formalized as the first Nannofossil Calcification Event (NCE I) based on DSDP Sites 105, 367, and 534A²⁴. Subsequent studies from the western Tethys demonstrated that this transition occurred in two successive phases: NCE I, characterized by the proliferation of *Conusphaera* and *Polycostella*, and NCE II, marked by the diversification, increasing abundance, and larger size of *Nannoconus* spp.^{21–23,25,26}. These calcification events developed during a prolonged interval of relatively cool climatic conditions, possibly associated with intermittent polar ice caps, increasing aridity across the Tethys and Central Atlantic, reduced fluvial runoff, low atmospheric CO₂, low seawater Mg/Ca ratios, elevated calcium availability,

and high carbonate saturation states, all of which favored enhanced pelagic biocalcification^{20,21,41,42}. NCE I occurred during the late Early to early Late Tithonian²⁴, whereas NCE II began in the Late Tithonian and continued into the Early Cretaceous^{21,26}. Increasing environmental stability during the Tithonian likely promoted K-selected life strategies, morphological diversification, and vertical niche partitioning among calcareous nannoplankton, further enhancing the success of heavily calcified taxa^{21,22}.

The BH-02 record documents this global transition exceptionally well. Three major calcareous nannofossil assemblage intervals reflect the progressive restructuring of the pelagic ecosystem through the Tithonian–Berriasian. The lower interval (181–146 m) is dominated by Jurassic-affinity assemblages composed mainly of *Watznaueria* and *Cyclagelosphaera*. This is followed by a transitional interval (146–84.5 m) characterized by the rapid expansion of heavily calcified taxa, particularly *Conusphaera*, *Polycostella*, and, progressively, *Nannoconus*, before evolving into a distinctly Cretaceous-affinity assemblage above 84.5 m, where *Biscutum*, *Rhagodiscus*, *Lithraphidites*, and *Nannoconus* dominate. This long-term succession records the replacement of typical Jurassic floras by the heavily calcified Cretaceous assemblages that subsequently became the principal producers of pelagic carbonate. Superimposed on these long-term assemblage changes, BH-02 preserves two distinct intervals characterized by marked increases in the abundance and diversity of heavily calcified nannoliths, corresponding to the two NCEs previously recognized in Tethyan and Atlantic successions^{21,24,25}. Here, the term NCE refers to intervals dominated by heavily calcified nannolith taxa rather than direct measurements of cellular calcification intensity. NCE I (146–122 m) is characterized by the acme of *Conusphaera* and *Polycostella*, whereas NCE II (100.5–84.5 m) records the rapid diversification and ecological expansion of *Nannoconus*, which reaches approximately 40% of the assemblage. Following NCE

II, *Nannoconus* continues to increase in abundance throughout the Berriasian, eventually becoming the dominant constituent of the nannofossil assemblage, reflecting the establishment of the Early Cretaceous pelagic carbonate factory. A pronounced Late Tithonian-Early Berriasian radiation of heavily calcified nannoliths from Saudi Arabia, Kuwait, Oman, and Yemen has been documented^{29,43}, consistent with the observations presented here. Although Nannofossil Calcification Events were not formally recognized, the successive first occurrences and abundance increases of *Conusphaera mexicana mexicana*, *Conusphaera maledicto*, *Conusphaera rothii*, *Polycostella senaria*, *Polycostella infans*, *Nannoconus compressus*, and later *Nannoconus wintereri* correspond closely to the evolutionary succession identified here as NCE I and NCE II. Furthermore, the acme and last occurrence of *Polycostella senaria* and the last occurrence of *Conusphaera maledicto* immediately precede the first occurrences of *Nannoconus steinmannii minor* and *Nannoconus kamptneri minor*, in association with the influx of small globular *Calpionella alpina*, provides an important regional framework demonstrating that these biotic changes closely bracket the J–K boundary across the Arabian Plate⁴³.

Carbon stable isotopes

The bulk carbonate $\delta^{13}\text{C}$ curve (‰ VPDB; **Fig. 2**) from the BH-02 core ranges from 0.02‰ to 1.23‰ and shows a long-term decrease from the Early Tithonian to the Early Berriasian, followed by a gradual upward recovery through the Berriasian. The highest $\delta^{13}\text{C}$ values occur in the lower part of the section (178.4–165.1 m), where values fluctuate between 0.89‰ and 1.23‰, reaching a maximum of 1.23‰ at 173.9 m. Above this interval, $\delta^{13}\text{C}$ values progressively decline through the Tithonian, marking the onset of the first negative carbon-isotope excursion (shift 1.) between 146 and 122 m. Within this interval, $\delta^{13}\text{C}$ decreases from 0.72‰ at 144.1 m to 0.50‰ at 122.4 m, with local minima recorded at 138.1 m (0.54‰), 129.1 m (0.55‰), and 122.4 m (0.50‰). Across

216 the J–K transition, $\delta^{13}\text{C}$ values remain relatively low and define a second negative carbon-isotope
217 excursion (shift 2) between 100.5 and 84.6 m. Values decrease from 0.59‰ at 99.1 m to 0.28‰ at
218 90.1 m, then reach a local minimum of 0.24‰ at 81.1 m, immediately above the excursion interval.
219 The J–K boundary, placed at 96 m, occurs within this prolonged interval of low $\delta^{13}\text{C}$ values and is
220 characterized by several short-term negative shifts, including values of 0.34‰ at 111.5 m (shift
221 1), 0.28‰ at 90.1 m (shift 2), and 0.024‰ and 0.04‰ at 76.6 m and 69 m, respectively (shift 3,,
222 double peak, **Fig. 2**). These perturbations correspond closely to the negative carbon-isotope
223 excursions reported from other Tethyan J–K boundary sections ³⁹. The lowest $\delta^{13}\text{C}$ value of the
224 entire record (0.02‰) occurs at 76.6 m in the lower Berriasian. Above this level, $\delta^{13}\text{C}$ values
225 gradually recover, increasing from 0.04–0.20‰ between 75.1 and 69.1 m to 0.49‰ at 24.1 m.
226 Although the recovery is modest, it represents a clear reversal of the long-term declining trend
227 observed throughout the Tithonian and the earliest Berriasian. The $\delta^{13}\text{C}$ profile defines two major
228 phases: (i) a long-term decline from the Early Tithonian maximum of 1.23‰ at 173.9 m to the
229 minimum value of 0.00‰ at 76.6 m, encompassing NCE I, NCE II, and the J–K transition; and
230 (ii) a gradual recovery from 76.6 m upward through the Berriasian. All $\delta^{13}\text{C}$ values remain positive
231 or near-zero throughout the section and fall within the expected range reported for Tithonian–
232 Berriasian successions of the Tethyan Realm, supporting preservation of a primary carbon-isotope
233 signal with limited diagenetic overprint (Supplementary Materials). The Early Tithonian in the
234 BH-02 core is identified by the FO of *Conusphaera mexicana Mexicana* and Carbon Isotope
235 Excursion (CIE). The three negative $\delta^{13}\text{C}$ excursions (~0.4‰) between 115 and 70 m (**Fig. 2c**) are
236 interpreted as correlating with the negative carbon-isotope excursions documented across the J–K
237 boundary along the northern Tethyan margins³⁹. The second excursion, occurring in the earliest
238 Berriasian just above the boundary, likely correlates with the Alpina event³⁹.

Oxygen stable isotopes

The $\delta^{18}\text{O}$ values range from -7.97‰ to -3.90‰ VPDB throughout the Tithonian–Berriasian interval (**Fig. 2**). In the lower part of the section (178.4–146 m), corresponding to the Early Tithonian and the peak abundance of early nannolith taxa, values range from -6.42‰ to -4.38‰ , with most clustering between -5.5‰ and -4.5‰ . This interval coincides with the Early Tithonian nannolith peak and the occurrence of *Zeugrhabdotus embergeri* and *Conusphaera mexicana minor*. Across NCE I (146–122 m), $\delta^{18}\text{O}$ values vary between -5.66‰ and -4.12‰ and show a progressive shift toward less negative values, culminating in a local maximum of -4.12‰ at 124.6 m. This interval corresponds to the proliferation of *Nannoconus* spp. and the appearance of characteristic Tithonian taxa, including *Conusphaera crassus* and *C. riyadhensis*, suggesting gradual cooling. Near the J–K boundary (96 m), $\delta^{18}\text{O}$ values remain relatively stable, ranging from -4.60‰ at 96.1 m to -4.33‰ at 99.1 m. Within NCE II (100.5–84.6 m), values range from -4.84‰ to -3.90‰ , with the least negative value occurring at 87.1 m. This enrichment coincides with increased abundances of *Nannoconus* spp., *Watznaueria*, and *Cyclagelosphaera*, the combined evidence of which suggests cooler surface-water conditions. From 69 m to the top of the core (Middle-Late Berriasian), $\delta^{18}\text{O}$ shifts toward more negative values, -7.49‰ at 45.1 m and -7.97‰ at 24.1 m. This trend coincides with increased *Nannoconus* spp abundance and proliferation of *Watznaueria barnesiae*, and *W. britannica* during the late Berriasian. The highest $\delta^{18}\text{O}$ values occur between 125 and 69 m, indicating peak cooling during the Late Tithonian–Early Berriasian, whereas lower $\delta^{18}\text{O}$ values below and above this interval reflect relatively warmer conditions (**Fig. 2**). Although some diagenetic influence on bulk-rock $\delta^{18}\text{O}$ values cannot be excluded, the bulk-rock $\delta^{18}\text{O}$ record is considered reliable because sampling targeted the least

diagenetically altered carbonate intervals within the core in addition to the weak covariance between $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values (**Supplementary Materials**).

Strontium isotope

The $^{87}\text{Sr}/^{86}\text{Sr}$ record exhibits a systematic increase across the J–K boundary (96 m depth), with Tithonian samples yielding lower values (0.70705–0.70716) and overlying Cretaceous samples displaying higher values (0.70717–0.70730). To minimize the effects of diagenetic alteration, only samples with bulk carbonate $\delta^{13}\text{C}$ values $> -1\text{‰}$ were selected for Sr-isotope analysis, as these are most likely to preserve primary seawater signatures following established screening criteria. Numerical ages were assigned using the seawater $^{87}\text{Sr}/^{86}\text{Sr}$ calibration of ⁴⁴, updated to the GTS2020 timescale, yielding age uncertainties of $\pm 0.1\text{--}0.7$ Ma when analytical and calibration uncertainties are combined. The observed increase in $^{87}\text{Sr}/^{86}\text{Sr}$ closely follows the global seawater Sr-isotope curve of ⁴⁴, with Tithonian values corresponding to the expected latest Jurassic seawater range ($\sim 0.70705\text{--}0.70715$) and Cretaceous values matching published Berriasian–Valanginian compositions ($\sim 0.70715\text{--}0.70735$). The agreement with the global seawater trend suggests that the measured ratios record a primary marine signal rather than local diagenetic overprinting⁴⁵. Because seawater Sr isotopic composition is globally homogeneous owing to the long residence time of Sr relative to ocean mixing times, secular variations in marine $^{87}\text{Sr}/^{86}\text{Sr}$ are generally interpreted to reflect changes in the balance between radiogenic Sr supplied by continental weathering and less radiogenic Sr derived from mantle and hydrothermal sources. Accordingly, the upward shift toward more radiogenic values across the J–K boundary is consistent with an increased contribution of continentally derived Sr to the oceans, implying enhanced continental weathering during the Berriasian relative to the Tithonian. Spectral gamma-ray logs (K, U and Th) show no significant long-term changes across the Sulaiy Formation or at the Jurassic–Cretaceous boundary.

Instead, the records are characterized by persistent, repetitive fluctuations, particularly in Th, indicating sustained low-amplitude cyclic variations in detrital input rather than major shifts in continental weathering or sediment supply (Supplementary Materials).

Sediment accumulation history of the Tithonian–Berriasian BH-02 core

Bayesian age–depth modelling, constrained by calcareous nannofossil bioevents, $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ages, and astronomically derived tie points (**Fig. 3**), reconstructs the sediment accumulation history of the BH-02 Tithonian–Berriasian succession. The resulting age–depth model exhibits a nearly linear relationship throughout the studied interval, indicating remarkably uniform long-term sediment accumulation with no major changes in depositional regime. Sedimentation rates remain relatively constant, increasing only gradually from approximately 1.4 cm kyr⁻¹ in the lower Tithonian to ~1.6–1.8 cm kyr⁻¹ across most of the succession, before reaching ~1.96 cm kyr⁻¹ in the uppermost Berriasian (**Fig. 3a**). No abrupt shifts in accumulation rate or slope changes are observed across the J–K boundary, indicating the absence of significant depositional hiatuses or condensed intervals and supporting the interpretation of a continuous sedimentary archive.

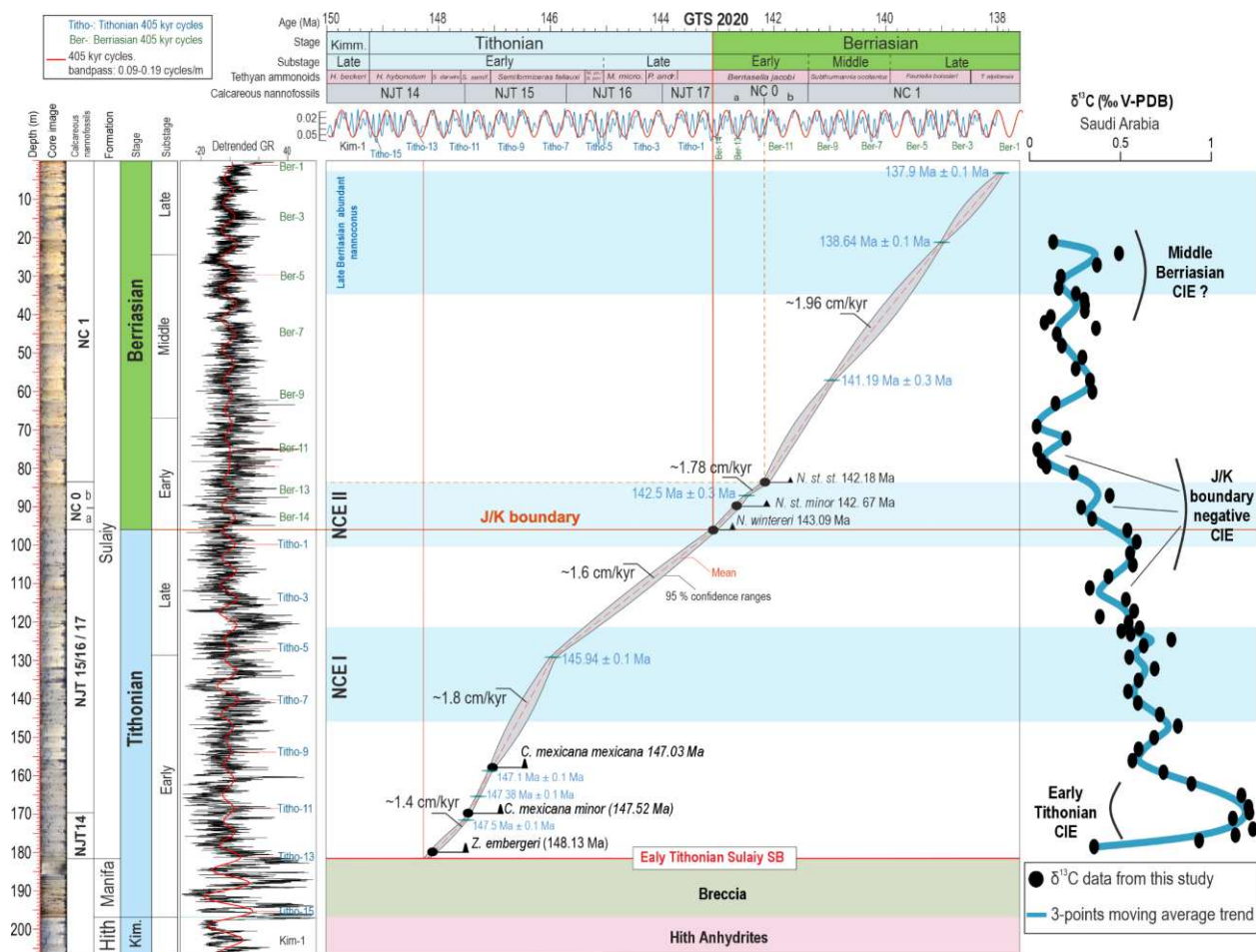


Figure 3. Integrated Bayesian age–depth model and astronomical calibration of the BH-02 core (Sulay Formation, Saudi Arabia). Bayesian age–depth model generated using *Bacon* by integrating calcareous nannofossil biostratigraphy, $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ages, and cyclostratigraphic tie points. Grey shading shows the ensemble of age–depth realizations, grey dashed lines indicate the 95% confidence interval, and the red dashed line represents the mean age–depth model. Black circles denote the calibration points used to constrain the model, and sediment accumulation rates (cm kyr^{-1}) are indicated along the model. The left panel shows the tuned gamma-ray (GR) record resampled at 5-kyr resolution with the filtered 405-kyr eccentricity signal and interpreted Tithonian and Berriasian cycle nomenclature. The upper panel shows the calibrated chronostratigraphic framework, including calcareous nannofossil biozones (NJT and NC), stage boundaries, and selected bioevents. Blue shaded intervals indicate the stratigraphic positions of Nannofossil Calcification Events (NCE I and NCE II). The right panel shows the bulk carbonate $\delta^{13}\text{C}$ record (black circles) and its three-point moving average (blue line). Horizontal blue bands mark the intervals discussed in the text.

The Bayesian model is further characterized by narrow 95% confidence envelopes throughout the succession, reflecting the strong agreement among independent chronological constraints provided by calcareous nannofossil biostratigraphy, $^{87}\text{Sr}/^{86}\text{Sr}$ ages, and cyclostratigraphic tie

points. The close correspondence between these datasets produces a well-constrained age–depth relationship with limited age uncertainty and demonstrates the internal consistency of the integrated chronological framework. Collectively, the stable sediment accumulation, absence of major stratigraphic discontinuities, narrow model uncertainties, and agreement between multiple independent dating methods indicate that the BH-02 core preserves an expanded and exceptionally continuous Tithonian–Berriasian record suitable for subsequent high-resolution astronomical calibration and cyclostratigraphic analysis.

Spectral analysis and detection of astronomical metronomes

Unlike previously studied Tethyan successions, where widespread Tithonian aridity reduced the preservation of orbitally forced sedimentary cyclicity^{9,14}, the BH-02 core exhibits well-preserved eccentricity-scale cyclicity in the K, Th, and U gamma-ray records, providing an excellent archive for high-resolution astrochronology (**Supplementary Information**). The multitaper method (MTM) spectrum of the uncalibrated GR series across the full stratigraphic interval reveals a hierarchy of dominant wavelengths at approximately 31, 13, 6.8, 3.1–2.5, 1.8, 1.3–1.1, and 0.7–0.4 m (**Figs. 4 and 5**). Because the evolutive spectrogram (evoFFT; **Fig. 4**) indicates changes in sedimentation rate and signal expression through the section, the cyclostratigraphic analysis was subdivided into two core intervals: 0–73.2 m and 73.2–205.13 m (**Fig. 4b**). Both intervals consistently display strong spectral peaks at ~6.8 m, ~2.9–3.2 m, ~1.4–1.8 m, and ~0.3–0.16 m. Using an average sedimentation rate of 1.8 cm/kyr (0.018 m/kyr), derived from strontium isotope stratigraphy, and consistent with TimeOpt, and COCO analyses (**Supplementary Materials**), these wavelengths can be converted into time periods and linked to Milankovitch forcing. Longer-wavelength cyclicity at ~31 m is interpreted as the g₄-g₃ long-term eccentricity modulation (~2.4 Myr⁴⁶), while the ~13 m cycle (0.7–1.2 Myr) reflects the s₄-s₃ long-

period obliquity modulation (1.2 Myr⁴⁶). Intermediate-scale cyclicities include ~6.8 m (378–405 kyr), corresponding to the g₂-g₅ 405 kyr eccentricity metronome, and ~3.1–2.5 m (140–180 kyr), attributed to the s₃-s₆ obliquity modulation (178 kyr⁴⁶). Accordingly, shorter cycles at ~1.8 m (100 kyr) match short eccentricity, while ~1.3–1.1 m cycles reflect obliquity-related variability, and 0.7–0.4 m cycles likely correspond to precession forcing. The spectral correspondence between stratigraphic wavelengths and astronomical periodicities indicates strong orbital pacing of sedimentation. The MTM spectrum of the 405-kyr-calibrated GR record identifies significant periodicities at ~2.2 Myr, ~1.2 Myr, ~714 kyr, 434 kyr, ~180 kyr, ~140 kyr, ~123 kyr, and ~78–65 kyr (99% confidence).

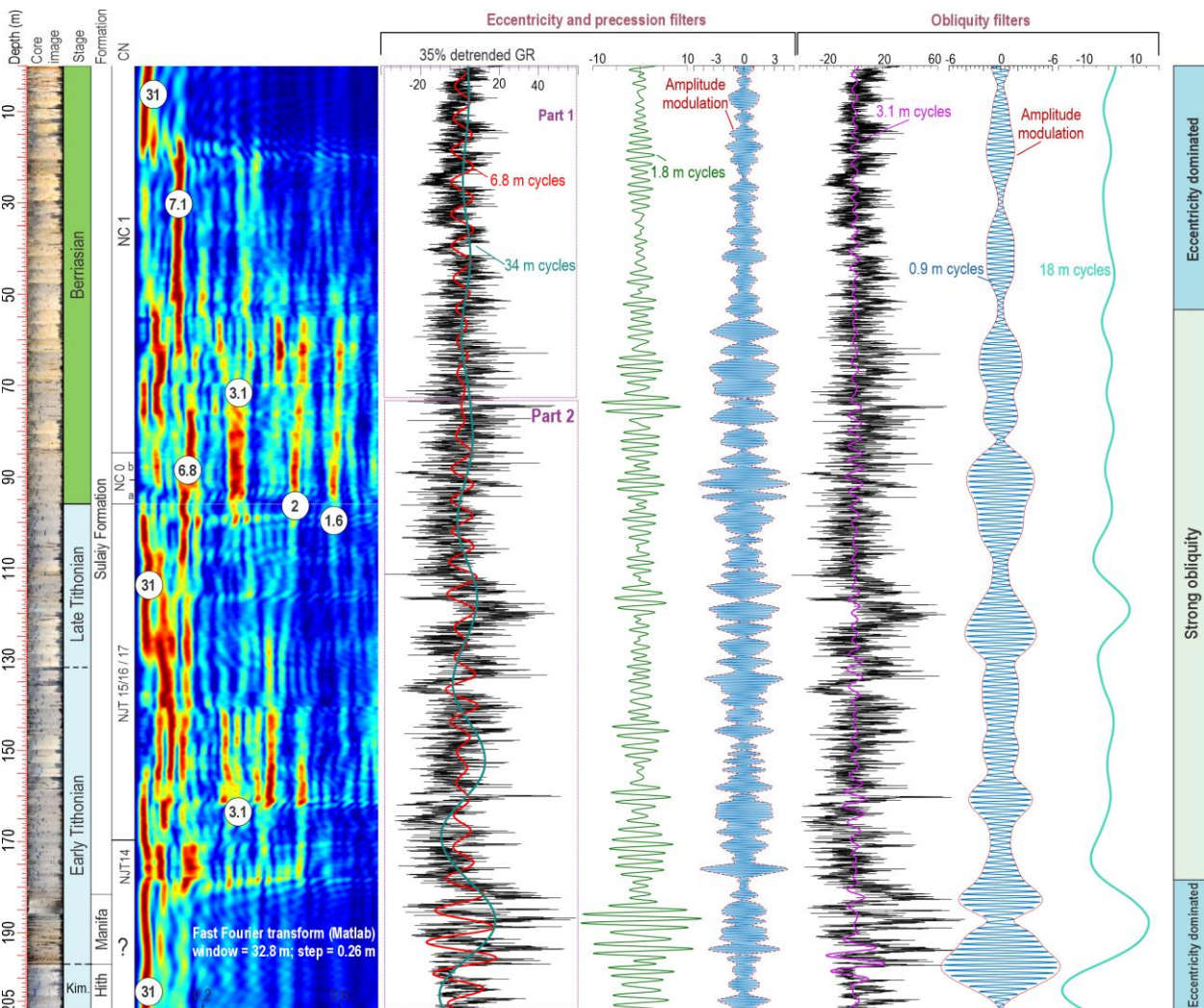


Figure 4. Fast Fourier transform analysis and amplitude modulation analyses. Amplitude modulation analysis of the precession band modulation (17-25kyr) versus 100 kyr cycle (90-120 kyr passband). Amplitude modulation analysis of the obliquity band modulation (27-40 kyr) versus 173 kyr cycle (155-195 kyr passband) and 173 kyr modulation (155-195 kyr passband) versus 1.2 Myr cycle (1150-1300 kyr passband).

The obliquity component is clearly expressed in the spectra (**Figs. 4 and 5**). This is somewhat unexpected given that the study area—located in present-day Saudi Arabia—was situated at relatively low paleolatitudes ($\sim 20\text{--}25^\circ\text{N}$) during the J–K transition. Under typical climatic conditions, obliquity forcing exerts its strongest influence at high latitudes ($\sim 60^\circ\text{--}80^\circ$), where its impact on insolation is maximized. The pronounced obliquity signal at such low latitudes therefore suggests an atypical climate configuration, potentially reflecting a transfer of power in high-latitude climate signals toward the tropics. This phenomenon is most commonly associated with intervals of global cooling and glaciation, when expanded ice sheets and enhanced meridional gradients can amplify and propagate obliquity-driven climate variability into lower latitudes^{47–49}.

Amplitude modulation analysis of the BH-02 core from the Sulaiy Formation (Saudi Arabia) provides further support for orbital forcing during the Tithonian–Berriasian. Matching sedimentary cyclicities with expected astronomical periods shows that modulation of the ~ 405 kyr eccentricity cycle reproduces a longer ~ 2.4 Myr cycle. In comparison, modulation of the ~ 178 kyr obliquity signal generates a ~ 1.2 Myr periodicity (**Figs. 4 and 5**). The consistent expression of these hierarchical cycles within the stratigraphic record indicates that both eccentricity and obliquity forcing are accurately registered in the GR time series. This nested orbital pattern confirms astronomically paced deposition in the Sulaiy Formation, recording insolation-driven climate variability across the Tithonian–Berriasian.

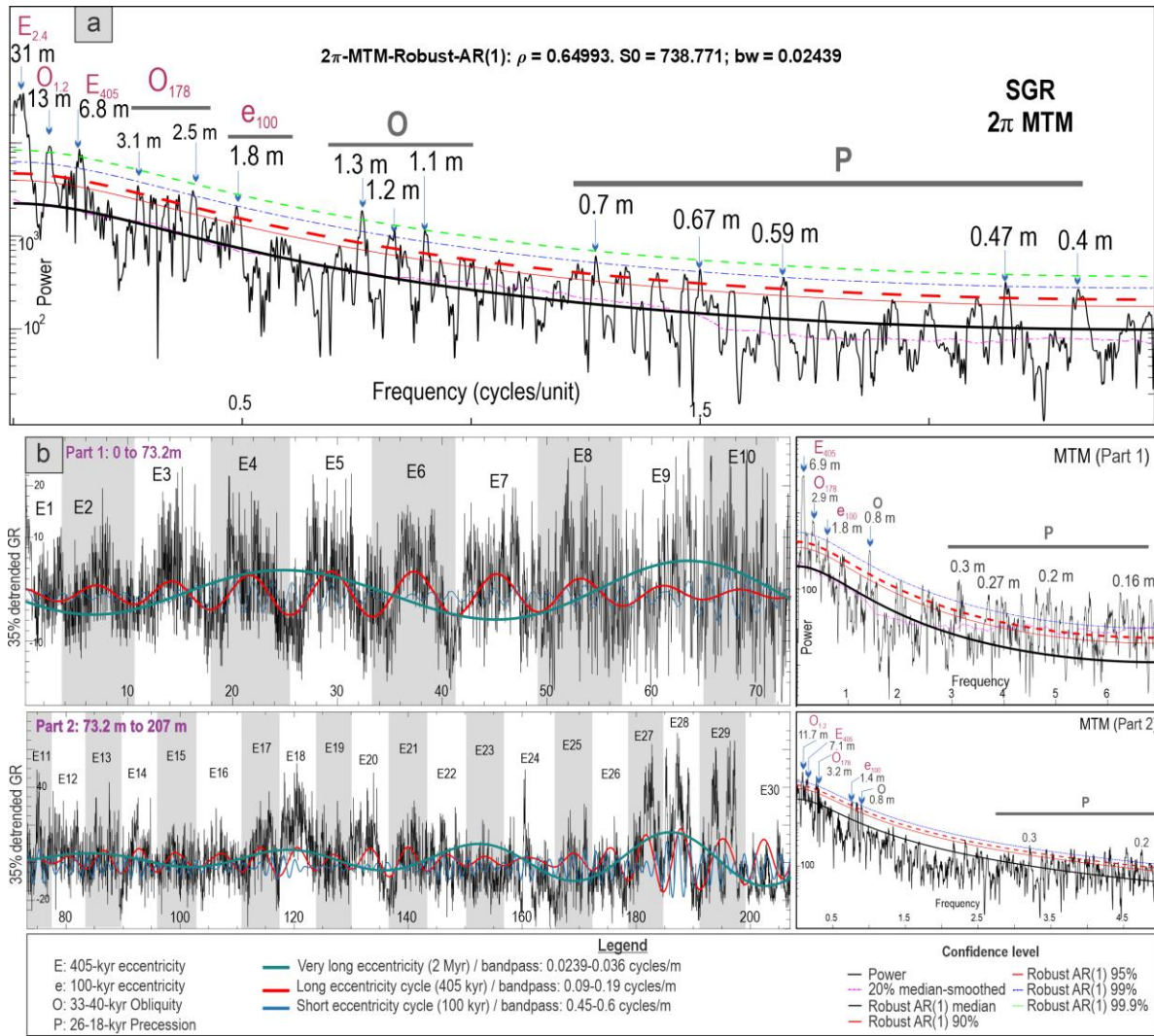


Figure 5. Orbital-scale cyclicity in GR log revealed by 2 π -MTM spectral analysis and detailed cyclostratigraphy. (a) 2 π -MTM power spectra of GR variations. Spectrum of the untuned interval (= depth domain) with the dominant cycles in meters. Symbols: P for precession; O for obliquity; e for short (100 kyr) eccentricity; E405 for 405 kyr eccentricity. kyr – kilo year; MTM – Multi-Taper Method; Myr – Million year. (b) Detailed depth-scale expression of cyclicity in the 35% detrended gamma-ray (GR) log for Part 1 (0-73.2 m) and Part 2 (73.2–207 m). Left panels show the detrended GR curves with extracted low- and high-frequency filter outputs, highlighting the counting of the well-expressed 6.8 m cycles (E1 to E30, interpreted here as the long-eccentricity cycles). Right panels present the MTM spectra for both intervals, with significant peaks above the robust AR(1) confidence levels and annotated depth-periodicities.

The GR record of the BH-02 core (**Figs. 3–5**) is dominated by the ~6.8 m cycle (405-kyr-long eccentricity, E405), which shows the highest amplitude in the evoFFT and the most persistent imprint on the signal. A discontinuous ~3.1 m cycle—attributed to obliquity modulation (~178 kyr)—is evident between 175 m and 50 m. The succession of ~30 long-eccentricity (E405) cycles

Figure 6. Integrated geochronological framework for the BH-02 core spanning the Tithonian–Berriasian interval. From left to right, panels show core depth and lithostratigraphy (including Hith Anhydrites, breccia, and Sulaïy Formation), stage assignments, calcareous nannofossil zonation, and key bioevents that provide primary biostratigraphic constraints. These are complemented by a high-resolution $^{87}\text{Sr}/^{86}\text{Sr}$ isotope profile tied to the global seawater Sr curve, supplying independent age control. Downcore GR data and the corresponding detrended signal are presented alongside the bandpass-filtered 6.8 m component, interpreted as the expression of 405-kyr-long eccentricity cycles. These cyclostratigraphic signals define the internal temporal structure of the succession and enable astronomical tuning. Anchor tie points used in the age–depth model are indicated, integrating (i) biostratigraphic datums (e.g., key nannofossil first occurrences), (ii) strontium isotope-derived ages (e.g., $\sim 142.5 \pm 0.3$ Ma near the J–K boundary), and (iii) astronomically tuned cycle boundaries. The J–K boundary is placed at ~ 96 m depth within the lower Sulaïy Formation, calibrated to $\sim 143.1 \pm 0.6$ Ma, supported by Sr-isotope data.

Correlation across the studied intervals reveals a coherent orbital framework throughout the Tithonian–Berriasian succession, with multiple well-defined 405-kyr cycles. Cycles Titho-11 and Titho-12 are less distinctly expressed than the surrounding 405-kyr cycles, probably reflecting reduced orbital forcing and/or minor variations in sedimentation rate and proxy sensitivity rather than a disruption of the continuous sedimentary record (**Fig. 6**).

Refining the age of the Tithonian–Berriasian and the J–K boundary

The astronomically calibrated chronology presented in Figures 7 and 8 provides a robust temporal framework for evaluating environmental evolution across the Jurassic–Cretaceous (J–K) transition. Astronomical tuning of twenty-nine 405-kyr eccentricity cycles constrains the investigated Tithonian interval to ~ 149.2 – 143.5 Ma (15×405 -kyr cycles; ~ 6.1 Myr) and the Berriasian to ~ 143.5 – 137.8 Ma (14×405 -kyr cycles; ~ 5.4 Myr), placing the J–K boundary at ~ 143.1 Ma as defined by¹³. This framework provides numerical ages for major bio- and chemostratigraphic markers, including the Early Tithonian carbon-isotope excursion (147.75–147.2 Ma), the first occurrences of *Conusphaera mexicana minor* (147.57 Ma), *C. mexicana mexicana* (146.2 Ma), *Nannoconus wintereri* (~ 143.1 Ma), *N. steinmannii minor* (~ 142.17 Ma), and *N. steinmannii* (~ 141.4 Ma), together with three latest Tithonian–earliest Berriasian negative

Orbital pacing of climate evolution across the Jurassic–Cretaceous transition

The Tithonian–early Barremian was a relatively cool interval characterized by intermittent polar ice sheets, low atmospheric CO₂, arid climates, reduced terrigenous input, and seawater conditions that favoured carbonate production and calcification^{21,50,51}. Recent paleoclimate reconstructions indicate that the principal cooling phase of the Jurassic–Cretaceous transition occurred during the late Tithonian–early Berriasian (~145–141.5 Ma), accompanied by the development of substantial high-latitude ice sheets that may have reached up to one-third of the present-day Antarctic ice volume^{32,50,52}. Our astrochronological record from the Arabian Tethys shows that this same interval coincides with a prolonged phase of enhanced obliquity power (~146.1–140.2 Ma; **Fig. 8G**), from 146.6 Ma to 140.2 Ma and overlapping three successive negative $\delta^{13}\text{C}$ excursions (**Fig. 8D**). The temporal correspondence between intensified obliquity forcing, peak cooling, and previously inferred ice-sheet expansion suggests that the enhanced obliquity expression recorded in the southern Tethys was linked to a cooler climate state. Although obliquity exerts only a modest direct influence on subtropical insolation, it strongly affects high-latitude seasonality and ice-sheet mass balance, allowing cryosphere variability to amplify the climatic response to obliquity and propagate its signal to lower latitudes through changes in meridional temperature gradients and atmospheric–oceanic circulation^{47,48,53}. We therefore interpret the strengthened obliquity signal to reflect an enhanced sensitivity of the climate system during the late Tithonian–early Berriasian cooling interval, consistent with previously proposed episodes of transient ice-sheet expansion. Comparable increases in the relative importance of obliquity have been documented during major episodes of cryosphere expansion, including the Ordovician, the Eocene–Oligocene transition, the Middle Miocene Climate Transition, and the

461 Quaternary^{54–58}, where ice-sheet growth amplified the climatic expression of obliquity through
 462 feedbacks involving sea level, ocean circulation, and the carbon cycle.

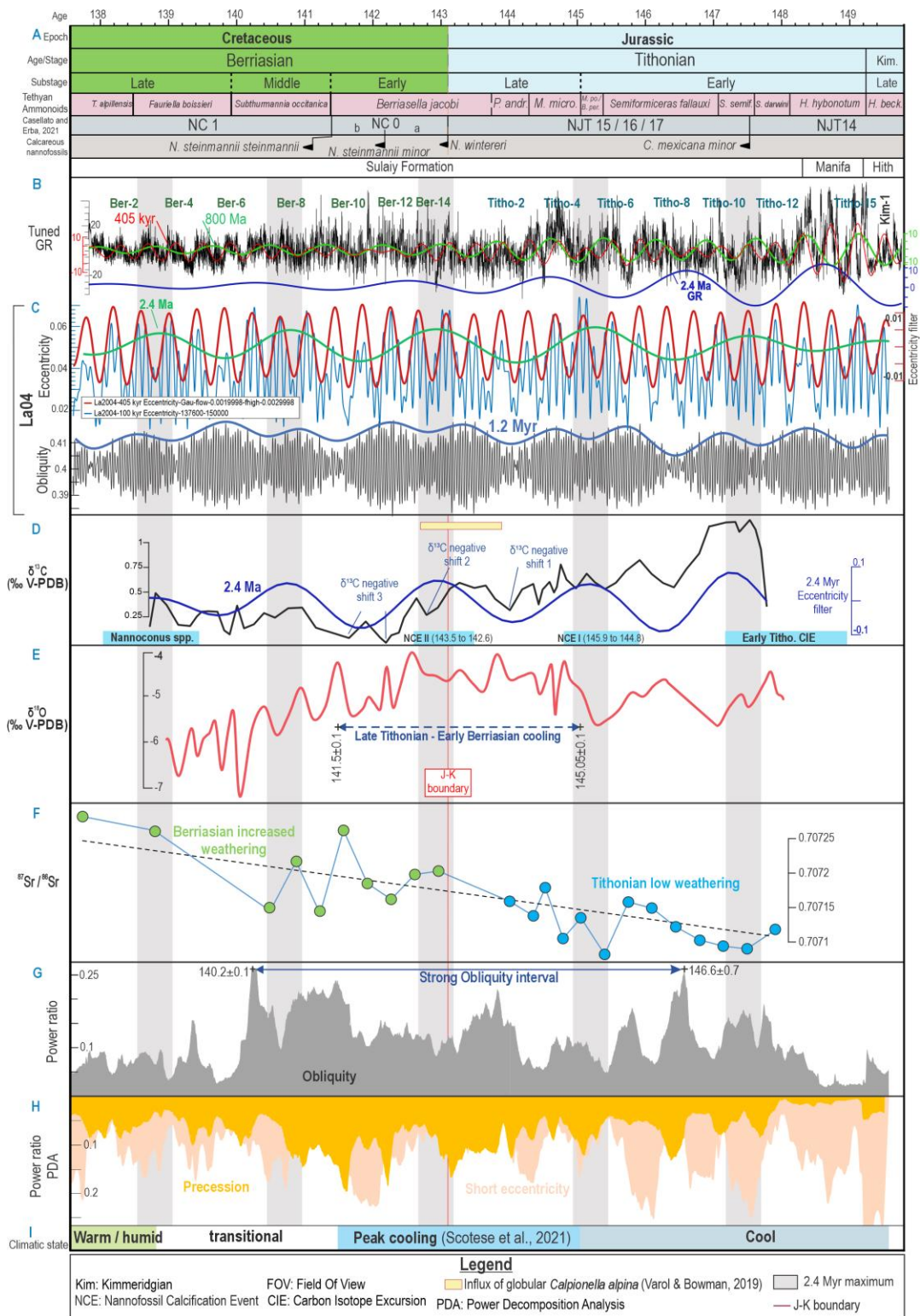


Figure 8. Integrated astrochronological, geochemical, and biostratigraphic framework across the Tithonian–Berriasian transition (BH-02 core, central Saudi Arabia). (A) Astronomically calibrated age model showing lithostratigraphy, calcareous nannofossil biozonation, key bioevents, and the J–K boundary. (B) Tuned gamma-ray (GR) record with extracted 405-kyr eccentricity (red), ~800-kyr modulation (green), and ~2.4 Myr eccentricity (blue). (C) La2004⁵⁹ astronomical solution showing eccentricity and obliquity for comparison with the tuned sedimentary record. (D) Bulk carbonate $\delta^{13}\text{C}$ record with the extracted ~2.4 Myr component, highlighting the Early Tithonian carbon-isotope excursion (CIE), three subsequent negative $\delta^{13}\text{C}$ excursions, and the timing of Nannofossil Calcification Events (NCE I and II). (E) Bulk carbonate $\delta^{18}\text{O}$ record showing progressive cooling, with peak cooling between ~145 and 141.5 Ma. (F) Seawater $^{87}\text{Sr}/^{86}\text{Sr}$ record indicating relatively weak continental weathering during the Tithonian followed by intensified weathering through the Berriasian. (G–H) Orbital power decomposition showing enhanced obliquity forcing during peak cooling and temporal variations in precession and short eccentricity. (I) Integrated palaeoclimatic interpretation showing a transition from relatively warm, humid conditions in the Early Tithonian to cooler, more arid, oligotrophic conditions during the Late Tithonian–Early Berriasian. Grey bands mark maxima of the ~2.4 Myr eccentricity cycle. The yellow rectangle indicates the influx of small globular *Calpionella alpina* recorded in the Arabian Plate⁴³.

The tuned gamma-ray and carbonate $\delta^{13}\text{C}$ records both preserve a persistent ~2.4 Myr modulation comparable to that of the La2004 astronomical solution (**Fig. 8B–D**). The filtered $\delta^{13}\text{C}$ component closely follows the phase of the astronomical modulation, whereas the gamma-ray filter is expressed in near antiphase. This phase offset indicates that the two proxies recorded different components of the climate system: the $\delta^{13}\text{C}$ record primarily reflects changes in the global carbon cycle, whereas gamma-ray records local variations in terrigenous input and sedimentation. The presence of the same periodicity, despite the opposite phase relationship, therefore supports a common astronomical pacing while indicating contrasting environmental responses within the global carbon cycle and the Arabian Tethyan depositional system. At shorter timescales, the three latest Tithonian–earliest Berriasian negative $\delta^{13}\text{C}$ excursions occur at different phases of the ~2.4 Myr eccentricity cycle, with shift 1 and shift 3 developing near successive minima and shift 2 near an intervening maximum (**Fig. 8D**). This variable phase relationship indicates that the long-period eccentricity cycle did not directly trigger individual carbon-cycle perturbations. Instead, it likely

established the long-term climatic boundary conditions within which shorter-timescale orbital forcing, including the 405-kyr eccentricity cycle, paced the timing of individual $\delta^{13}\text{C}$ excursions.

Astronomically constrained evolution of the pelagic carbonate factory

The Tithonian–earliest Berriasian marks a major reorganization of the global pelagic carbonate factory, characterized by NCE I and NCE II that reflect the rapid ecological expansion of heavily calcified calcareous nannoplankton. Our astronomically calibrated chronology presented here demonstrates that these calcification events were essentially synchronous across the tropical Tethys and proto-Atlantic (**Fig. 9**). In the Sulaiy Formation, NCE II spans 145.9–144.8 Ma, whereas NCE I extends from 143.5–142.6 Ma. Equivalent intervals are recognized in Italy, where NCE II corresponds to the upper NJT17 through most of the NC0a Zone, and NCE I extends from the NJT15b to the lower NJT16b Zone ²¹. The Hungarian succession and the astronomically calibrated records from DSDP Site 534A preserve the same two intervals, while DSDP Site 105 records equivalent events despite its lower temporal resolution (**Fig. 9**). The close agreement in timing among these geographically distant successions indicates that both NCEs were basin-wide paleoceanographic events rather than regionally diachronous evolutionary expansions. Minor differences in the onset, duration, and expression of the calcification intervals are more plausibly explained by variations in sedimentation rate, preservation, local ecological thresholds, and nutrient availability than by significant temporal offsets. The near-synchronous development of the two calcification phases therefore provides strong evidence that the reorganization of the pelagic carbonate factory was driven by large-scale climatic and oceanographic forcing operating across the Tethyan realm. Our astronomically calibrated record refines this interpretation by placing the two calcification events within a precise carbon-isotope framework. NCE I (145.9–144.8 Ma) coincides with the first major Late Tithonian negative $\delta^{13}\text{C}$ excursion, followed by a

recovery toward more positive values before NCE II (143.5–142.6 Ma), which developed during the subsequent decline toward the Early Berriasian $\delta^{13}\text{C}$ minimum. The same first-order relationship is observed in the high-resolution Hungarian succession (**Fig. 9**), indicating that the coupling between carbonate-factory evolution and carbon-isotope trends was regionally consistent across the tropical Tethys and proto-Atlantic. Rather than implying that individual carbon-isotope excursions directly triggered the calcification events, these observations suggest that both the NCEs and the long-term $\delta^{13}\text{C}$ evolution represent parallel responses to the same large-scale climatic and paleoceanographic reorganization.

Although the long-term Tithonian decline in $\delta^{13}\text{C}$ and the carbon-isotope excursions associated with NCE I and NCE II are closely linked to the progressive establishment of the Late Jurassic–Early Cretaceous pelagic carbonate factory, not all carbon-isotope perturbations across the J–K transition can be explained solely by changes in pelagic biocalcification. Figure 9 illustrates that carbon-cycle evolution was spatially heterogeneous, with the tropical Tethys and proto-Atlantic recording relatively subdued carbonate $\delta^{13}\text{C}$ variability superimposed on a long-term decline, whereas Boreal basins exhibit the much larger-amplitude Volgian Isotopic Carbon Excursion (VOICE). Previous studies have attributed this Boreal–Tethyan asymmetry to regional oceanographic restriction, variations in organic carbon burial, basin connectivity and circulation patterns rather than to global changes in pelagic carbonate production alone^{60–63}. Consequently, while the temporal coincidence between NCE I, NCE II and successive negative $\delta^{13}\text{C}$ excursions supports a close coupling between carbonate-factory expansion and long-term carbon-cycle reorganization in the tropical oceans, other carbon-isotope shifts likely reflect additional regional controls superimposed on this global background signal. Within this context, the principal contribution of the present study is not to redefine the mechanisms responsible for Boreal–Tethyan

carbon-cycle evolution, but to provide a high-resolution astronomical framework demonstrating that climatic cooling (~145–141.5 Ma), the two principal NCEs, the successive late Tithonian–earliest Berriasian carbon-isotope excursions, and the broader reorganization of the pelagic carbonate factory occurred within the same tightly constrained interval of Earth-system change. This refined chronology provides a robust temporal reference for testing the synchronicity of climatic, palaeoceanographic and biological events across different ocean basins and for evaluating their links to Tithonian–Berriasian sea-level change and marine ecosystem turnover.

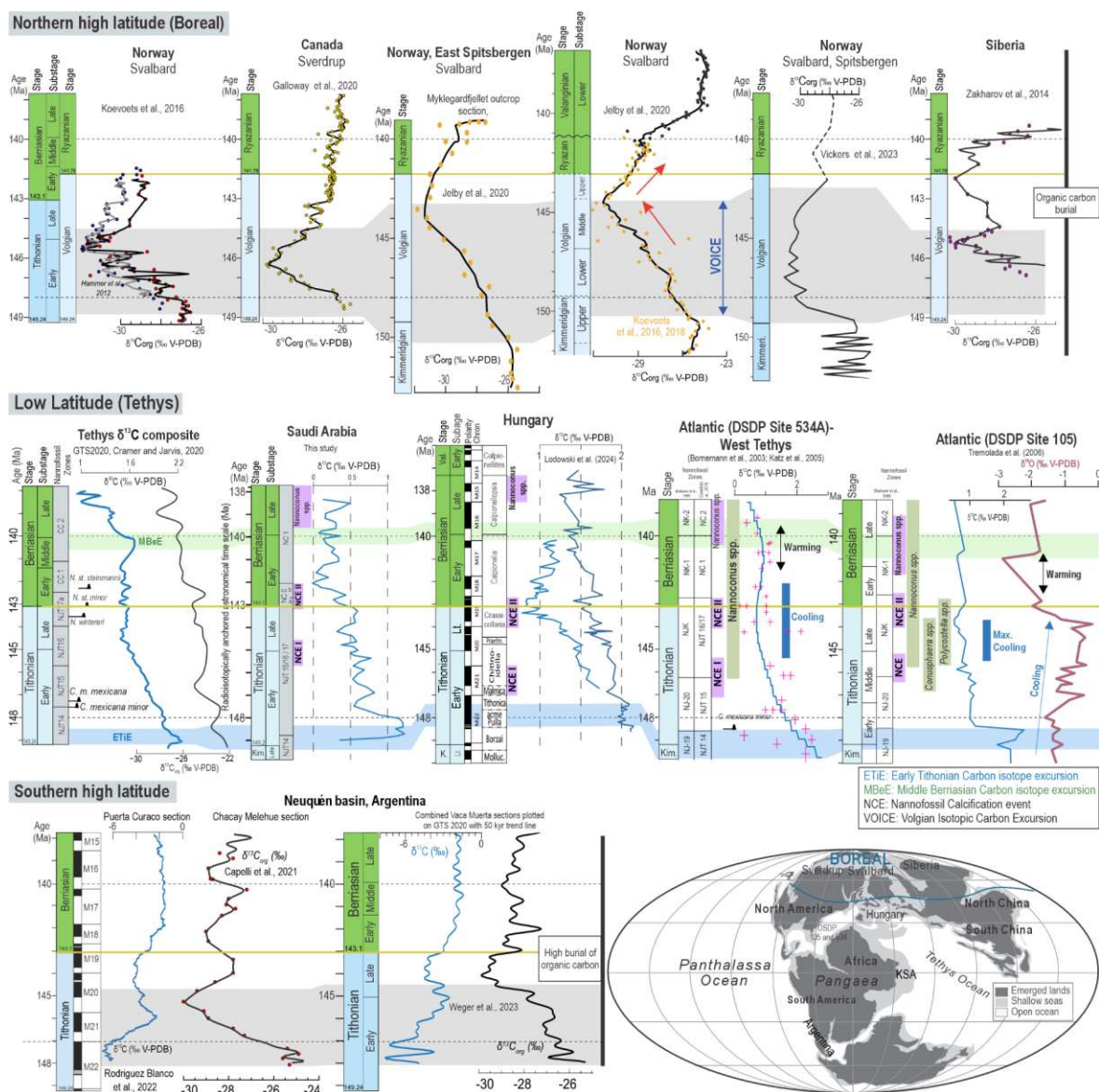


Figure 9. Comparison of latest Jurassic–earliest Cretaceous carbon-isotope records across latitudinal realms, showing clear differences in amplitudes and trends. Boreal and southern high-latitude records display a major Volgian (middle–late Tithonian) negative excursion, with Boreal $\delta^{13}\text{C}_{\text{org}}$ values falling by $\sim 6\text{‰}$ (from $\sim -22\text{‰}$ to $\sim -28\text{‰}$) before recovering toward the Jurassic/Cretaceous boundary. In contrast, low-latitude Tethyan records show a gentler long-term decrease, from $\sim +2\text{‰}$ in the early Tithonian to near 0‰ by the boundary, with relatively stable background $\delta^{13}\text{C}_{\text{carb}}$ values commonly around $+1$ to $+1.5\text{‰}$. Superimposed on this Tethyan trend are three latest Tithonian–earliest Berriasian negative excursions close to the boundary. The figure emphasizes strong latitudinal asymmetry, with amplified multi-per-mil variability in semi-restricted high-latitude basins compared with more buffered open-ocean Tethyan and proto-Atlantic signals.

Conclusion

The cyclostratigraphic and astrochronological analyses presented here establish a robust astronomical timescale for the Tithonian–Berriasian interval spanning ~ 149.2 to 137.7 Ma, confirming the persistence of the 405-kyr eccentricity cycle throughout the succession. Astronomical tuning of 30 long-eccentricity cycles provides a high-resolution temporal framework that constrains the duration of the Tithonian (~ 6.1 Myr) and the studied Berriasian (~ 5.6 Myr) and places the Jurassic–Cretaceous boundary at ~ 143.1 Ma. This chronology enables precise calibration of major carbon-isotope excursions, calcareous nannofossil evolutionary events, and climatic changes across the Jurassic–Cretaceous transition. In particular, it demonstrates that the interval of enhanced obliquity forcing (~ 146.6 – 140.2 Ma) closely overlaps the principal cooling interval inferred from relatively enriched carbonate $\delta^{18}\text{O}$ values (~ 145.05 – 141.5 Ma), indicating a strong temporal relationship between orbital forcing and climate evolution. Although this correspondence is consistent with an increased influence of high-latitude cryosphere dynamics, the mechanisms responsible remain a hypothesis requiring independent verification. The astronomically calibrated chronology further refines the timing of the decoupling between Boreal and Tethyan carbon-isotope records and demonstrates that major carbon-cycle perturbations were not globally synchronous. Likewise, the calibrated first occurrences of key nannofossil taxa show that the principal nannofossil calcification events developed under contrasting paleoenvironmental conditions, indicating that their proliferation cannot be explained solely by changes in trophic state.

By integrating astrochronology with calcareous nannofossil biostratigraphy, Strontium stratigraphy, and stable carbon- and oxygen-isotope records, this study provides one of the highest-resolution chronological frameworks currently available for the Jurassic–Cretaceous transition. The resulting timescale strengthens temporal correlations among orbital forcing, climate evolution, carbon-cycle variability, and marine biotic change, providing a robust reference framework for evaluating Earth-system evolution during one of the least constrained intervals of the Mesozoic.

Methods

Study material and sampling

This study is based on the BH-02 continuous subsurface core from central Saudi Arabia (Fig. 1), which preserves a complete Tithonian and an almost complete Berriasian succession of the Sulaiy Formation. The core was recovered with nearly 100% recovery, providing an exceptionally continuous carbonate archive across the Jurassic–Cretaceous (J–K) transition suitable for high-resolution stratigraphic investigation. Sampling focused on maximizing temporal resolution while minimizing the influence of diagenetic alteration. The core was first examined through detailed sedimentological and petrographic logging to identify intervals preserving primary depositional fabrics. Carbonate samples displaying fractures, stylolites, veins, recrystallization, or secondary mineralization were excluded wherever possible. A total of 96 samples were collected for calcareous nannofossil analysis, with sampling density increasing across key biostratigraphic boundaries. Bulk rock powders for carbon and oxygen isotope analyses were obtained by microdrilling from selected micritic carbonate horizons showing minimal evidence of diagenetic alteration. Based on petrographic screening and elemental composition, 30 carbonate samples with Sr concentrations exceeding 200 ppm were selected for $^{87}\text{Sr}/^{86}\text{Sr}$ analysis to maximize preservation of the primary seawater isotopic signal.

C and O isotope analysis

Isotopic analyses were performed using a MAT-253 (Thermo Scientific) stable isotope ratio mass spectrometer (IRMS) coupled with a Kiel IV Carbonate Device (Thermo Scientific) at the Pôle Spectrométrie Océan (PSO, Plouzané, France). Oxygen stable isotope ratios were standardized in the VPDB scale using NBS-19 and NBS-18 international carbonate standards⁶⁴. For NBS-19, assigned value is: $\delta^{18}\text{O VPDB} = -2.20\text{‰}$ and for NBS-18, designated value is: $\delta^{18}\text{O VPDB} = -23.01\text{‰}$. External precision (1σ), based on repeated measurements of an in-house standard, was $\pm 0.04\text{‰}$.

Sr isotopes analysis

Guided by detailed petrographic observations and the selection criteria of $\text{Sr} > 200\text{ ppm}$ and $\text{Mn/Sr} < 1$, a total of 30 samples were chosen for strontium isotope analysis to best preserve the primary seawater isotopic signature best. About 50 mg of samples were weighed in savillex beakers. They were dissolved in HNO_3 1M for 24h at 100°C on a hot plate. After centrifugation, solutions were loaded on Biorad® columns using Trisikem Sr-Resin⁶⁵. Sr was eluted in 2ml of hot ultrapure H_2O . Samples were loaded on W filaments and Sr isotope compositions were measured in static mode on a Thermo TRITON at the PSO (Pôle de Spectrométrie Océan) in Brest, France. All measured Sr ratios were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. During the course of analysis, Sr isotope compositions of standard solution NBS987 gave $^{87}\text{Sr}/^{86}\text{Sr} = 0.710263 \pm 0.000005$ (2sd, $n=3$, recommended value 0.710250)

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios as a proxy for continental weathering

The secular evolution of seawater $^{87}\text{Sr}/^{86}\text{Sr}$ reflects the balance between two principal sources of strontium to the oceans: radiogenic ^{87}Sr derived from continental silicate weathering and less radiogenic Sr supplied by mantle-derived material through hydrothermal exchange at mid-ocean

ridges and volcanic inputs⁶⁶. Variations in the relative contributions of these sources produce predictable changes in the isotopic composition of seawater over geological timescales. Enhanced continental weathering increases the riverine flux of radiogenic ⁸⁷Sr, resulting in higher seawater ⁸⁷Sr/⁸⁶Sr values, whereas increased hydrothermal activity or mantle-derived inputs shift seawater toward lower ratios. Consequently, marine carbonate ⁸⁷Sr/⁸⁶Sr ratios provide a robust archive of seawater composition and are widely used to reconstruct long-term changes in continental weathering, tectonic activity, and the global carbon–silicate cycle⁶⁷. Because silicate weathering consumes atmospheric CO₂, long-term increases in seawater ⁸⁷Sr/⁸⁶Sr may also reflect periods of enhanced CO₂ drawdown and climatic cooling. However, the proxy primarily records changes in the global strontium cycle rather than climate directly.

Age depth Model

A Bayesian age–depth model was constructed using the **Bchron** R package (Brooks, 2011) to independently evaluate the chronology and quantify age uncertainties. Using Markov Chain Monte Carlo (MCMC) iterations, Bchron can produce visualizations like age-depth plots, illustrating the range of possible ages at different depths (Brooks, 2011; De Vleeschouwer and Parnell, 2014). The Bayesian Bchron model was used, which is integrated into the Bchron R software package (<https://CRAN.R-project.org/package=rbacon>). We ran the Bacon model for every 2 m depth interval (as in De Vleeschouwer and Parnell, 2014; Messaoud et al., 2021). The input for the Bacon script includes Min Age = 137,000 ka, Max Age = 150,000 ka, Acc. Mean = 20, and 10 intervals of 20 m.

Cyclostratigraphy and time-series analysis

Cyclostratigraphic analyses and astronomical calibration were based on the continuous spectral gamma-ray record. In addition to the total GR signal, potassium (K), uranium (U), and thorium

(Th) records were analysed independently to assess the reproducibility and robustness of the orbital cyclicity identified in the composite gamma-ray dataset. Cyclostratigraphic analyses were primarily performed on the gamma-ray record because it provides the most continuous and highest-resolution proxy for variations in siliciclastic input and depositional cyclicity. Independent cyclostratigraphic analyses were also carried out on the K, U and Th records, which yielded consistent spectral characteristics and orbital interpretations, confirming the robustness of the GR-based astronomical framework (Supplementary materials). Before spectral analysis, all datasets were linearly interpolated to constant sampling intervals and detrended to remove long-wavelength variations unrelated to orbital forcing. Dominant periodicities were identified using the Multi-Taper Method (MTM) with significance evaluated against an AR(1) red-noise background model. Evolutionary Fast Fourier Transform (eFFT) was used to assess temporal variations in spectral power and to identify changes in sedimentation rate through the succession. Gaussian band-pass filters and Hilbert transforms were subsequently applied to isolate individual orbital components and evaluate their amplitude modulation. All spectral analyses were performed using Acycle

Time-series protocol

The cyclostratigraphic workflow followed the steps below:

- i. The GR dataset was linearly interpolated to a constant sampling interval of 5 cm and detrended using a locally weighted scatterplot smoothing (LOWESS) function to remove long-wavelength variations unrelated to orbital forcing while preserving astronomical-scale variability.
- ii. Multi-Taper Method (MTM) spectral analysis was performed using robust AR(1) red-noise significance testing to identify statistically significant periodicities. Spectral peaks were

evaluated at the 90%, 95%, 99%, and 99.9% confidence levels, and significance was further assessed using a 5% False Discovery Rate (FDR) correction to minimize false-positive orbital frequencies.

iii. The significant wavelengths were compared with the expected Milankovitch frequency ratios for the Late Jurassic–Early Cretaceous, considering the range of plausible sedimentation rates.

iv. Evolutionary Fast Fourier Transform (eFFT) was applied using a moving window to evaluate changes in spectral power and frequency through the succession and to identify intervals of relatively constant sedimentation suitable for astronomical calibration.

v. Mean sedimentation rates were independently estimated using TimeOpt, which determines the sedimentation rate that maximizes the agreement between observed cyclicities and the theoretical eccentricity–precession relationship. Statistical significance was evaluated by Monte Carlo simulations against AR(1) red-noise models.

vi. The principal orbital components were isolated using Gaussian band-pass filters, and Hilbert transforms were applied to extract amplitude envelopes and evaluate eccentricity modulation of shorter orbital cycles.

vii. The stable 405-kyr-long eccentricity cycle was selected as the primary tuning target. Floating astronomical time scales were generated using the Age Scale function in Acycle by matching successive filtered 405-kyr cycles to the astronomical solution of Jacques Laskar.

viii. The floating astronomical time scale was anchored to absolute time using independently constrained calcareous nannofossil bioevents and $^{87}\text{Sr}/^{86}\text{Sr}$ isotope ages. These chronostratigraphic constraints were subsequently integrated within a Bayesian age–depth

model to produce the final astronomically calibrated chronology and its associated uncertainty estimates.

ix. The astronomically calibrated time series were reanalysed in the time domain to verify the expression of the 405-kyr eccentricity cycle and shorter eccentricity, obliquity, and precession frequencies, and to establish the orbital framework used throughout this study.

Data availability

All data used in this study are provided in the Supplementary Information. Source data are provided with this paper.

Code availability

The Acycle ⁷¹ software used in this study is available for download at <https://github.com/mingsongli/acycle>. Astrochron package can be accessed from [https://cran.r-project.org/web/packages/astrochron/](https://cran.r-project.org/web/packages/astrochron/index.html) index.html. Additional code and configuration files relevant to the analyses are provided in the Supplementary Information. Age model was developed using the Bayesian software Bacon v2.4.3 (<https://CRAN.R-project.org/package=rbacon>)

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