Synchronizing rock clocks in the late Cambrian

Zhengfu Zhao, Nicolas R. Thibault, Tais W. Dahl, Niels H. Schovsbo, Aske L. Sørensen, Christian M. Ø. Rasmussen & Arne T. Nielsen

The Cambrian is the most poorly dated period of the past 541 million years. This hampers analysis of profound environmental and biological changes that took place during this period. Astronomically forced climate cycles recognized in sediments and anchored to radioisotopic ages provide a powerful geochronometer that has fundamentally refined Mesozoic–Cenozoic time scales but not yet the Palaeozoic. Here we report a continuous astronomical signal detected as geochemical variations (1 mm resolution) in the late Cambrian Alum Shale Formation that is used to establish a 16-Myr-long astronomical time scale, anchored by radioisotopic dates. The resulting time scale is biostratigraphically well-constrained, allowing correlation of the late Cambrian global stage boundaries with the 405-kyr astrochronological framework. This enables a first assessment, in numerical time, of the evolution of major biotic and abiotic changes, including the end-Marjuman extinctions and the Steptoean Positive Carbon Isotope Excursion, that characterized the late Cambrian Earth.
D uring the late Cambrian, profound changes in the Earth’s oceanic physio-chemical conditions took place along with shifts in atmospheric oxygen levels. These changes coincided with biotic turnover, and conspicuous perturbations in the global carbon cycle and marine redox landscape. Precise temporal constraints are fundamental for understanding their timing, duration and links to causal mechanisms. However, compared to other Phanerozoic intervals, the ages of Cambrian stratigraphic boundaries are poorly resolved, as dated bentonite beds are rare in the Cambrian stratigraphic record. The ages currently available for the Cambrian stage boundaries were estimated simply by assuming that successive biozones represent equal time intervals. This is unlikely, however, as evolutionary turnover rates are not constant and as the uniformity in palaeontological practice for biozonal designation varies across clades and geographical occurrences.

As a further complication, global biostratigraphic correlation is hampered by the pronounced faunal provincialism at this time and as a result, stage boundaries within the Cambrian system have proven particularly difficult to ratify by the International Union of Geological Sciences.

Cyclostratigraphy is a powerful tool for refining the geological time scale, but thus far applications in the early Palaeozoic have been relatively few. Astronomically forced climate cycles expressed in sediments, when tuned to an astronomical solution, yield a high-resolution astronomical time scale. During the past two decades, the construction of an astronomical time scale has been well underway for the Cenozoic–Mesozoic eras, assisted by orbital solutions to the solar insolation on Earth. Despite the lack of complete orbital solutions prior to 50 Ma, the 405-kyr long orbital eccentricity, caused by gravitational interactions between Jupiter and Venus, is considered stable over most of Earth’s history, enabling it to be used as a reliable astronomical metronome.

Well-expressed orbital cycles have been found in 1.4 Ga Proterozoic marine sediments, assisted by orbital solutions to the solar insolation on Earth. Despite the lack of complete orbital solutions prior to 50 Ma, the 405-kyr long orbital eccentricity, caused by gravitational interactions between Jupiter and Venus, is considered stable over most of Earth’s history, enabling it to be used as a reliable astronomical metronome.

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X-Ray fluorescence core scanning of the Albjāra-1 core at 1 mm resolution yielded geochemical profiles for an array of chemical elements. Among them, we selected aluminium (Al) for cyclostratigraphic analysis because (i) Al is hosted mainly in aluminosilicates that are the predominant component of clay, and thus, highly affected by continental weathering processes, (ii) Al is hosted in insoluble phases and, thus, less sensitive to diagenetic alteration, and (iii) a previous study of other Alum Shale superzones subdivided into 31 zones based on trilobites and agnostoids and three Tremadocian zones based on graptolites, provides an important stratigraphic framework for comparison of sections across Scandinavia.

Al stratigraphic framework for the Albjāra-1 drill core has been established on the basis of the correlation of fossil, gamma-ray log patterns, and δ13Corg chemostratigraphy from multiple localities in Scania (Sweden) and on Bornholm (Denmark).

Results

The multitemporal method (MTM) spectrum of the uncalibrated Al series through the entire stratigraphic interval shows dominant wavelengths of 1.79–2.90, 0.48–0.76, 0.13–0.22 and 0.08–0.11 m (Supplementary Fig. 4a), with ratios that fit well with those of the theoretical late Cambrian orbital parameters (see Supplementary Note 2 for details). Given the variable sedimentation rates revealed by our evolutive spectrogram (evolutionary Fast Fourier transform [evoFFT]; Supplementary Fig. 4b), we conducted the cyclostratigraphic analysis in four subsets, viz. core intervals 0–18, 18–41, 41–55 and 55–74 m. These four intervals display robust peaks at ~1.85, ~2.44, ~2.78 and ~1.84 m, respectively, which are all interpreted as reflecting 405-kyr eccentricity cycles (Supplementary Fig. 4c), based on an average (compacted) sedimentation rate estimation of 4–5 mm/kyr in Scania (ref. 3; Supplementary Note 3). When 405 kyr is used to time-calibrate these stratigraphic cycles, the significant spectral peaks in addition to the 405-kyr peak indicate cycles with periods consistent with the theoretical ratio of the astronomical parameters for the late Cambrian (Supplementary Note 2). Variations in the sedimentation rate at 405-kyr scale also
Lamination cycles are closely tracked by Al concentration variations (the 178.52–181.21 m interval is shown as an example). The obliquity modulation has not been reported from the Cambrian before, but due to the extended duration of the interval studied here (~16 Myr) at a very high resolution (2–3 kyr), it could be detected and demonstrated as a significant component in our dataset. The collective array of cyclostratigraphic results, thus, confirms a strong insolation-forced imprint on the late Cambrian climate and on sedimentation in the Alum Shale basin. More details on the cycling modulation peripheries with pronounced expression at 60°–80° latitude, and Baltica was located at ~60° S palaeolatitude at this time. Amplitude modulations of the obliquity cycles reveal persistent periods at ~1.3 Myr (Supplementary Fig. 7), near the secular frequency (4k) originating from Mars and Earth’s orbital inclination variations at ~1.2 Myr. This modulation is also an important feature in Cenozoic–Mesozoic sedimentary records. This modulation periodicity has not been reported from the Cambrian before, but due to the extended duration of the interval studied here (~16 Myr) at a very high resolution (2–3 kyr), it could be detected and demonstrated as a significant component in our dataset. The collective array of cyclostratigraphic results, thus, confirms a strong insolation-forced imprint on the late Cambrian climate and on sedimentation in the Alum Shale basin. More details on the cyclostratigraphic interpretation are provided in Supplementary Note 3.
Discussion

Comparison with Milankovitch cycles published for the late Cambrian. Sørensen et al. recently reported Milankovitch cycles from a ~8.7 Myr interval across the Miaolingian–Furongian boundary in two Alum Shale drill cores, Fågeltofta-2 from eastern Scania (southern Sweden), and Billegrav-2 from Bornholm (Denmark). The 405-kyr cycles identified in the Albjära-1 core show overall an excellent match with these results. Although the previous cyclostratigraphic analysis focused on sulfur (S), a strong anti-correlation between the detrended Al and S signals (ref. 27, their Supplementary Fig. 5) facilitates correlation with the present study. Figure 2 shows a nearly perfect correlation between the three cores, which are constrained by biostratigraphy and molybdenum (Mo) trends in the overlapping intervals. The correlation points match twenty-two 405-kyr cycles (E16–E37) but with two discrepancies: in the lower Parabolina Superzone where one 405-kyr cycle (E25) in the Albjära-1 core correlates with two cycles (Pa-4 and Pa-5) in the Fågeltofta-2 and Billegrav-2 cores, and in the Agnostus pisiformis Zone, where two 405-kyr cycles (E34 and E35) in the Albjära-1 core correspond to only one cycle (Ap-1) in the Billegrav-2 core.

To investigate these discrepancies further, more detailed cyclostratigraphic analyses of the uncalibrated Al series from the lower Parabolina Superzone and the A. pisiformis Zone in the Albjära-1 core were conducted (Supplementary Fig. 8). The detailed analysis of the E25 interval of the Albjära-1 core confirms our initial interpretation (Supplementary Fig. 8a, b), but the possibility that one 405-kyr cycle is condensed or missing cannot be excluded, considering the sea-level lowstand conditions that prevail during the deposition of the lower Parabolina Superzone (Supplementary Fig. 5, and the fact that the Pa-4 and Pa-5 cycles are well expressed in the corresponding interval of the Fågeltofta-2 and Billegrav-2 cores (Fig. 2). Although the 16-Myr record represented by the Albjära-1 section provides the most complete astrochronological record, a (possible) local hiatus in the lower Parabolina Superzone suggest that dates for boundaries below the Parabolina Superzone may carry an additional error, which is included in the calculated uncertainty of the ages of biozone and stage boundaries (see section “Establishing and testing a radioisotopically anchored late Cambrian astronomical time scale”). The new data show two well-expressed E34 and E35 cycles associated with higher-frequency cycles in the A. pisiformis zone, which are well recorded in the sulfur data from that core. Apart from these two discrepancies, the antiphase relationship between the Al- and S-derived 405-kyr cycles is interrupted at cycle E37 (Ap-3 in the Billegrav-2 core) (Fig. 2). Detailed analysis of this interval revealed well-expressed higher-frequency oscillations (~32.7-kyr and ~18.5-kyr cycles) within the E37 cycle (Supplementary Fig. 8e, f), and this cycle can also confidently be correlated with that of the Al-based Ap-3 cycle in the Billegrav-2 core, as supported by correlation of the molybdenum profiles (Fig. 2). Therefore, the insolation forcing on Al may be more robust than S in this interval, because in the anoxic Alum Shale basin, S (hosted mainly in pyrite, FeS₂) is affected by the iron supply to the basin via multiple plausible sources such as benthic iron shuttle, aeolian dust and clastic input.27,40

Establishing and testing a radioisotopically anchored late Cambrian astronomical time scale. The COB age of 485.4 ± 1.9 Ma, published in the GTS201210 and GTS201645, was calculated by a spline fit of 26 radioisotopic age determinations through the late Cambrian–Early Devonian interval. In GTS2020, the number of radioisotopic dates increased to 49, and an age of 486.9 ± 1.5 Ma was recalculated for the COB.46 Nonetheless, the general scarcity of stratigraphically well-constrained age determinations in the Cambrian creates a large uncertainty for the calculated COB age. A U-Pb date of an ash bed from the uppermost Furongian Acroicrane ecorne Zone at Bryn-Ilin-fawr, North Wales, located just ~4 m below the first occurrence of planktic graptolite Rhabdina pora (traditional index fossil for the base of the Ordovician), provides a precise numerical age constraint of 489 ± 0.6 Ma.11 In GTS2020, this age was recalculated at 486.78 ± 0.53 Ma using a corrected U decay constant.47 Anchoring our 405-kyr calibrated time series to this U-Pb date, which is well within the range of the calculated age (486.9 ± 1.5 Ma) based on a spline fit of 49 radioisotopic dates from the lower Palaeozoic (cf. GTS2020), enables the construction of an anchored astronomical time scale for the late part of the Cambrian and the earliest Ordovician, spanning from 499.9 ± 0.9 to 483.9 ± 0.7 Ma (Fig. 4).

The astronomical time scale carries the following uncertainties: (i) the error of the 486.78 ± 0.53 Ma U-Pb dating of the COB; (ii) the uncertainty in precisely determining the position of the COB in the studied core based on δ¹³Corg data, as the rising limb of the COB positive excursion straddles a 0.29-m-thick interval (146.71–147.00 m), which corresponds to 0.05 Myr (i.e., ±0.03 Myr error if the COB is assumed located at 146.86 m in the middle of that interval); (iii) the assumption of a constant sedimentation rate between every two 405-kyr cycle minima; (iv) the uncertainty of spectral peak assignments in the cyclostratigraphic signal due to nonlinear climatic response that potentially caused variable time lags between orbital forcing and sedimentation cyclic expression; here, we follow the previously proposed assumption of ±0.10 Myr27; (v) the uncertainties in identifying the exact location of biozone or stage boundaries in the Albjära-1 core; these uncertainties in metres are translated into durations using the 405-kyr-derived sedimentation rate, and the resulting...
errors of which (labelled as $e_{bio}$) range between 0.07 and 0.35 Myr, see Supplementary Note 1 for details; (vi) due to the single discrepancy between the analysis of the Fågeltofta-2 core (indicating 5 cycles in the Parabolina Superzone\textsuperscript{27}) and that of the present study (4 cycles), we have adopted the average of the two studies (i.e., 4.5 cycles), and therefore added an additional error of ±0.20 Myr (half 405-kyr cycle) to all ages below the Parabolina Superzone. All in all, the uncertainties of dating the biozone and stage boundaries above and below the Parabolina Superzone are estimated to be 0.66$+e_{bio}$ ($=0.53 + 0.03 + 0.10 + e_{bio}$) Myr and 0.86$+e_{bio}$ ($=0.53 + 0.03 + 0.10 + 0.20 + e_{bio}$) Myr, respectively.

The radioisotopically anchored astronomical time scale (Fig. 4) is further constrained by two additional isotope dates. The first one is an adjusted U-Pb zircon date at 488.71 ± 1.17 Ma, based on a
The ages of the bases of the late Cambrian Jiangshanian, Paibian and Guzhangian stages are, respectively, calculated at $494.1 \pm 1.0$, $488.71 \pm 1.17$ Ma zircon date and $483.9 \pm 0.7$ Ma for the top of the Alum Shale Formation, which is part of Tøyen Formation, a few metres above the top of Alum Shale Formation. This is consistent with the estimated age of $483.9 \pm 0.7$ Ma for the top of the Alum Shale Formation, which is $\sim 2.8$ Myr older than the dated uppermost Tremadocian bentonite from Cape Breton. Hence, the few existing radioisotopic dates in the lower part of the Tøyen Formation, at Cape Breton, Canada. In Scania, the Alum Shale Formation is overlain by the Bjørkåsholmen Formation, in accordance with Henningsmoen’s scheme, but recently, the revised excursion at the Cambrian–Ordovician boundary can be confidently determined for the Albjära-1 well, which is in accordance with the biostratigraphic data at hand. Ac. Acerocarina, Pe Peltura, Rh Rhabdinopora spp., Ae Acerocare ecorne, Ws–Pc Westergaardia scanica, Acerocarina granulata and Peltura costata, Pm Parabolina heres megalops; I. f Hirsutodontus Hirsutus, C. a Cordylodus angulatus, La lapetognathus, C. i Cordylodus lindstromi, C. i Cordylodus intermedius, C. p Cordylodus proovus, C. pr Cordylodus prolindstromi, C. h Clavohamulus hintzei, C. s Hirsutodontus simplex, C. e Clavohamulus elongatus, F. i Fryxellodontus inornatus, H. h Hirsutodontus hirsutus.

The Baltoscandian astrochronology in a global context. The current study provides new and significantly more detailed temporal constraints on the palaeoenvironmental and biological changes during the late Cambrian than previously published (Fig. 5). The globally recognized Steptoean Positive Carbon Isotope Excursion (TOCE) excursion, see the section below). In Scandinavia, $\delta^{13}$C values are of potential importance for the construction of the Baltoscandian Astrochronology and the feasibility of building an astronomical time scale for the late Cambrian.
isotope excursion (post-SPICE in Fig. 5) centres at ~494 Ma with a duration of ~1.2 Myr. This excursion is similar in position and magnitude to a reported positive δ¹³C feature with an amplitude of up to 2‰ immediately above the SPICE event in carbonate successions from Siberia, Kazakhstan and Laurentia⁶⁰,⁶¹, as well as shales from Avalonia and Baltica⁸,⁶². The HERB, by some referred to as the TOCE, has been recognized in Laurentia, Gondwana, China and Baltica⁸,⁵₂,⁵³,⁶³–⁶⁷. However, whether HERB and TOCE are synonymous remains contentious⁶⁸,⁶⁹, and for this reason, we provisionally refer to the excursion as HERB/TOCE. Regardless of its name, our astrochronologic framework suggests that this excursion peaked at ~488.0 Ma (Fig. 5).

Fig. 4 Comparison between the radioisotopically anchored astronomical time scale and the international chronostratigraphic time scales. The age model was anchored to the U-Pb age of 486.78 ± 0.53 Ma for the Cambrian–Ordovician boundary¹¹,⁴⁷, and supported by the 481.13 ± 1.12 Ma for the uppermost Tremadocian²⁸,⁴⁷, and 488.71 ± 1.17 Ma for the upper Parabolina scarabaeoides Zone²⁹,⁴⁷. The 405-kyr long orbital eccentricity cycles (red curve) were extracted using a bandpass Taner filter (passband: 0.00247 ± 0.00055 cycles/kyr).
Fig. 5 Temporal correlation of late Cambrian–earliest Ordovician biotic and abiotic events calibrated to the Baltoscandian radioisotopically anchored astrochronological framework. Elevated extinction rates coincide with extreme heat and high sea level, whereas the rapid Jiangshanian rebound occurs at ~492 Ma while temperatures were lower. Generic richness data based on refs. 5,88; δ13Corg data from the Albjära-1 core in this study and δ13CCarb curve from GTS202049. Temperature data based on ref. 74 with blue shading denoting the current tropical sea surface temperature range, red above that window. Sea-level curve adopted from ref. 5. The base of Stage 10 defined as in Fig. 1. Blue and orange shaded intervals represent Scandinavian biozones as shown in Fig. 2 except the abbreviation Ac Acerocarina Superzone.
refined temporal framework serves to clarify the timing and relationship between the major late Cambrian carbon cycle perturbations, environmental changes, and biotic turnovers.

During the latest Miaoliangian–earliest Furongian, loss of richness among shelf faunas has been reported from both south-western marginal Laurentia \(^{70-72}\), South China \(^{7,72}\), as well as in global compilations \(^{73}\). The event is known as the end-Marjumanian extinctions, and it partially overlaps with the onset of the SPICE event \(^{73}\). Our temporal compilation of the rates of biotic and abiotic events (Fig. 5) shows that as extinctions peaked during the latest Miaoliangian, sea water temperatures and sea level were both at their late Cambrian maximum. Late Cambrian–Early Ordovician extreme heat has been suggested by, for instance, clumped isotope evidence \(^{42,75}\). This “hyper-warming” is proposed resulting from increasing global insolation due to major eustatic rise and marine onlap of cratons, which probably reduced ocean circulation, lowered oceanic oxygen solubility and promoted epeiric sea anoxia \(^{76}\). This extreme warming interval straddles four 405-kyr cycles (E34–E37) of the Agnote boreform zone in Baltic. Hereafter, twelve 405-kyr cycles follow from E33 to E22 that encompass the Paibian Olenus Superzone and Jiangshanian Parabolina Superzone before a rapid burst in generic richness occurred during the short Leptoplostus Superzone spanning only 1.3 405-kyr cycles (i.e., ~500 kyr). This rapid rebound appears to have occurred at least ~4.8 Myr after the extinctions and coincides with isotopic evidence for a dramatic ocean cooling in the palaeo-tropics to temperatures the extinctions and coincides with isotopic evidence for a Superzone spanning only 1.3 405-kyr cycles (i.e., ~500 kyr). This burst in generic richness occurred during the short cycles follow from E33 to E22 that encompass the Paibian Superzone and Jiangshanian Parabolina Superzone before a rapid burst in generic richness occurred during the short Leptoplostus Superzone spanning only 1.3 405-kyr cycles (i.e., ~500 kyr). This rapid rebound appears to have occurred at least ~4.8 Myr after the extinctions and coincides with isotopic evidence for a dramatic ocean cooling in the palaeo-tropics to temperatures similar to the modern equatorial range \(^{74}\) (Fig. 5). The richness burst peaked during the Protobetula Superzone and coincided with a sea-level rise (Fig. 5).

This calibrated 405-kyr framework thus presents a first step towards establishing a well-constrained temporal perspective on the late Cambrian world. Further investigations are needed to understand why the rates of biotic turnover, as well as the environmental determinants, apparently fluctuated so rapidly during the studied interval.

Methods

**XRF-core scanning.** Albjära-1 is a fully cored shallow scientific well with a total depth of 237.40 m made by the University of Copenhagen and the Geological Survey of Denmark and Greenland. The drill site is located about 5 km NE of the small town Svalöv in Scania, Sweden, and the approximate coordinates are 55°56’9.03”N 13°10’42.52”E. The core diameter is 55 mm and the core recovery was essentially 100%. The Alum Shale Formation was penetrated between 135.12 and 232.50 m below ground level at the drill site. The bulk elemental composition of the Alum Shale Formation was measured at the Geological Survey of Denmark and Greenland using a handheld Niton \(^{90}\) XRF device (HH-XRF) equipped with an Ag anode. Each measurement lasted for 120 s at a 30 kV voltage and 200 mA current. The scanned area is about 5 mm in diameter. In total, 175 shale samples were measured, including 30 from two unbroken intervals (166.25–166.42 and 166.53–166.72 m) for calibration with the XRF-CS concentration (Supplementary Fig. 2), and 145 from broken intervals. The Al concentrations measured by the HH-XRF and XRF-CS methods show a good correlation with Pearson correlation coefficient (\(r^2\)) values of 0.93 (Supplementary Fig. 2). Based on the fitted curve, the HH-XRF data were corrected and a complete Al series along the entire length of the core was obtained.

**Organic carbon isotopes.** 366 Alum Shale powder samples devoid of visible macroscopic pyrite concretions, calcite veins and limestone intercalations were collected using a low-speed micro-drill across the studied interval in the Albjära-1 and Gislovhammer-2 cores. Appropriate amounts (~15 mg) of powder were loaded into open silver-foil capsules. The samples were decarbonated in a vacuum desicator (5 L) by using concentrated (12 M) hydrochloric acid fumigation for 48 h. Subsequently, the carbonate-free residue was rinsed with deionized water to get a nearly neutral pH. After drying at a temperature of 45°C for 4 h, the samples with silver-foil capsules were transferred to tin combustion cups and closed. The stable carbon isotope analysis was performed at the University of Copenhagen, using an elemental analyzer (CE1110, Thermo Electron, Milan, Italy) connected to an isotope ratio mass spectrometer (IRMS; Finnigan MAT Delta Plus, Thermo Scientific, Bremen, Germany). The analytical precision was maintained at ±0.08‰ (SD) based on replicated analyses of certified reference material of loamy soil (calibrated by Elemental Microanalysis, Oxford, UK). All data are reported in the delta notation (\(\delta^{13}C_{\text{org}}\)) relative to the international standard Vienna Pee Dee Bellemite.

**Time series methods.** The uncalibrated elemental data were first smoothed every 12 measuring points, corresponding to ~2–3 kyr temporal resolution (12 mm). This procedure enhances the signal to noise with minimal risk of overlooking Milankovitch cycles \(^{79}\), and translates into a longer exposure time (120 s) sufficient for semi-quantitative analysis of detectable elements \(^{79}\). Long-term trends in the uncalibrated Al data were removed by subtracting an 8% and 35–80% weighted average (LOESS) from the data series of the entire and four subsets (0–18, 18–41, 41–55, 55–74 m), respectively. Power spectral analysis was performed using the MTM \(^{35}\), with confidence levels of 90%, 95%, 99% and 99.9% calculated from a robust AR(1) noise model \(^{80}\). The power decomposition method \(^{81}\) was applied to identify frequency changes due to sedimentation rate variations \(^{82}\). By identifying long orbital eccentricity cycle nodes and defining equal time spans of 405 kyr between every two minima, the sedimentation rate was calculated and compared to the results of the eCO3 function \(^{83}\). All cyclostratigraphic tools are from the software Acycle 2.1 for cyclostratigraphy \(^{4}\) except for the Taner filter used for isolating potential astronomical parameters (the script of the latter is shared by Linda Hinnov at http://mason.gmu.edu/~lhinno/cyclotools/tanerfilter.m). Further details of data handling are presented in Supplementary Note 3.

**Data availability.** The geochemical data used in this study are provided in the Supplementary Data file. Source Data are provided with this paper.

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**References.**

1. Saltzman, M. R. et al. Pulse of atmospheric oxygen during the late Cambrian. *Proc. Natl Acad. Sci. USA.* 108, 3876–3881 (2011).
2. Gill, B. C. et al. Geochemical evidence for widespread euxinia in the Later Cambrian ocean. *Nature* 460, 80–83 (2011).
3. Dhal, T. W. et al. Uranium isotopes distinguish two geochemically distinct stages during the later Cambrian SPICE event. *Earth Planet. Sci. Lett.* 401, 313–326 (2014).
Saltzman, M. R., Edwards, C. T., Adrain, J. M. & Westrop, S. R. Persistent oceanic anomaly and elevated extinction rates separate the Cambrian and Ordovician radiations. *Geology* 43, 807–810 (2015).

Rasmussen, C. M. Ø., Kröger, B., Nielsen, M. L. & Colmenar, J. Cascading trend of Early Paleozoic marine radiations paused by Late Ordovician extinctions. *Proc. Natl Acad. Sci. USA* 116, 7207–7213 (2019).

Fan, X. J. et al. A high-resolution summary of Cambrian to Early Triassic marine invertebrate biostratigraphy. *Science* 367, 272–277 (2020).

Zhang, S. H., Fan, J. X., Morgan, C. A., Henderson, C. M. & Shen, S. Z. Quantifying the middle–late Cambrian trilobite diversity pattern in South China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 570, 110361 (2021).

Zhao, Z. et al. High-resolution carbon isotope chemostratigraphy of the middle Cambrian to lowermost Ordovician in southern Scandinavia: implications for orbital correlation. *Glob. Planet. Change* 209, 103751 (2022).

Peng, S. C., Babcock, L. E. & Ahlberg, P. The Cambrian Period. in Zhang, S. H., Fan, J. X., Morgan, C. A., Henderson, C. M. & Shen, S. Z. Quantifying the middle–late Cambrian trilobite diversity pattern in South China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 570, 110361 (2021).

Cooper, R. A., Sadler, P. M., Hamer, O. & Gradstein, F. M. The Ordovician Period. in *Geologic Time Scale 2012* (eds Gradstein, F. M., Ogg, J. G., Schmitz, M. D. & Ogg, G. M.) 469–523 (Elsevier, Amsterdam, Netherlands, 2012).

Landing, E. et al. Cambrian–Ordovician boundary age and duration of the lowest Ordovician Tremadoc Series based on U–Pb zircon dates from Avalonian Wales. *Geol. Mag.* 137, 485–494 (2000).

Hinnov, L. A. Cyclostratigraphy and its revolutionizing applications in the earth and planetary sciences. *Geol. Soc. Am. Bull.* 125, 1703–1734 (2013).

Hinnov, L. A. Cyclostratigraphy and astrochronology In 2018. in *Stratigraphy and Time Scales Vol. 3* (ed Montenari, M.) 1–80 (Academic Press, Amsterdam, 2018).

Berger, A. & Loutre, M. F. Astronomical theory of climate change. *J. de Phys. IV* (Proc. 121, 1–37 (2004).

Wu, H. C. et al. Time-calibrated Milankovitch cycles for the late Permian. *Nat. Commun.* 4, 1–8 (2013).

Hinnov, L. A. & Hågæn, F. J. Cyclostratigraphy and astrochronology. In *Geologic Time Scale 2012* (eds Gradstein, F. M., Ogg, J. G., Schmitz, M. D., & Ogg, G. M.) 63–83 (Elsevier, Amsterdam, Netherlands, 2012).

Laskar, J. et al. A long-term numerical solution for the insolation quantities of the Earth. *Astron. Astrophys.* 428, 261–285 (2004).

Laskar, J., Fienga, A., Gastineau, M. & Manche, H. La2010: a new orbital solution for the long-term motion of the Earth. *Astron. Astrophys.* 532, A89 (2011).

Berger, A., Loutre, M. F. & Laskar, J. Stability of the astronomical frequencies over the earths history for paleoclimatic studies. *Science* 255, 560–566 (1992).

Zhang, S. C. et al. Orbital forcing of climate of 1.4 billion years ago. *Proc. Natl Acad. Sci. USA* 112, E1406–E1413 (2015).

Meyers, S. R. & Malinverno, A. Proterozoic Milankovitch cycles and the history of the solar system. *Proc. Natl Acad. Sci. USA* 115, 6386–6386 (2018).

Lotagnostus americanus: new information on the uppermost Cambrian (Stage 10): FAD of the conodont Eoconodontina notchebackii and the Lawsonian Stage. In *The 15th Field Conference of the Cambrian Stage Subdivision Working Group* (eds Fatka, O. & Budil, P.) 18 (Czech Geological Survey, Prague, 2010).
proxy series with evolutionary correlation coefficients and hypothesis testing. Earth Planet. Sci. Lett. 501, 165–179 (2018).

44. Li, M. S., Hinov, L. A. & Kump, L. R. Acrin: time-series analysis software for paleoclimate research and education. Comput. Geosci. 127, 12–22 (2019).

45. Scotese, C. R. Atlas of Cambrian and Early Ordovician Paleogeographic Maps (Mollweide Projection), Maps 81–88, Volumes 5, The Early Paleozoic, PALROMAP Atlas for ArcGIS, PALROMAP Project, Evanston, Ill. (2014).

46. Miller, J. F., Evans, K. R., Freeman, R. L., Ripperdan, R. L. & Taylor, J. F. The proposed GSSP for the base of Cambrian Stage 10 at the First Appearance Datum of the conodont Eocnochondrites notchpeakensis (Miller, 1969) in the House Range, Utah, USA. GFF 136, 189–192 (2014).

47. Wang, X. F. et al. Correlating the global Cambrian-Ordovician boundary: precise comparison of the Xiaoyangqiao section, Dayanrnga, North China with the Green Point GSSP section, Newfoundland, Canada. Palaeoworld 28, 243–275 (2019).

48. Kröger, B., Francke, F. & Rasmussen, C. M. Ø. The evolutionary dynamics of the early Paleozoic marine biodiversity accumulation. Proc. R. Soc. B 286, 20191634 (2019).

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