

A new chronostratigraphic anchor for the early Cambrian: Integrating $\delta^{13}\text{C}$ chemostratigraphy and Bayesian astrochronology in West Gondwana (Anti-Atlas, Morocco)

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43 **Abstract**

44 The early Cambrian represents a critical interval in Earth's history characterized by rapid biological
 45 innovation and significant perturbations in global carbon cycling. However, a comprehensive
 46 understanding of the processes at play and their spatial and temporal relationships is hindered by fossil
 47 provincialism, diachronous bioevents, and inadequate high-precision geochronology. The Tiout section
 48 (Anti-Atlas, Morocco) offers a unique opportunity to address these challenges as it is a continuous
 49 1205 m-thick succession of sedimentary rocks with multiple volcanic ash beds, together with the
 50 lowest occurrence (LO) of determinable, mineralized trilobites and a refined biostratigraphy in West
 51 Gondwana. In this study, we present new high-resolution $\delta^{13}\text{C}_{\text{carb}}$ stratigraphy, coupled with portable
 52 XRF elemental geochemistry and Bayesian astrochronology, to refine the temporal framework of this
 53 lower Cambrian succession. The Tiout $\delta^{13}\text{C}_{\text{carb}}$ record captures multiple global excursions, including
 54 the termination of the Shiyantou Carbon Isotope Excursion (SHICE), excursions II and III, and the
 55 early Atdabanian/*Repinaella* Zone Excursion (EAREZE or excursion IV), which has been commonly
 56 confused with the Cambrian Arthropod Radiation Excursion (CARE). Cyclostratigraphic analysis of
 57 the detrital SiO_2 proxy combined with U–Pb-dates confirms previous interpretation of an eccentricity-
 58 precession origin for the decameter-scale rhythmic alternations between lighter-colored marlstones and
 59 darker limestones expressed in the weathering profile. The EAREZE peak below the LO of
 60 determinable trilobites is dated at 520.046 ± 0.097 Ma. The Tiout section provides a robust, multi-
 61 proxy reference for a potential Global Stratotype Section and Point (GSSP) for Cambrian Series 2.

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Introduction

The early Cambrian (Terreneuvian–Cambrian Series 2, ~539–506.5 million years ago, [Cohen et al. \(2013\)](#) represents a transformative interval in Earth’s history marked by rapid biological innovation, the diversification of complex life, and major shifts in global biogeochemical cycles ([Bowring et al., 1993](#); [Peng et al., 2012](#); [dos Reis et al., 2015](#); [Daley et al., 2018](#); [Linnemann et al., 2019](#); [Paterson et al., 2019](#); [Bowyer et al., 2022](#); [Potin and Daley, 2023](#); [Alexander et al., 2025](#)). The emergence of skeletonized metazoans, such as trilobites and archaeocyaths, fundamentally restructured marine ecosystems (e.g., [Wood et al., 1992](#)) with the development of complex trophic interactions and modified sediment dynamics (e.g., [Bottjer et al., 2000](#); [Mángano and Buatois, 2017](#)). These evolutionary events occurred in tandem with pronounced fluctuations in the carbon cycle recorded as global $\delta^{13}\text{C}$ excursions that reflect changes in ocean chemistry, primary productivity, and organic carbon burial ([Maloof et al., 2005](#); [Maloof et al., 2010](#); [Fan et al., 2011](#); [Young, 2015](#); [Betts et al., 2018](#); [Holmes et al., 2025](#)). Understanding the timing, nature, and drivers of these biogeochemical changes is crucial for reconstructing Earth’s early biosphere and environmental dynamics. Correlating these events on a global scale remains challenging due to the complex interplay of regional depositional environments, diagenetic overprints, strong biotic endemism (e.g., [Sdzuy et al., 1999](#); [Geyer and Shergold, 2000](#); [Landing et al., 2013a](#); [Peng et al., 2020](#)), and the limited but growing number of available high-precision radioisotope ages ([Landing et al., 1998](#); [Zhu et al., 2006b](#); [Peng et al., 2020](#); [Landing et al., 2023](#)). In this context, integration of carbon isotope stratigraphy with biostratigraphy, radioisotope ages and astrochronology is key for synchronizing stratigraphic successions across paleocontinents ([Fan et al., 2011](#); [Cramer and Jarvis, 2020](#); [Zhao et al., 2022](#); [Farrell et al., 2025](#)).

Yet, despite these advances, a central issue remains unresolved: the formal criterion for defining the base of the Cambrian Stage 3, corresponding with the Terreneuvian–Cambrian Series 2 boundary. Traditionally, this boundary has been placed at or near to the LO (lowest occurrence) of trilobites ([Geyer and Shergold, 2000](#); [Shergold and Geyer, 2003](#); [Peng et al., 2012](#); [Zhang et al., 2017](#)). This horizon is typically termed the “First Appearance Datum” (FAD) of trilobites, but the designation FAD should be limited to a horizon marking the phyletic origin of trilobites and which will not be found in the course of field and laboratory work ([Landing et al., 2013a](#); [Aubry, 2015](#)). In addition, the FAD horizon is further obscured in field settings as the earliest trilobites likely originated and diversified as non-mineralized forms well before the mineralization of trilobites with onset of a calcite sea (e.g., [Paterson et al., 2019](#); [Landing et al., 2024](#)).

While trilobite-based biostratigraphy remains a powerful regional correlation tool, its application as a global chronostratigraphic marker at the base of Cambrian Series 2 is considerably undermined by the diachronous nature of the LO of mineralized trilobites between paleocontinents ([Geyer and Shergold, 2000](#); [Hollingsworth, 2005a](#); [Peng and Babcock, 2011](#); [Landing et al., 2013a](#); [Landing et al., 2018](#)). Their limited facies distribution and endemism further complicate the use of a trilobite LO (“FAD”) as a globally synchronous marker.

Consequently, alternative criteria have been proposed to serve as a GSSP marker for Cambrian Stage 3. These include the FADs of small shelly fossils (SSFs; e.g., *Mobergella radiolata* ([Rozanov et al., 2011](#)) or *Pelagiella subangulata* ([Steiner et al., 2011](#)) = *Pseudopelagiella subangulata* sensu ([Landing et al., 2021a](#))), acritarch species (e.g., *Skiagia ornata*; [Moczyłowska and Zang \(2006\)](#)), and, most notably, a globally recognizable $\delta^{13}\text{C}$ positive excursion termed excursion IV or CARE ([Magaritz et al., 1986](#); [Kirschvink et al., 1991](#); [Magaritz et al., 1991](#); [Zhu et al., 2004](#); [Maloof et al., 2005](#); [Dilliard et al., 2007](#); [Landing et al., 2013a](#); [Landing and Kouchinsky, 2016](#); [Betts et al., 2018](#); [Peng et al., 2020](#)).

This peak has been linked to widespread oceanographic and ecological transformations during the Stage 2–3 transition ([Alexander et al., 2025](#)) and is increasingly regarded as an important feature in the global correlation of this boundary ([Landing and Kouchinsky, 2016](#); [Zhang et al., 2017](#); [Landing et al., 2021b](#)). However, the “type” CARE was chosen for sections on the South China paleocontinent where it lies approximately at the levels of the Chengjiang and Qingjiang biotas ([Zhu et al., 2006b](#); [Fu et al., 2019](#)). Thus, biostratigraphic evidence indicates that the CARE postdates carbon isotope excursion IV on the Siberian Platform, which has been mistakenly identified as the CARE. This confusion has contributed to continuing debate over its precise stratigraphic position, reproducibility, and association with biotic events ([Landing et al., 2013a](#); [Zhang et al., 2017](#); [Geyer, 2019a](#)). To overcome this confusion, [Geyer \(2019a\)](#) suggested the term EAREZE (Early Atdabanian/*Repinaella* Zone Excursion), which is applied herein. Stage boundaries within the Cambrian System have proven particularly difficult to ratify by the International Union of Geological Sciences: one series and four of the ten stages are still undefined, underscoring the need for continuous, fossiliferous, and radiometrically dated sections that record multiple independent chronostratigraphic signals to confidently select a Global Boundary Stratotype Section and Point (GSSP).

The Tiout section in the western Anti-Atlas of Morocco offers a rare opportunity to satisfy the requirements. It includes multiple volcanic zircon ID-TIMS U–Pb ages ([Compston et al., 1992](#); [Landing et al., 1998](#); [Maloof et al., 2005](#); [Maloof et al., 2010](#); [Landing et al., 2021b](#)) and records

the LO of mineralized, identifiable trilobites in West Gondwana, which belong to the bigotinids (such as *Hupetina antiqua*) and the fallotaspidids (such as *Eofallotaspis tioutensis*) along with archaeocyaths and brachiopods that enable a precise biostratigraphical scheme (Geyer, 2019b). However, it must be emphasized that unidentifiable trilobite fragments have long been known to occur ca. 40 m lower in the lower Igoudine Formation (Geyer and Landing, 1995, 2006). Cyclostratigraphic analysis of the Tiout section by Sinnesael et al. (2024) demonstrated that the meter-scale lithological cyclicity observed in the section by Monninger (1979) reflects an astronomical origin, primarily controlled by precession and short eccentricity (~20–100 kyr) cycles. The integration of these individual astronomical cycles with available U–Pb geochronology into a Bayesian age-depth model provided a refined age estimate for the LO of unidentified trilobite remains in West Gondwana (519.70–519.54 Ma 95% highest posterior distribution).

In addition to its biostratigraphic and geochronologic significance, the Tiout section also holds potential for global chemostratigraphic correlations. Preliminary low-resolution $\delta^{13}\text{C}_{\text{carb}}$ profiles from Tiout (Tucker, 1986; Kirschvink et al., 1991) revealed a distinct positive $\delta^{13}\text{C}_{\text{carb}}$ excursion, peaking in the lower member of the Igoudine Formation and below the LO of the identifiable trilobites, but within the range of trilobites as indicated by small fragments of sclerites (Geyer, 2019c). This excursion was correlated with excursion IV in the *Repinaella* Zone of the lower Atdabanian Stage in Siberia (Brasier and Cowie, 1989; Latham and Riding, 1990; Kirschvink et al., 1991). This correlation is supported by the high-resolution $\delta^{13}\text{C}_{\text{carb}}$ profile obtained from the nearby Oued Sdas section that is stratigraphically equivalent to the Tiout section, where a comparable positive $\delta^{13}\text{C}_{\text{carb}}$ shift is recorded (Maloof et al., 2005; fig. 2; Maloof et al., 2010; Landing et al., 2021b).

As part of ongoing efforts to address global correlation challenges at the base of Cambrian Series 2, we generated a new high-resolution geochemical dataset including $\delta^{13}\text{C}_{\text{carb}}$ chemostratigraphy and bulk-rock portable x-ray fluorescence (pXRF) elemental data through the 1205-meter-thick continuous sedimentary succession at Tiout. This work aims to clarify the structure, magnitude, and stratigraphic position of the peak of the EAREZE $\delta^{13}\text{C}_{\text{carb}}$ positive excursion in relation to the LO of identifiable trilobite remains and co-occurring U–Pb zircon ages at Tiout. We also use pXRF-derived detrital proxies, together with $\delta^{13}\text{C}_{\text{carb}}$ chemostratigraphy, biostratigraphy, and U–Pb geochronology, to build a Bayesian astrochronological age-depth model that improves temporal resolution and enables more robust global correlations of early Cambrian successions. Finally, we discuss and integrate those new West Gondwana results in global context and provides methodological guidance

along with our perspective for establishing Global Boundary Stratotype Sections and Points (GSSPs).

2. Materials and method

2.2 Geological Background

During the early Cambrian, the Anti-Atlas of Morocco was part of the western margin of Gondwana. It is commonly portrayed as located at ~60° South ([Fig. 1; Scotese, 2021](#)). However, evaporitic minerals in the Adoudou Formation and development of carbonate platform deposits with archaeocyath-microbial mound developments in the Igoudine and Amouslek formations are evidence of a low latitude, tropical environment consistent with a counterclockwise rotation of Gondwana in the Cambrian ([McKerrow et al., 1992](#); [Landing et al., 2022](#); [Keppie et al., 2024](#)).

The Tiout section, situated along the northern edge of the Anti-Atlas, is a continuous and expanded marine succession that extends from the lowest Cambrian (Terreneuvian) into Series 2. The composite succession, as documented by [Monninger \(1979\)](#), records a total thickness of ~1600 m and encompasses the upper portion of the Adoudou, Lie de vin, Igoudine (including the Tiout Member), and Amouslek formations (Fig. 1A). The following provides a summary of litho- and biostratigraphy. For a detailed overview of the regional geology of the Anti-Atlas we refer to [El Kabouri et al. \(2025\)](#).

The Lie de vin Formation ([Choubert, 1953](#)) is composed of cyclically interbedded siltstones and limestones, including microbialites such as stromatolites and thrombolites and evaporite pseudomorphs that indicate a restricted shallow marine paleoenvironment. At Tiout, this formation reaches up to 940 m in thickness and contains various trace fossils such as (sub)horizontal burrows and U-shaped burrows identified as *Diplocraterion* ([Latham and Riding, 1990](#)). The formation also records several dated ash beds (e.g., Ti 566, 521.06 ± 0.12 Ma (see [Landing et al., 2021b for the most recent works](#))). Key ash beds within time-equivalent Lie de vin deposits exposed at Oued Sdas approximately 25 km east of Tiout have also been radiometrically dated by [Maloof et al. \(2010\)](#) including the tuff M234, yielding a weighted mean U–Pb zircon age of 523.17 ± 0.16 Ma ([Landing et al., 2021b](#)), that anchors the lowermost part of the Lie de vin in the terminal Terreneuvian Series.

The overlying Igoudine Formation ([Geyer, 1989](#)) records a transition from restricted to more open-marine conditions. At Tiout, the formation reaches a thickness of ~300 m ([Geyer, 2019c](#)). It is subdivided into a lower unnamed member (~185 m) composed of black

laminated limestones and dolosiltites, interpreted as having been deposited under dysoxic to anoxic conditions and an upper Tiout Member (~115 m) characterized by oolitic and fossiliferous grainstone representing wave-agitated shoals (Geyer and Landing, 2006; Geyer, 2019c). Fossils in the lower unnamed member include *Hyolithellus* tubes and poorly preserved undetermined trilobite sclerites (Sdzuy and Geyer, 1988; Geyer and Landing, 1995), while the Tiout Member contains a diverse fauna of early skeletal metazoans, such as trilobites (*Eofallotaspis*, *Fallotaspis*, various bigotinids), archaeocyaths, hyoliths, and cancelloriids (Debrenne and Debrenne, 1978; Sdzuy, 1978; Debrenne and Debrenne, 1995; Geyer and Landing, 1995; Geyer, 2019c). The abrupt appearance of mineralized trilobite sclerites in this interval is attributed to a shift in taphonomic or environmental conditions, with perhaps a change to a calcite ocean, rather than reflecting a true evolutionary radiation (Geyer, 2019c).

The Amouslek Formation is ~260 m-thick at Tiout and records a clear but gradual transition from a carbonate-dominated setting (Igoudine Formation) to siliciclastic mudstones, indicative of further marine deepening. The contact with the underlying Igoudine Formation is a regional sequence boundary, marked by a volcanic tuff dated to 519.23 ± 0.14 Ma (Ti-Am0.0; Landing et al., 2021b)—placing it near the top of the *Fallotaspis plana* Zone and the base of the *Choubertella* Zone (Geyer, 2019b; Landing et al., 2021b).

2.1 Section measurement and sampling strategy

In this study, we systematically measured and sampled a 1205-meter-thick stratigraphic succession extending from the lower Lie de vin Formation to the lower Amouslek Formation. A total of 744 samples were collected at approximately 1.5-meter intervals. The composite section was divided into ten intervals defined by lithologic markers, linked by using lithologic markers and drone imagery (Fig. 2; Fig. S1). Key marker beds, including ash layers and the LO of trilobites, were precisely identified and located in the succession during fieldwork. Drone imagery facilitated an accurate evaluation of potential astronomically-forced climatic cycles in these lower Cambrian strata, which are several hundred meters thick and must be seen from a broader perspective to identify potential bundling. The limited vegetation cover in the area is an important parameter that allows for such a survey. Drone imagery also served as an integrative tool: it documented formation boundaries that are not easily identifiable when standing on the outcrop itself, enabled precise location of measured intervals, and allowed location of key marker beds, such as volcanic ash layers and the LO of trilobites in the section, previously identified by field observation (Fig. 3). These images were also critical for

field planning as they enabled efficient selection of the most continuous and accessible stratigraphic intervals for detailed logging and sampling, and they will continue as a reference for future field work.

2.3. Elemental geochemistry (pXRF)

All collected samples were cut using a circular saw to create a flat surface and to remove potential weathered material. Samples were then measured with a pXRF spectrometer Bruker Tracer 5g (Liège University, Belgium) equipped with the following parameters: 4 Watt, 200 μ A and 50 keV X-Ray Rhodium source, a 1 μ m graphene window, resulting in a resolution <140 eV at 250 000 cps. Measurements were performed in dry air conditions (i.e., normal conditions without specific gas flow), using an 8 mm collimator and an acquisition time of 70 seconds, which is considered suitable to get accurate pXRF data (De Winter et al., 2017; Da Silva et al., 2023). All major and trace element data were generated using the GeoExploration internal quantification protocol and are expressed in wt.%. The full dataset is provided in Supplemental Material File 1.

2.4. Stable isotope geochemistry ($\delta^{13}\text{C}_{\text{carb}}$, $\delta^{18}\text{O}_{\text{carb}}$)

455 samples were measured at an average 3-m resolution for the Lie de vin Formation and ~1.5 m resolution for the Igoudine and Amouslek formations for carbonate carbon and oxygen stable isotopes ($\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$). Aliquots of the rock powders were reacted with 100% phosphoric acid at 70°C using a Gasbench II connected to a Thermo Fisher Delta V Plus mass spectrometer at the University of Erlangen (Germany). All values are reported in per mil relative to the Vienna Pee Dee Belemnite limestone standard (VPDB). Reproducibility and accuracy were monitored by replicate analysis of laboratory standards calibrated by assigning a $\delta^{13}\text{C}_{\text{carb}}$ of +1.95‰ to NBS19 and -47.3‰ to IAEA-CO9 and a $\delta^{18}\text{O}_{\text{carb}}$ of -2.20‰ to NBS19 and -23.2‰ to NBS18. Reproducibility for $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ was better than ± 0.04 ‰ and ± 0.10 ‰ (1 std. dev.), respectively. Replicate analyses of NBS 19 were used for quality control of the measurements.

2.5. Spectral analysis and Bayesian age modeling

To detect and interpret potential Milankovitch cycles, time-series analysis was conducted on the detrital SiO_2 records measured using pXRF (Fig. 4). The numerical interpretations were cross-validated with field observations and high-resolution drone imagery, which provided essential context for stratigraphic continuity and lithological cyclicity. Time-series analysis

was conducted using different tools including Continuous Wavelet Transform (CWT) as provided in the “WaverideR” R package ([Arts et al., 2024](#)) and Taner bandpass filtering, Hilbert transform, and multi-taper method (MTM) as provided in the “Astrochron” R package ([Meyers, 2019](#)). Time-series analysis script is available in Supplemental Material File S2.

We constructed an integrated Bayesian age–depth model for the Tiout section by combining high-precision CA–ID–TIMS U–Pb zircon geochronology with cyclostratigraphic constraints derived from the floating astronomical timescale built on the interpreted short eccentricity cycles. This approach was implemented using OxCal version 4.4 ([Ramsey, 2009](#)), which relates stratigraphic depth, expressed in interpreted short-eccentricity cycles to time under the assumption of a constant but unknown sediment accumulation rate following the framework of [Sinnesael et al. \(2024\)](#) but adapted to incorporate the precise sedimentological and geochronological succession of the Tiout composite. To represent the floating astronomical time scale, we expressed stratigraphic depth as units of interpreted short-eccentricity cycles of 20–40 m-thick rhythmic bundles expressed in drone-based imagery and supported by CWT and MTM spectral analysis of the log₁₀-transformed SiO₂ time series. These cycles were interpreted to reflect the ~110 kyr component of Earth's eccentricity, based on their bundling and spectral expression. A prior distribution for ~110 kyr cycle duration was assigned as a normal distribution with a mean of 110 kyr and one standard deviation of 7.5 kyr.

This differs from the approach of [Sinnesael et al. \(2024\)](#) who adopted a shorter short eccentricity cycle duration (mean of 96.5 kyr, $\sigma = 2$ kyr) derived from the time differences between successive maxima in full numerical orbital solution ([Lantink et al., 2022](#)). Our longer 110 kyr prior was intended to accommodate such practical sources of stratigraphic uncertainty as decimeter- to meter-scale horizons of cycle boundaries and minor hiatuses. We assumed a constant sediment accumulation rate within each short eccentricity cycle and no significant depositional hiatuses within the stratigraphic interval modeled. The depth model served as a reference framework to assign stratigraphic positions. We first established a depth model from our field measurements, which provided the reference framework to place all stratigraphic markers, including radiometric age constraints, the levels of the EAREZE and excursions II and III peaks, and the lowest occurrence (LO) of identifiable trilobites. At this stage, the framework is depth-only, without a floating age model applied. To convert depth into time, we then integrated our new SiO₂-based cyclostratigraphic dataset, which allowed recognition of eccentricity-scale cyclicity. This cyclostratigraphic model is anchored by high-precision U–Pb zircon ages from interbedded bentonitic ashes (M234, Ti566, Ti-Am-0.0). Volcanic zircons were interpreted as syndepositional with negligible reworking. Age

uncertainties are reported as 95% highest posterior density (HPD) intervals. Full model priors, OxCal code, and posterior outputs are provided in Supplementary File S2.

3. RESULTS AND DISCUSSIONS

3.1. Lithostratigraphic correlation and framework of the Tiout section

The composite stratigraphic framework of the Tiout section presented in Figure S1 is based on ten laterally correlated intervals spanning a total of 1204.5 m in stratigraphy that brackets the Lie de vin, Igoudine, and Amouslek formations. Stratigraphic continuity between measured partial sections that comprise the entire Tiout section was ensured with drone imagery, which helped in the precise tracing of key lithological contacts at the top/bottom of measured intervals. The complete stratigraphy can be visualized in a composite image created from a series of drone photographs (Fig. 2B). Formation boundaries were confidently identified in the field based on consistent differences in color, weathering profiles, and distinctive lithological characteristics as described in [Monninger \(1979\)](#), Geyer and Landing (2006) and Landing et al. (2019).

3.2. $\delta^{13}\text{C}_{\text{carb}}$ stratigraphy of the Tiout section

The $\delta^{13}\text{C}_{\text{carb}}$ profile from the Tiout section (Fig. 3) captures a continuous, well-preserved signal through more than a one kilometer of lower Cambrian strata. Measured $\delta^{13}\text{C}_{\text{carb}}$ values range from -6‰ to $+4\text{‰}$ (VPDB), averaging near 0‰ , and capture major global excursions, including the termination of the SHICE, excursions II and III, and the EAREZE (or excursion IV). The lack of statistically significant covariance between $\delta^{13}\text{C}_{\text{carb}}$ and $\delta^{18}\text{O}_{\text{carb}}$ ($R \approx 0.012$; Fig. S2), is not in itself definitive evidence of preservation, but it is consistent with only limited diagenetic influence on the $\delta^{13}\text{C}_{\text{carb}}$ record ([Kaufman and Knoll, 1995](#)). Whereas $\delta^{18}\text{O}_{\text{carb}}$ values are low (-12‰ to -2‰), this depletion likely reflects post-depositional fluid interaction, as $\delta^{18}\text{O}_{\text{carb}}$ is more sensitive to alteration than $\delta^{13}\text{C}$, which often retains its original marine signal ([Banner and Hanson, 1990](#)). Although post-depositional alteration is evident in the oxygen isotope record, the long-term $\delta^{13}\text{C}_{\text{carb}}$ pattern remains consistent with primary marine signals and is therefore suitable for high-resolution chemostratigraphic correlation ([Álvaro et al., 2008](#); [Jamart et al., 2025](#)).

The following carbon isotope descriptions are based on the 35-point moving average general trend observed in the $\delta^{13}\text{C}_{\text{carb}}$ data.

The $\delta^{13}\text{C}_{\text{carb}}$ curve recorded in Tiout closely matches the composite curves of [Maloof et al. \(2010\)](#) for other sections in the western Anti-Atlas of Morocco. Their curves were used in the

GTS 2020 volume ([Cramer and Jarvis, 2020](#); [Peng et al., 2020](#)) to reconstruct the global carbon isotope excursion framework of the Cambrian in terms of excursion morphology, magnitude, and stratigraphic position. At the base of the section (0 to ~70 m) within the lower Lie de vin Formation, $\delta^{13}\text{C}_{\text{carb}}$ values start near -4‰ and define a sustained negative value that is interpreted as the termination of the SHICE. First described from the Chiungchussu Formation in eastern Yunnan, South China platform ([Zhu et al., 2006a](#)), the negative SHICE is a (sub)globally traceable carbon cycle perturbation recorded in Cambrian Stage 2. [Zhu et al. \(2006b\)](#) associated the SHICE with an extinction of SSFs in South China, that is also documented in North Gondwana (South Australia, ([Betts et al., 2018](#))). Although the SHICE should be seen as a low diversity interval with persistence of a number of earlier appearing fossil genera and species, coeval strata in East Siberia and the Avalonia do not show a loss in diversity or faunal turnover in SSF communities that appeared with the onset of the older, strongly positive ZHUCE excursion ([Landing and Kouchinsky, 2016](#); [Kouchinsky et al., 2017](#); fig. 5).

The fall of the SHICE to negative values marks the transition from the positive Zhujiaping Carbon Isotope Excursion (ZHUCE) to more stable isotopic values in upper Terreneuvian strata. SHICE values typically range from -4‰ to -6‰ , reaching as low as -9‰ in South China ([Zhu et al., 2006a](#)), and have been identified in Siberia (“6n”; [Kouchinsky et al. \(2007\)](#)), South Australia ([Betts et al., 2018](#)) and in the nearby Oued Sdas section of the Moroccan Anti-Atlas ([Maloof et al., 2010](#)).

At Tiout, the SHICE is temporally constrained by several undated volcanic ash beds near ~88.5 m, which are stratigraphically consistent with ash bed M234 from the Oued Sdas section (dated at 523.17 ± 0.16 Ma; [Maloof et al., 2010](#)), providing a chronostratigraphic anchor for the lower part of the section.

Following the SHICE, two minor $\delta^{13}\text{C}_{\text{carb}}$ peaks occur: the lower one at $\sim -1.5\text{‰}$ around 300 m, and a second at $\sim -3\text{‰}$ around 450 m (Fig. 3). These are interpreted as excursions II and III, respectively, originally recorded in lower Cambrian strata on the Siberian Platform ([Magaritz et al., 1986](#); [Kirschvink et al., 1991](#)). On the Siberian platform, both excursions fall within the *Dokidocyathus regularis* Zone of the regional middle Tommotian Stage ([Kouchinsky et al., 2007](#); [Kouchinsky et al., 2015](#)).

From that level, $\delta^{13}\text{C}_{\text{carb}}$ values decrease gradually upsection at Tiout, reaching to a broad negative excursion that bottoms out at -4‰ at ~600 m. This represents the most depleted interval in the section and aligns stratigraphically with ash bed Ti 566, dated at 521.06 ± 0.12 Ma ([Landing et al., 2021b](#)).

Between ~600 m and ~1150 m, the $\delta^{13}\text{C}_{\text{carb}}$ curve displays a broad, symmetric positive excursion, corresponding to the EAREZE (Fig. 3). The EAREZE positive excursion has been recognized in several regions, including the Siberian Platform (Magaritz et al., 1986; Brasier et al., 1994; Derry et al., 1994; e.g., Kouchinsky et al., 2007), Morocco (Maloof et al., 2010), and northwesternmost Canada (Dilliard et al., 2007). However, the positive excursion in Australia ((peak II in Betts et al. (2018); CARE in Betts et al. (2024)) and South China (Yang et al., 2025) likely represents the slightly younger CARE peak (e.g., Geyer, 2019a). The $\delta^{13}\text{C}_{\text{carb}}$ values for the EAREZE range from approximately +1.4‰ in Siberia to +3.4‰ in the Moroccan sections.

The EAREZE, as well as the CARE (believed in some reports to be coeval), were considered to align roughly with the initial radiation of trilobites and diverse arthropods (Brasier et al., 1994; Zhu et al., 2006a; Bowyer et al., 2022) and to be more-or-less coeval with the LO of trilobites in a number of regions (Zhu et al., 2006a). However, the CARE isotope event in South China corresponds with the *Parabadiella huoi* Zone for which a radiometric date of ca. 518 Myr has been recorded (Yang et al., 2018; Fu et al., 2019). High precision dating in the Tiout section prove an age of >519.5 Myr (Landing et al., 2021b) for the EAREZE peak. Stratigraphically, the EAREZE peak lies several trilobite biozones below the *Choubertella* Zone. Since the *Choubertella* Zone is thought to correlate with the *Parabadiella huoi* Zone of South China (Geyer, 2019a), this indicates that the EAREZE peak predates the interval of the CARE event. On the Siberian Platform, the EAREZE peak lies in the *Repinaella* Zone, above the base of the regional Atdabanian Stage (Geyer, 2019a), with its base marked by the LO of *Profallotaspis jakutensis*, approximately in the lowest part of excursion IV (e.g., Varlamov et al., 2008).

In this study, the LO of identifiable trilobites at Tiout and in West Gondwana is recorded at ~1048.3 m on the declining limb of the EAREZE excursion, based on *in situ* field indicators “T” identified by Sdzuy (1978) and confirmed by Geyer (2019c). Similarly old trilobite assemblages with a comparable composition are known from the Pedroche and Alconera formations of southern Spain (Liñán et al., 2005; Liñán et al., 2008), but the relevant sections appear to be unsuitable for revealing carbon isotope signatures. In Tiout, the EAREZE peaks at +2‰, corresponding to ~910 m within the lower Igoudine Formation. The EAREZE is bracketed by two dated volcanic ash beds: Ti 566 at its base and Ti-Am.0.0 at 1137.7 m (dated at 519.23 ± 0.14 Ma, Landing et al. (2021b)).

3.3. Identification of astronomical forcing in detrital proxies

To investigate astronomical forcing recorded in the Tiout section, we selected SiO₂, TiO₂, and Al₂O₃ as geochemical proxies (Figs. 3–5). These chemicals are well-established indicators of terrigenous input in mixed carbonate-siliciclastic systems (Calvert and Pedersen, 2007) and are commonly used in deep-time paleoclimate reconstructions (Li et al., 2019; Sinnesael et al., 2019; Arts et al., 2024; Pas et al., 2024). Elevated concentrations of these detrital proxies in marine sediments is typically associated with increased runoff, likely linked to intensified precipitation or sea-level fall (e.g., Da Silva et al., 2013; Pas et al., 2018). However, the expression of detrital input may vary depending on the temporal resolution and depositional context. Among these elements, SiO₂ was chosen as the reference proxy for time series analysis due to its high variability in our record, pronounced sensitivity to climatic variations (Calvert and Pedersen, 2007) and strong correlation with other detrital proxies (Fig. 3), which also indicate minimal diagenetic alteration.

As documented in previous studies (Monninger, 1979; Sinnesael et al., 2024), the lower Cambrian Stage 2 strata of the Tiout section are marked by striking rhythmic alternations between lighter-colored marlstones and darker limestones, which is particularly well expressed in the Lie de vin Formation (Fig. 4). These rhythmic patterns occur across several scales of bundled cyclicity: meter-scale alternation “rhythms”, decameter-scale “cyclothems” composed of several rhythms, 100 m-scale sequences “supercycles,” and long-term trends spanning several hundred to over a thousand meters. The bundling of meter-scale depositional rhythms into higher-order cyclothems, expressed in the Tiout section weathering profile, has been interpreted as the sedimentary manifestation of paleoclimate changes driven by precession and short-eccentricity cycles (Sinnesael et al., 2024). This interpretation is supported by independent high-precision U-Pb zircon CA-ID-TIMS ages from multiple bentonite layers throughout the stratigraphic interval.

To evaluate the imprint of orbital forcing on the detrital proxy record at the cyclothem scale (20-40 m), we compared the weathering profile captured in drone imagery with the highly resolved SiO₂ stratigraphic profile. As illustrated in Fig. 4, elevated SiO₂ concentrations consistently coincide with marlstone-rich intervals, indicating that detrital input faithfully tracks lithological alternations at this scale. This supports the use of SiO₂ as a robust proxy for time-series analysis throughout the Tiout section. In this study, all published bentonite-based ages were located with a resolution of 1.5 m in the succession. Using the thickness of the section and the time interval constrained by numerical ages at its base and top, we estimate an average sediment accumulation rate of 260 m/Myr, which is consistent with values in other reports (Landing et al., 2021b; Sinnesael et al., 2024).

To account for changes in sedimentation rate as observed in previous studies, we assume that the short eccentricity cycle is expressed with a wavelength ranging from 20 to 40 m. Based on this range, the corresponding expected wavelength would be approximately ~74–147 m for the long eccentricity (405 kyr), ~5.8–11.6 m for obliquity (~32 kyr), and ~3.3–6.7 m for precession (~18.3 kyr). These estimates are based on the predicted early Cambrian astronomical frequency ratios (22.13:3.6:1) ([Laskar et al., 2004](#); [Waltham, 2015](#); [Farhat et al., 2022](#)).

The CWT of the $\log_{10}$ -transformed SiO_2 series (Fig. 5A) reveals prominent spectral powers at wavelength bands interpreted as the ~110 kyr short eccentricity cycle, as well as the expected obliquity and a precession cycles. Weaker spectral power is also observed at the ~405 kyr long eccentricity cycle. Due to the 1.5-m sampling resolution, our confidence in interpreting cycles thinner than ~6 m is limited ([Martinez et al., 2016](#)), and the 5.5 m peak lies at the lower threshold of reliable detection. The precession–eccentricity origin for the Tiout sedimentary record was assessed by filtering out the 5.5 m periodicity and applying spectral analysis on its Hilbert transform envelope (Fig. S3). The power spectrum shows one main amplitude modulation frequency at 0.035 cycles/cm (28 m), which indicate a modulation of m-scale cyclicity by decameter-scale cycle (i.e., “cyclothem” of this report).

3.4. Astronomical calibration for the Tiout section

Assuming that Milankovitch forcing governs the multi-scale cyclicity in the Tiout section and given the particularly well-expressed short eccentricity component in the stratigraphic record, we applied a Taner bandpass filter targeting the 20–40 m wavelength range. Assuming a short-eccentricity cycle of ~110 kyr we constructed a floating astronomical timescale spanning 4.87 ± 0.11 Myr for the Tiout section (Fig. 5B). The CWT of the astronomically calibrated SiO_2 series (Fig. 5B) reveals distinct power in the 1.2 Myr, 405 kyr, ~110 kyr (calibrated) and ~32 kyr range, and a weaker but high non-negligible power in the band of 173 kyr obliquity, precession cycles (~18.2 kyr), and a ~55 kyr, which correspond to a secondary obliquity-related component in today’s time ([Laskar, 2020](#)), but whether an analogous component operated in the Cambrian is unknown. The periodicity of power peaks in the CWT scalogram of the tuned SiO_2 series aligns with the expected early Cambrian duration ([Laskar et al., 2004](#); [Waltham, 2015](#); [Farhat et al., 2022](#); [Wu et al., 2024](#)), which supports our astronomical interpretation.

Band-pass filters for wavelength bands of 20–40 m ($0.025\text{--}0.05\text{ m}^{-1}$) and 70–130 m ($0.0077\text{--}0.0143\text{ m}^{-1}$) representing short and long eccentricity (~405 kyr) are also shown in Fig. 5B. The

short eccentricity (~110 kyr) filter and its Hilbert transform envelope shows amplitude modulation that is mostly in antiphase with the 405 kyr filter, which supports an astronomical forcing for the observed cyclicity. This antiphase relationship, further detailed in Fig S4, likely indicates the processes that drive the proxy record (e.g. SiO₂) respond in the opposite direction than the astronomical forcing. Modulation of precession is further confirmed by spectral analysis of the precession-filter envelope, which reveals a robust ~110 kyr amplitude modulation (Fig. S4).

The short-eccentricity cycle (~110 kyr) is the most visually striking and laterally consistent cyclicity present in the Tiout section. Based on lithological and geochemical observations, darker intervals (dominated by carbonate-rich facies) alternate with lighter-colored, detrital-rich intervals. We interpret these alternations as the climatic response to eccentricity pacing: eccentricity maxima, associated with intensified monsoon will drive enhanced water circulation and nutrient supply allowing thrombolite to thrive (e.g., higher carbonate productivity). Minima will promote lower carbonate productivity under less stable, open marine conditions.

While our interpretation differs in its underlying mechanism, it corresponds closely in the observed stratigraphic expression to the cyclothem framework established by [Monninger \(1979\)](#), which identified a recurring ~30 m-thick facies cycle based on patterns in lithology, bed thickness, and the relative abundance of carbonate and detrital units. [Monninger \(1979\)](#) documented that stromatolitic–thrombolite bioherms tend to peak near the center of these cycles, with variations in size and abundance reflecting transitions from more restricted to more open marine conditions. We suggest that these environmental gradients were likely controlled by orbital eccentricity. In this context, short eccentricity maxima, associated with enhanced water circulation and open marine conditions, likely promoted increased water circulation, providing more nutrient and more stable marine conditions that enhanced stromatolite growth and carbonate accumulation ([Andres and Reid, 2006](#)) and resulted in well-developed bioherms near the center of each cycle. In contrast, eccentricity minima decrease water circulation and possible restriction or turbidity, conditions less favorable for algal colonization and carbonate precipitation. Thus, the ecological and sedimentological patterns documented in [Monninger \(1979\)](#) are consistent with a climatic control paced by eccentricity forcing, with nutrient and water circulation effects dominate carbonate sedimentation and thrombolites developments. This integrated view reconciles nonlinear sedimentary and ecological responses to astronomically paced environmental change.

3.5. Bayesian astrochronology: new age constraints for early Cambrian events

The Bayesian age-depth model integrates high-precision CA-ID-TIMS U-Pb zircon ages ([Maloof et al., 2010](#); [Landing et al., 2021b](#)) with stratigraphic tie-points derived from well-expressed 20–40 m-thick cycles, interpreted to record ~110 kyr short eccentricity (Fig. 5). The peak of the EAREZE is now dated at $520.046 \pm 0.097/-0.095$ Ma (95% HPD) by this report, which is the most precise numerical age constraint for this carbon isotope excursion to date. While [Landing et al. \(2021b\)](#) estimated the peak of the EAREZE in the Anti-Atlas of Morocco at $520.27 \pm 0.59/-0.57$ Ma through interpolation between radiometrically dated tuffs and by assuming uniform sediment accumulation rates, the new high-resolution $\delta^{13}\text{C}_{\text{carb}}$ data presented here allow for a more precise stratigraphic location of the EAREZE peak within the Tiout section. By precisely locating the excursion in a well documented succession and integrating it with existing U-Pb geochronology and astrochronological data from the same section, our model reduces previous uncertainty estimates by nearly an order of magnitude. In addition, the lowest known occurrence (LO) of fragmentary and unidentifiable mineralized trilobites near the base of the lower member of the Igoudine Formation lies near the peak of EAREZE and is constrained to $519.62 \pm 0.11/-0.11$ Ma (95% HPD). This places the lowest known Moroccan trilobite fragments as an approximate correlative of lower *Repinaella* Zone trilobites in east Siberia ([Varlamov et al., 2008](#)). Simultaneously, the LO of identifiable trilobites in West Gondwana, marked by the appearance of the *Hupetina antiqua* faunule in the Tiout Member ([Geyer, 2019b](#)) is now constrained to $519.494 \pm 0.117/-0.113$ Ma (95% HPD), defining a ~552 kyr lag between this facies-controlled appearance nearly at the lithofacies transition from massive carbonates of the lower member of the Igoudine and the Tiout Member event and the peak of the EAREZE. The new LO age for the trilobite fragments is equivalent than the estimate from model A in [Sinnesael et al. \(2024\)](#) ($519.70\text{--}519.54$ Ma, 95% HPD) and ~330 kyr younger than the interpolated estimate of $519.95 \pm 0.43/-0.40$ Ma defined in [Landing et al. \(2021b\)](#), while still overlapping within uncertainty bounds.

In addition to calibrating the date on EAREZE and the lowest fragmentary trilobite remains and the date on the LO of the lowest identifiable trilobites, this model yields updated ages for other key early Cambrian $\delta^{13}\text{C}$ excursions and a new age for the LO of archaeocyaths (Fig. 6). Excursion II is now constrained to $522.413 \pm 0.071/-0.070$ Ma and excursion III to 521.724

+0.065/-0.065 Ma, while the LO of archaeocyaths yield an age of 519.44 +0.117/-0.113 Ma, all expressed with 95% HPD. All Bayesian ages model results are summarized in Table 1.

3.6. Implications for the timing of early Cambrian biogeochemical events in West Gondwana

These new ages estimate the lowest occurrences of mineralized trilobite fragments and the younger occurrence of identifiable trilobites and align with other global datasets, but with significantly reduced uncertainty (Fig. 6). A dated ash bed in the Caerfai Bay Shales Formation of Pembrokeshire, Wales, eastern Avalonia, located just above the LO of trilobites was dated at 519.30 ± 0.23 Ma ([Landing et al., 1998](#); [Harvey et al., 2011](#); [Landing et al., 2013b](#)). However, the trilobites on the Avalonia continent are locally known to be very late arrivals, with the oldest trilobites in the Brigus Formation of western Avalonia far younger and dating to somewhat older than ca. 507.91 ± 0.07 Ma. These dates demonstrate the very diachronous LO of trilobites ([Landing et al., 2023](#)). In South China, [Zhang et al. \(2022a\)](#) estimated the LO of trilobites at 520.11 ± 1.91 Ma, anchoring a floating astrochronology to a low-precision SHRIMP U-Pb date. In both cases, uncertainties exceed 460 kyr to nearly 4 Myr. In other sections worldwide, the precise timing of the trilobite LO remains indirectly constrained (i.e., absence of direct age control) and is inferred from its stratigraphic position relative to the EAREZE and CARE. No radiometric dates exist for the oldest strata with trilobites on the Baltica paleocontinent. This *Schmidtellus mickwitzii* fauna in Estonia has been equated with the *Skiagia ornata*–*Fimbriaglomerella membranacea* acritarch assemblage ([Moczyłowska, 1998](#); [Schoenemann et al., 2017](#)) and was considered as particularly old. However, the acritarch assemblage appears to be controlled by facies rather than indicating a robust age, and several data suggest a much younger age of these oldest trilobites of Baltica ([Geyer and Landing, 2018](#); [Geyer, 2019c](#)).

In Siberia, trilobites such as *Profallotaspis jakutensis* occur below the EAREZE peak (at the onset of EARZEE) at the base of the Atdabanian Stage ([Kirschvink et al., 1991](#); [Kouchinsky et al., 2007](#); [Rozanov et al., 2008](#); [Bowyer et al., 2022](#)). Similar stratigraphic relationships have been described for the Tarim Platform ([Yang et al., 2025](#)), and Laurentian northwestern Canada ([Dilliard et al., 2007](#)). However, the $\delta^{13}\text{C}$ excursions in these regions need to be examined in their relationship to precise biostratigraphical data. In South Australia ([Betts et al., 2018](#)), the oldest trilobite assemblage includes *Parabadiella huoi* and thus appears to be coeval with the onset of the trilobites in South China (Geyer, 2019). An SSF assemblage with

Micrina etheridgei slightly predates the *P. huoi* Biozone on the lower limb of the CARE positive excursion.

The oldest identified Laurentian trilobites are known from well studied sections in the Great Basin (southern Nevada and California) originally claimed to represent a *Fallotaspis* fauna similar to the oldest known trilobites of Morocco (e.g., [Hollingsworth, 2005a](#); [Hollingsworth, 2005b](#); [Hollingsworth, 2007](#)). Revised identifications suggest the oldest identified trilobites to represent a relatively endemic fauna dominated by archaeaspidids (*Fritzaspis* Zone) and subsequent fallotaspidids (e.g., [Hollingsworth, 2011](#)). Unfortunately, these fossiliferous sections from the Great Basin are dominated by siliciclastics and are unlikely to provide carbon isotope signatures. Records of $\delta^{13}\text{C}$ fluctuations are known from the Sekwi Mountains of the Canadian Cordillera and indicate a distinct positive shift in the “*Fallotaspis* Zone” ([Dilliard et al., 2007](#)). However, the fossil record in the relevant sections is sparse ([Fritz, 1976](#)) and does not allow a precise correlation with the Great Basin sections.

In contrast, in the Moroccan sections such as Tiout and Oued Sdas, the LO of the lowest known trilobite fragments and identifiable trilobites lies above or on the declining limb of the EAREZE excursion (this study; [Tucker, 1986](#); [Maloof et al., 2010](#); [Geyer, 2019c](#)).

The apparent broad global inconsistency in the stratigraphic position of trilobite LOs relative to the positive carbon isotope excursions means that careful consideration must be given to interregional correlations, which require a combination of $\delta^{13}\text{C}$ frameworks and inferred tie-points, precise radiometric dating, and biostratigraphic data. The Bayesian age modeling presented herein overcomes these limitations by anchoring the EAREZE within an integrated geochronologic and cyclostratigraphic constrained sequence providing a more robust temporal calibration.

3.7. Evaluation of the EAREZE (Excursion IV) as a global chronostratigraphic marker

Efforts to define a globally synchronous base for Cambrian Series 2 have been hindered by the diachronous nature of the trilobite first appearance datums, which vary regionally in both their absolute timing and taxonomic composition ([Geyer and Shergold, 2000](#); [Peng et al., 2012](#); [Landing et al., 2013a](#); [Zhu et al., 2019](#); [Landing et al., 2024](#)). Regional index fossils have been used to approximate the base of Cambrian Series 2, but none satisfies the key criteria for a GSSP of broad geographic distribution, consistent preservation, and near-synchronous definition between diverse paleoenvironments. Their utility is further limited by pronounced endemism, strong biofacies and taphonomic biases: these trilobites are typically restricted to inner-shelf siliciclastic settings and are rarely preserved or recoverable as

identifiable specimens in carbonate-dominated or deeper-water successions, limiting global correlation. In Morocco's continuous successions, this facies dependence likely explains the relatively young LO of identifiable trilobites, which is corroborated by undetermined trilobite remains lower in the Igoudine Formation ([Sdzuy and Geyer, 1988](#)). Such issues undermine the reliability of trilobite LOs as reliable global stratigraphic tie-lines, particularly in the lower Cambrian strata dominated by high provincialism ([Landing et al., 2013a](#)). As a result, attention has increasingly shifted toward geochemical markers, in particular carbon isotope excursions, as potential chronostratigraphic anchors. Among these, the EAREZE positive $\delta^{13}\text{C}_{\text{carb}}$ excursion has emerged as a leading candidate to help bracket the base of Cambrian Series 2. Its widespread stratigraphic expression on different paleocontinents (e.g., West Gondwana, Siberia, Avalonia, and Laurentia) below the CARE positive $\delta^{13}\text{C}_{\text{carb}}$ excursion of the South China and North China paleocontinents as well as Australia means that CARE can be used as an auxiliary marker. The temporal association of EAREZE with the later part of the early skeletal metazoan radiation, including trilobites and archaeocyaths ([Kirschvink et al., 1991](#); [Zhu et al., 2006a](#); [Kouchinsky et al., 2007](#); [Maloof et al., 2010](#); [Kouchinsky et al., 2012](#); [Betts et al., 2018](#)), highlights its importance (Fig. 7). Where both chemostratigraphic and biostratigraphic records are available, the LOs of identifiable mineralized trilobites generally occur in close stratigraphic proximity to the EAREZE peak: below in Siberia (*Profallotaspis* Zone), and apparently in the Sekwi Mountains of Laurentian northwestern Canada (i.e., earlier reported "*Fallotaspis*" interval) ([Kirschvink et al., 1991](#); [Zhu et al., 2006a](#); [Dilliard et al., 2007](#); [Kouchinsky et al., 2007](#); [Rozanov et al., 2008](#); [Betts et al., 2018](#); [Bowyer et al., 2023](#); [Yang et al., 2025](#)). In the Tiout section, the lowest determinable trilobites were collected above the EAREZE peak, but probably within the trilobite range as indicated by small, undeterminable sclerite fragments.

This temporally constrained coupling of biological and geochemical signals highlights the diagnostic utility of the EAREZE. It offers a chemostratigraphic framework against which diachronous trilobite appearances can be compared and calibrated. Its reproducibility, independence from facies control, and association with major biogeochemical reorganization - including increased carbonate platform development, possible redox shifts, and enhanced organic carbon burial, support its interpretation as a first-order perturbation in the early Cambrian ([Brasier et al., 1994](#); [Derry et al., 1994](#); [Zhu et al., 2006a](#); [Wood and Erwin, 2018](#); [Alexander et al., 2025](#)).

To sum up, the EAREZE (IV) excursion satisfies key requirements for consideration as part of the definition of a GSSP-level marker. It exhibits (1) wide geographic expression across

multiple paleocontinents; (2) a clear and reproducible geochemical signature; (3) independent confirmation across multiple stratigraphic datasets; and (4) a close temporal association with globally significant biotic transitions. The Tiout section, in particular, meets several additional criteria outlined for GSSP candidates: It is highly accessible, features an expanded and continuous sedimentary record and shows preservation with minimal tectonic deformation. Moreover, the precise age calibration of both the EAREZE and the LOs of fragmentary, unidentified and higher identifiable trilobites at Tiout provides a critical temporal anchor for synchronizing lower Cambrian successions globally.

The EAREZE is a strong candidate for bracketing the base of Cambrian Series 2 and for refining the chronology of the Cambrian Explosion. However, a GSSP of a geochronologic unit is a “golden spike” that defines a specific horizon and point at the unit’s type section, while the onset, peak, and fall of EAREZE brackets a significant stratigraphic interval at Tiout (Fig. 3). To resolve the ambiguity of the use of EAREZE/CARE in definition of a Series 2 and Stage 3 basal GSSP, [Landing et al. \(2013a\)](#) proposed the use of the peak of EAREZE (which they termed “CARE”) for interregional correlation and, specifically, the appearance of *Repinaella* at the Zhurinsky Mys section on the Lena River on the Siberian Platform ([e.g., Varlamov et al., 2008](#)) to define the base of Series 2 and Stage 3.

4. CONCLUSIONS

Resolving the global tempo and drivers of early Cambrian biological and geochemical changes requires stratigraphic sections that combine fossiliferous data, precise dating, and well-preserved environmental signals. The Tiout section in the western Anti-Atlas of Morocco meets these criteria. Through integration of our new $\delta^{13}\text{C}_{\text{carb}}$ data, biostratigraphy, high-precision CA-ID-TIMS U–Pb zircon dating, pXRF-based detrital proxies, and astrochronology, we present a comprehensive high-resolution chronostratigraphic framework for the late Terreneuvian–early Cambrian Series 2 interval.

Time series analysis of pXRF-derived log-SiO₂ and other detrital proxies reveals prominent cyclicities corresponding to Milankovitch-scale orbital forcing, including short eccentricity and precession. These results align with a previously suggested astronomical origin of the observed meter- to decameter-scale stratigraphic bundling and justify the construction of a floating astronomical time scale for the Tiout section that brackets a 4.87 ± 0.11 Myr interval. Building on our astronomical interpretation, we constructed a Bayesian age–depth model that integrates all available geochronological and paleontological data points, and major

geochemical events. This model constrains the peak of the EAREZE (excursion IV) to 520.046 +0.097/-0.095 Ma (95% HPD), provides the first direct numerical quantification of this geochemical event within a single stratigraphic framework, and embeds it in a global time scale.

The LO of identifiable trilobites in West Gondwana, recorded at Tiout by the onset of the *Hupetina antiqua* assemblage, is dated to 519.494 +0.117/-0.113 Ma, defining a ~552 kyr lag between the peak of the EAREZE and this LO event. Additionally, the Tiout age model also provides the first age estimate for the early Cambrian $\delta^{13}\text{C}_{\text{carb}}$ excursions II and III, at 522.413 +0.071/-0.07 Ma and 521.724 +0.065/-0.065 Ma, each with 95% HPD intervals of ~130–140 kyr.

The 552 kyr temporal decoupling between the onset of the EAREZE and the LO of identified is consistent with globally observed patterns: in regions such as on the Siberian Platform and Laurentian Canada, the LO of mineralized and identifiable trilobites lies slightly below the EAREZE peak, whereas the lowest determinable trilobites in the Moroccan Atlas ranges were collected above the peak (although the true onset in the Anti-Atlas appears to be lower). The slightly younger CARE first defined in South China Platform and reported on the Tarim Platform and in South Australia lies approximately at the LO of mineralized trilobites in these regions. These results enable the worldwide LOs of trilobites in the early Cambrian to be calibrated when stratigraphically associated with the EAREZE and CARE excursions.

The EAREZE meets key criteria for contributing to a GSSP-level marker for the base of Series 2 and Stage 3: (1) broad geographic distribution; (2) replicability; (3) high-resolution temporal constraint; and (4) strong evolutionary relevance. As such, the EAREZE is important for defining the base of Cambrian Series 2. However, the position of a global GSSP has to be defined within the range of EAREZE, with one multiproxy stratum suggested at the peak of EAREZE approximately at the LO of the trilobite *Repinaella* in eastern Siberia or a comparable useful candidate elsewhere. The idea of the use of a “FAD of trilobites” to define the base of Series 2 (e.g., [Zhu et al., 2019](#)) is not appropriate as the early diversification of trilobites was likely in the much older Terreneuvian and involved poorly/weakly mineralized taxa ([Paterson et al., 2019](#)) with mineralization controlled by the transition from an aragonitic to a calcitic ocean ([Porter, 2007](#); [Landing et al., 2024](#)).

Altogether, the Tiout section provides a temporally resolved, stratigraphically continuous, and geochemically calibrated reference for the early Cambrian. It significantly advances global correlation and stage boundary definition efforts by embedding fossil and new $\delta^{13}\text{C}_{\text{carb}}$ data within a high-resolution temporal framework. The Tiout model reinforces the EAREZE as a

primary chronostratigraphic anchor for the base of Cambrian Series 2 and contributes critical clarity to the tempo and structure of early animal radiation and Earth system reorganization.

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6. Supplementary

Supplementary Materials 1 – Geochemical dataset: Contains all the pXRF-derived proxies, $\delta^{13}\text{C}_{\text{carb}}$, $\delta^{18}\text{O}_{\text{carb}}$, lithological and key marker beds position.

Supplementary Materials 2 – Times series analysis scripts, full model priors, OxCal code, and posterior outputs.

Supplementary Materials 3 – Supplementary figures 1-5.

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8. Figures

9. Figures

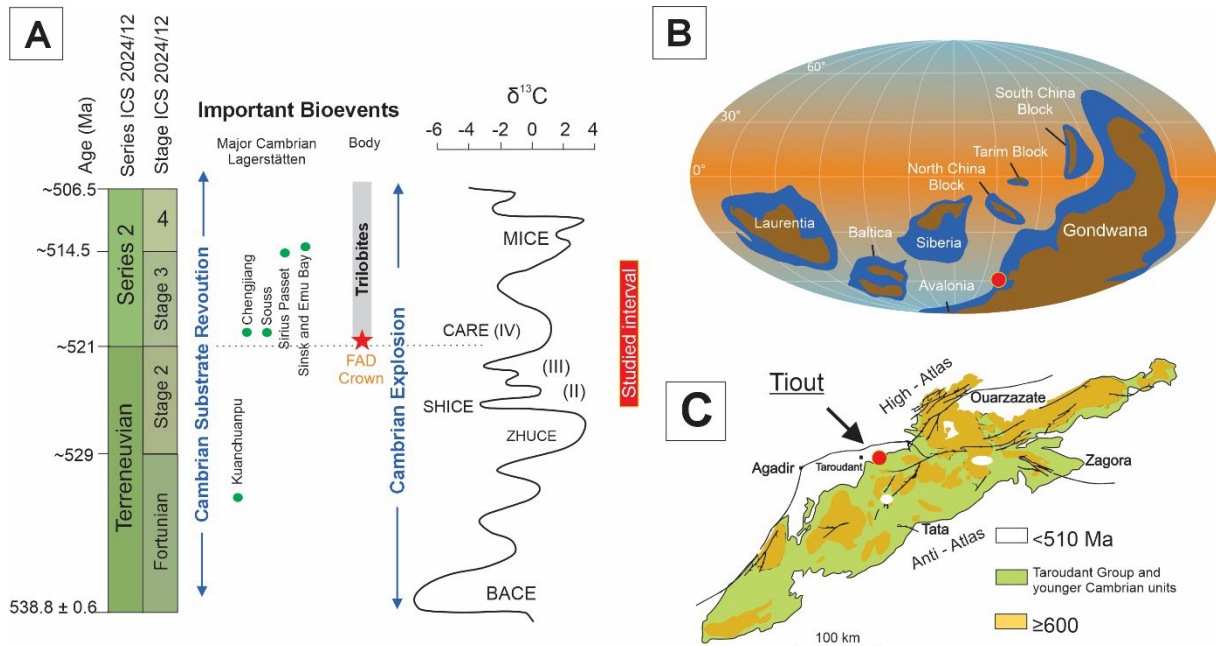


Fig. 1. Early Cambrian global composite $\delta^{13}\text{C}$ curve, biological and environmental events, paleogeographic location, and stratigraphic interval covered in this study (Marshall, 2006; Zhu et al., 2006b; Daley et al., 2018; Peng et al., 2020; Pruss and Gill, 2024). (B) Global Early Cambrian paleogeography showing the location of the study area (red dot) West Gondwana, modified from (Torsvik and Cocks, 2016; Merdith et al., 2021; Scotese, 2021). A paleogeographic alternative (Landing et al., 2022; Keppie et al., 2024) uses climate indicators (Adoudou Formation evaporites, carbonate platform development and archaeocyath reefs in the Igoudine and Amouslek) and rotation of Gondwana to place the Moroccan margin in the tropics, with Avalonia, separated from Gondwana and Baltica the only temperate paleocontinents. (C) geological map modified after Saadi et al. (1985) showing the Tiout study area within the western edge of the Anti-Atlas. Ad., Adoudou Formation. Note that the Taroudant Group records the Basal Cambrian carbon isotope Excursion (BACE).

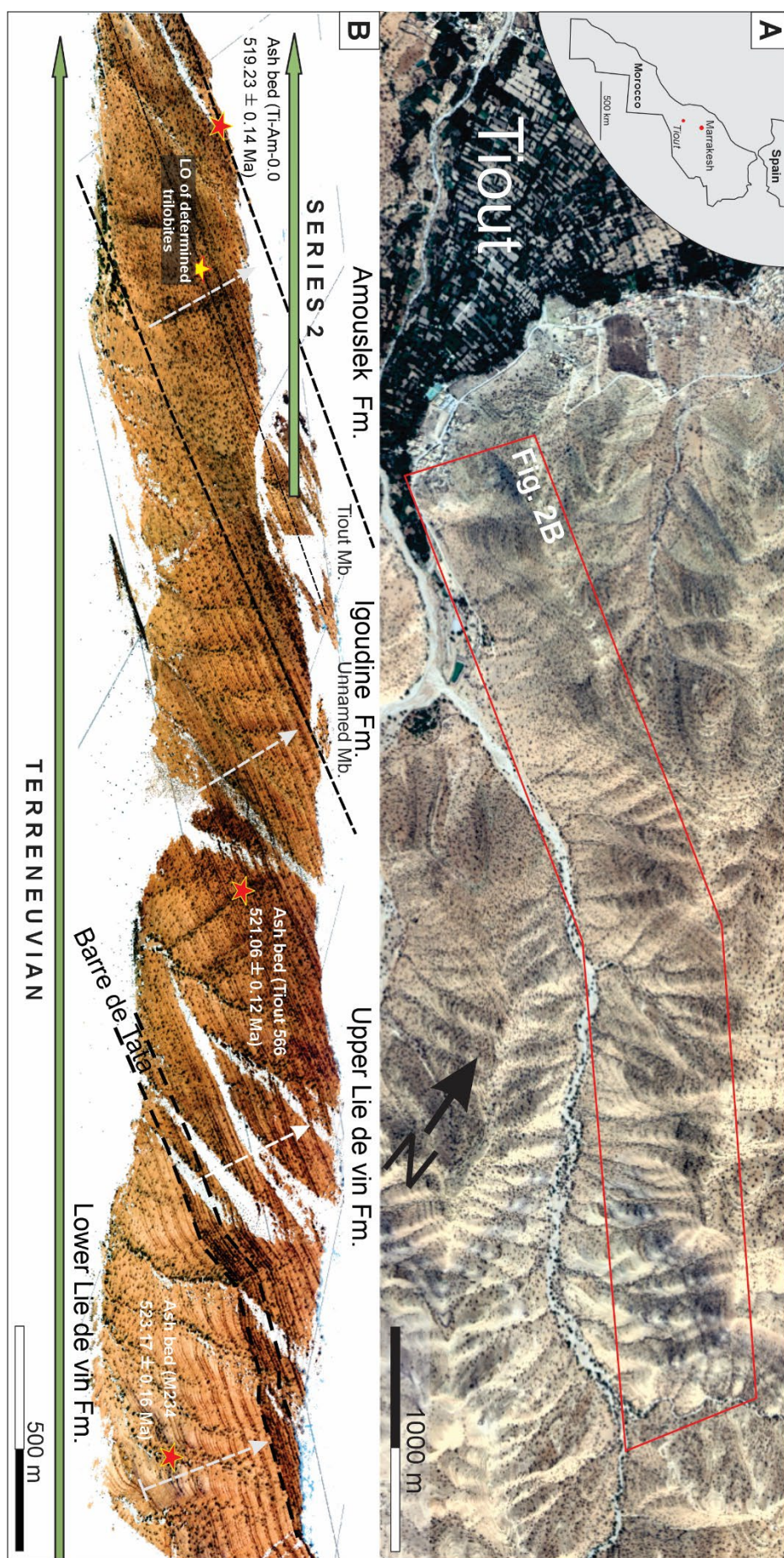


Fig. 2. Overview of the Tiout section. **(A)** Map of the study area (Tiout, Morocco) showing the section measured along the Oued irrigating the Tiout oasis. **(B)** Complete stratigraphic interval studied in Tiout (for location see inset in Fig. 2A) based on integration of multiple drone photographs. The figure shows the location of dated ash layers (Ti Am0.0, Ti-566 and M234), Formation and members boundaries from the terminal Terreneuvian to the early Cambrian Series 2. White dashed arrows represent a synthetic view of the measured stratigraphy (see Supplementary Figures 2 to see the location of each measured and sampled intervals in more detail).

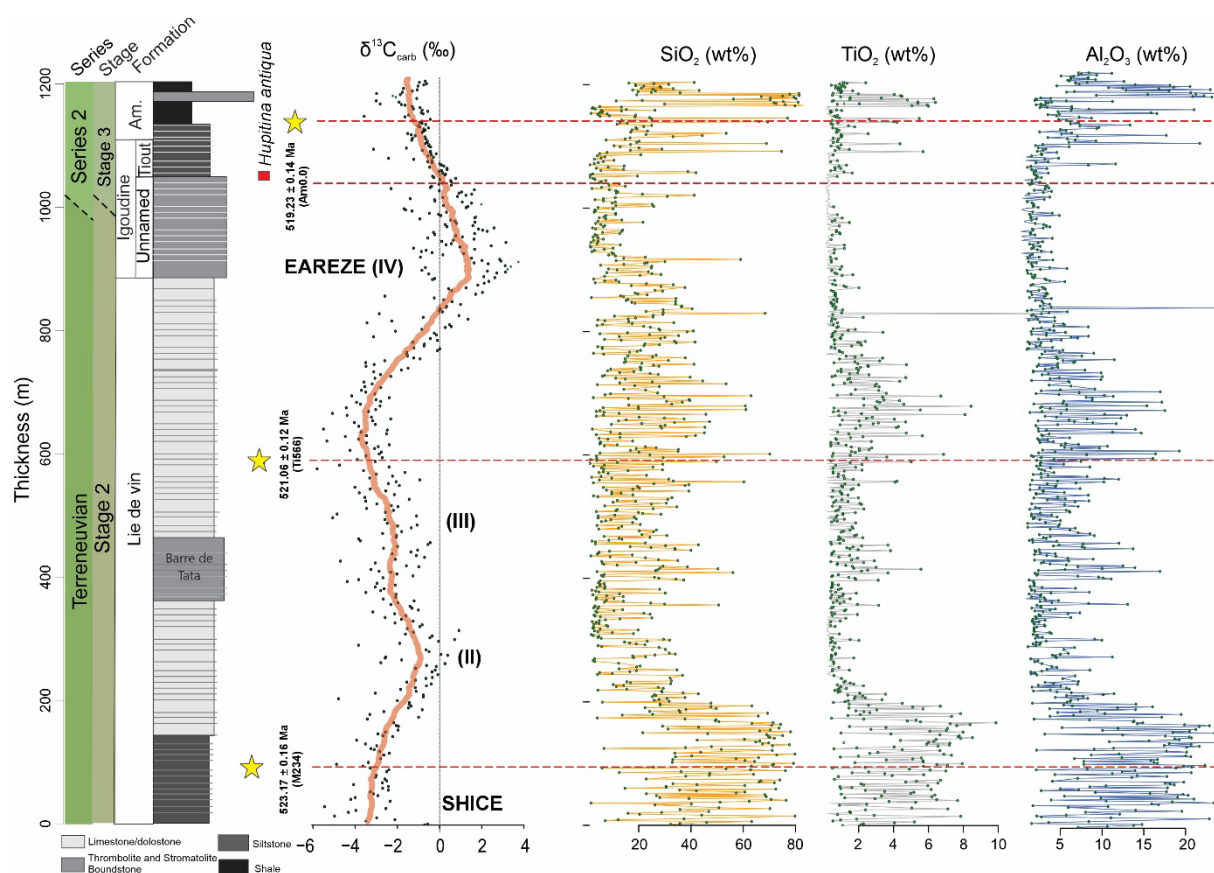


Fig. 3. Sedimentological versus chemostratigraphic profiles for the Tiout section with location of dated ash beds, the LO of identified trilobites and carbon isotope excursions (SHICE, excursion II and III and EAREZE (IV) are shown. Chemostratigraphic profiles include the $\delta^{13}\text{C}_{\text{carb}}$ (with corresponding 35 point moving average) and pXRF-derived detrital proxies SiO_2 , Al_2O_3 , K_2O assumed to represent detrital input delivery into the marine realm.

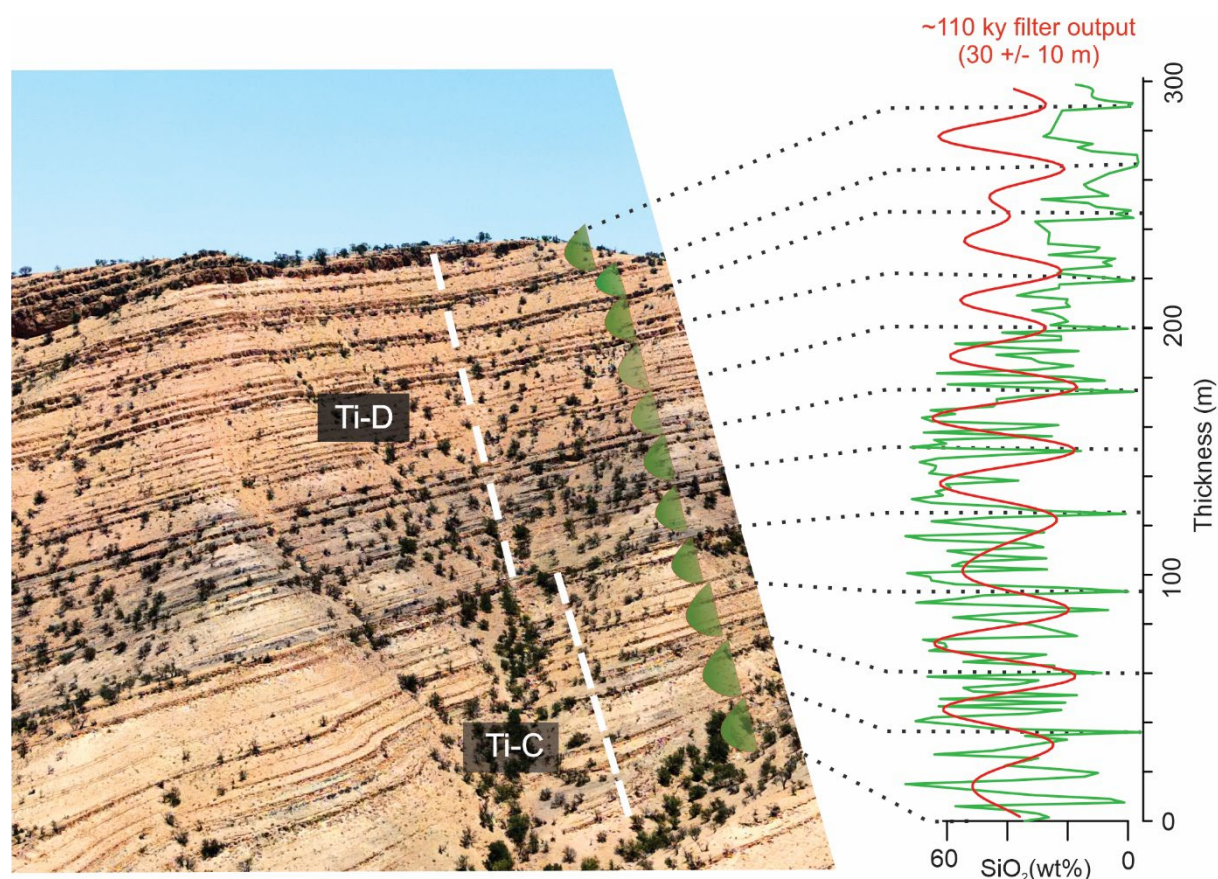


Fig. 4. Weathering versus SiO₂ profile in the lower Lie de vin Formation showing that elevated SiO₂ concentrations consistently coincide with marlstone-rich or highly weathered intervals at cyclothem scale (20–40 m). Ti-D and Ti-C and white dashed lines refer to sampled interval names used in this study (see supplementary materials for details).

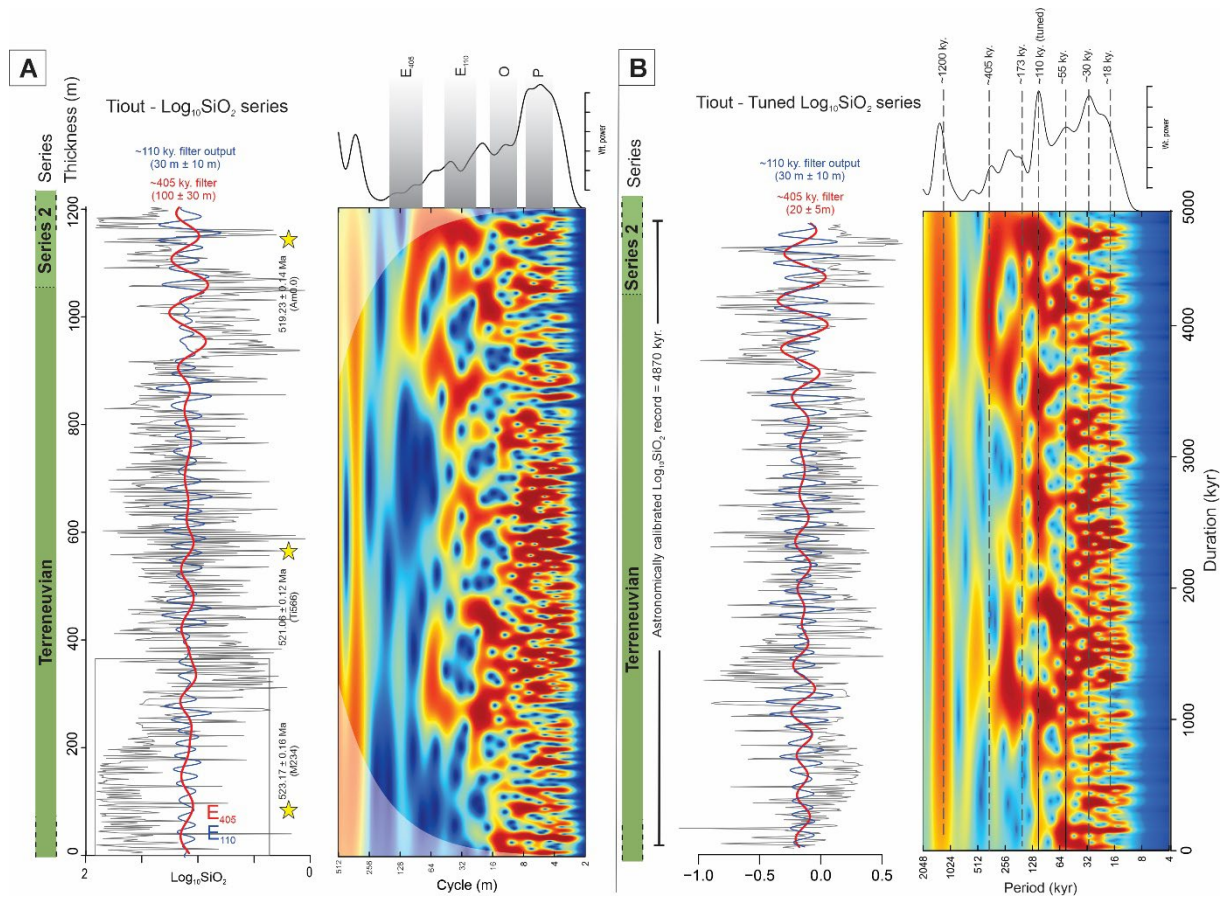


Fig. 5. (A) $\log_{10}\text{SiO}_2$ stratigraphic series with interpreted 405 kyr (E_{405} ; red), 110 kyr (E_{110} ; blue) Taner-filtered output series and location of dated ash beds (Astrochron; Meyers, 2014). CWT analysis (Arts, 2023) showing main wavelength bands expected for the Tiout section when considering that short eccentricity cycle is expressed in a 20–40 m windows. Bands are approximately ~74–147 m for the long eccentricity (405 kyr), ~5.8–11.6 m for the obliquity (~32 kyr), and ~3.3–6.7 m for precession (~18.3 kyr). These estimates are based on the predicted early Cambrian astronomical frequency ratios (22.13:3.6:1) (Laskar et al., 2004; Waltham, 2015; Farhat et al., 2022). **(B)** Short eccentricity (110 kyr) tuned $\log_{10}\text{SiO}_2$ series showing the 405 kyr (red), and 110 kyr (blue) Taner-filtered output and corresponding CWT with peak power at ~1200 kyr, ~405 kyr, ~173 kyr. ~110 kyr (tuned), ~55 kyr, ~30 kyr and ~18 kyr. Astronomical calibration for the Tiout section provides a duration estimate of 4870 ± 110 kyr.

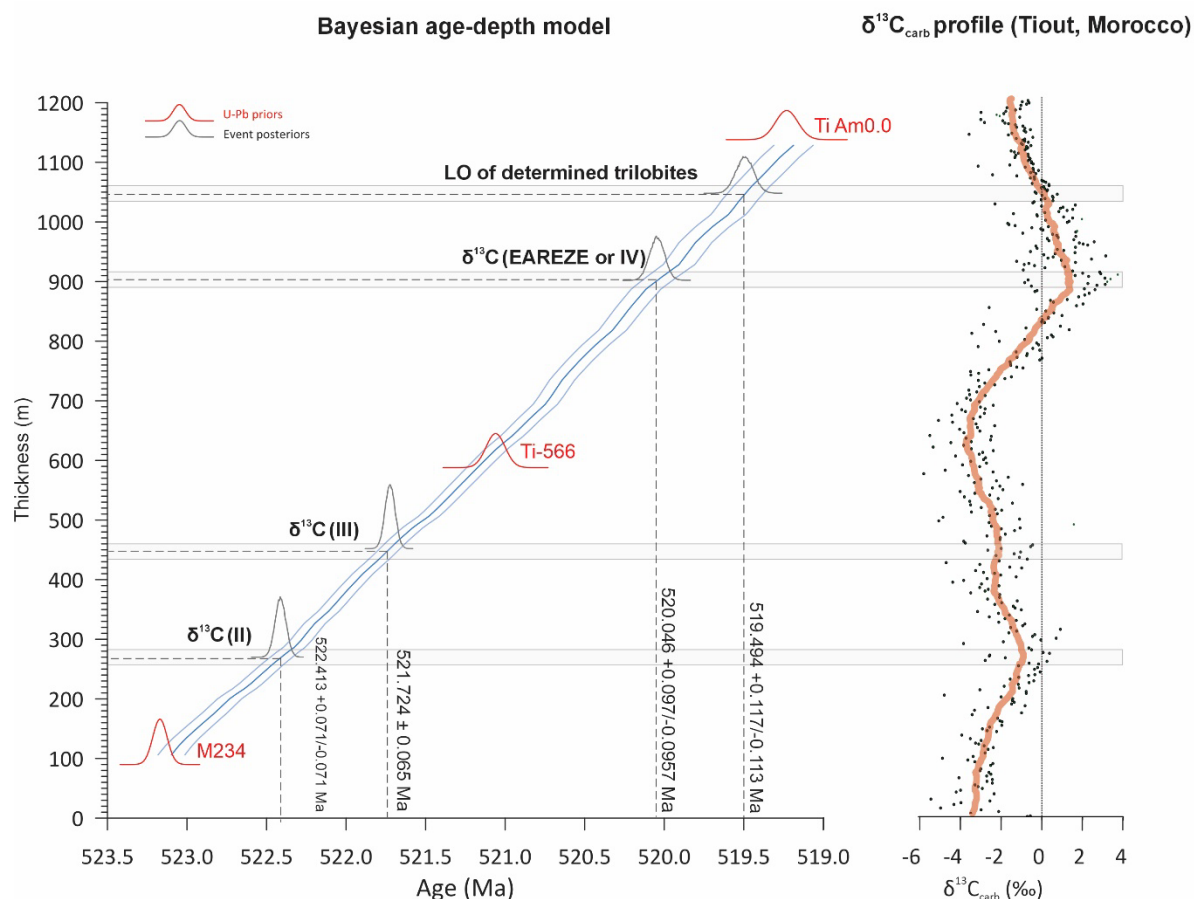


Fig. 6. Bayesian age modeling resulting from Our OxCal age-depth models for the Tiout section, Morocco against the $\delta^{13}\text{C}_{\text{carb}}$ profile. The integration of new astrochronological information from this study with the available U-Pb radioisotope age constraints provides age estimates for the several biogeochemical events within the lower Cambrian in West Gondwana. The depth scale is calculated in function of cycles depth for plotting. HPD—highest posterior distribution.

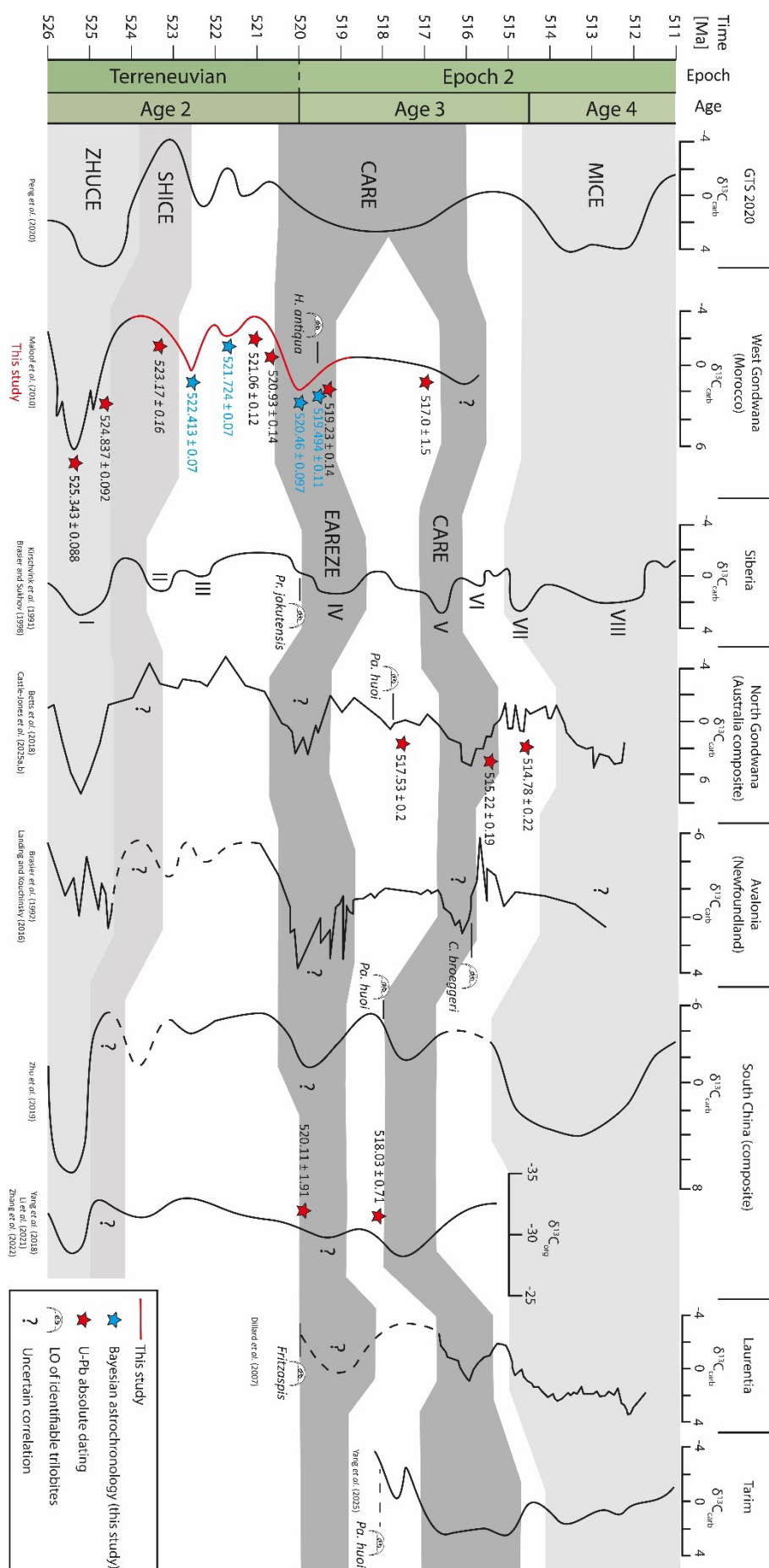


Fig. 7. Proposed global correlation scheme for the EAREZE and CARE. Tarim (Yang et al., 2025), Laurentia (Dilliard et al., 2007), South China (Yang et al., 2018; Zhu et al., 2019; Li et al., 2021; Zhang et al., 2022b), Avalonia (Brasier et al., 1992), North Gondwana (Australia composite) (Betts et al., 2018; Castle-Jones et al., 2025a; Castle-Jones et al., 2025b), Siberia (Kirschvink et al., 1991; Brasier and Sukhov, 1998), West Gondwana (Morocco)(Maloof et al., 2010). Abbreviation: *C.* – *Callavia*, *H.* – *Hupetina*, *Pa.* – *Parabadiella*, *Pr.* – *Profallotaspis*

Position in the Tiout composite section (m)	Event	Likelihood age (Ma, $\pm 95\%$ confidence interval)	Posterior age (Ma, $\pm 95\%$ HPD)	Formation/Member
88.5	Ash M234 equivalent	523.17 $\pm$ 0.16		Lie de vin/Lower
270	Excursion III		522.413 +0.071/-0.070	Lie de vin/Lower
453	Excursion III		521.72 +0.065/-0.065	Lie de vin/Lower
556.5	Ash Ti-566	521.06 $\pm$ 0.12		Lie de vin/Upper
901.5	EARZE (IV)		520.046 +0.097/-0.0957	Igoudine/Unnamed
1017.2	Trolobites sclerites		519.62 +0.11/-0.11	Igoudine/Unnamed
1048.3	LO of <i>H. antiqua</i>		519.494 +0.117/-0.113	Igoudine/Tiout
1062.9	LO Archeocyaths		519.44 +0.117/-0.113	Igoudine/Tiout
1137	Ti-Am0.0	519.23 $\pm$ 0.14		Amouslek

Table 1. Bayesian astrochronology age results for the composite Tiout section (Anti-Atlas, Morocco)