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Ordovician cyclostratigraphy and astrochronology



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Abstract: Cyclostratigraphy is an important tool for understanding astronomical climate forcing and for reconstructing geological time in sedimentary sequences, provided that an imprint of insolation variations caused by Earth's orbital eccentricity, obliquity and precession is preserved (Milankovitch forcing). Understanding astronomical climate forcing has proven fundamental for the study of Cenozoic climate systems and the construction of high-resolution continuous time scales (astrochronologies). Pre-Cenozoic astrochronologies face several challenges: (1) uncertainties in the deep-time astronomical solutions and parameters; (2) less complete and less well preserved strata; and (3) the sparsity of geochronologic anchor points. Consequently, Paleozoic astrochronologies are typically based on identification of the stable 405 kyr eccentricity cycle instead of shorter astronomical cycles. Here, a state-of-the-art review of Ordovician cyclostratigraphy and astrochronology is presented, as well as suggestions on their robust application in an Ordovician context. Ordovician astronomically driven climate dynamics are suggested to have influenced processes like glacial dynamics, sea-level variations and changes in biodiversity. Ordovician cyclostratigraphic studies can help to construct high-resolution numerical time scales, ideally in combination with high-quality radio-isotopic dating. As such, cyclostratigraphy is becoming an increasingly important part of an integrated stratigraphic approach to help disentangle Ordovician stratigraphy and palaeoenvironmental changes.

Cyclostratigraphy is a subdiscipline of stratigraphy dealing with the study of cyclic variations in the stratigraphic records (Strasser *et al.* 2006; Hinnov 2013, 2018; Meyers 2019; Laskar 2020). Of particular interest is the preserved record of the variations of astronomical parameters of the Earth's orbital eccentricity, obliquity and precession. The continuously changing position and orientation of the Earth relative to the Sun is a direct driver of climate change as it controls the amount and distribution of solar energy throughout the year (i.e. astronomical climate forcing). There are many examples of astronomical climate forcing, like the well-studied pacing of the Pleistocene ice ages (e.g. 'Milankovitch cycles'; Milankovitch 1941; Hays *et al.* 1976). Many of these astronomically forced climatic changes can influence sedimentary dynamics (e.g. via sea-level changes linked to global ice volumes) or can be recorded in the geochemical composition (e.g. isotope ratios) of the sediments we study today. By doing so, we can learn more about the past sedimentary and palaeoenvironmental dynamics. In addition, because of the very regular character of the astronomical cycles, they can also be used as a tool to

construct high-resolution time scales. It is also becoming apparent that the geological record of astronomical cycles can be used to reconstruct the history of Solar System dynamics (e.g. Meyers and Malinverno 2018; Olsen *et al.* 2019). This chapter (i) briefly introduces the main concepts of cyclostratigraphy and astrochronology, and particular challenges in an Ordovician context; (ii) presents an overview of existing Ordovician cyclostratigraphy literature; (iii) discusses some examples and possible research strategies; and (iv) concludes with providing suggestions and practical tools for how to proceed in the future.

Main concepts and Ordovician challenges

The redistribution of solar energy is the engine of the Earth's climatic system, which redistributes this energy latitudinally as well as vertically. Throughout geologic history, the total amount of insolation, as well as its seasonal and latitudinal distribution, varied periodically on 10⁴- to 10⁶-year time scales (Milankovitch 1941; Hays *et al.* 1976; Laskar 2020).

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These variations result from the quasi-periodically alternating astronomical parameters: eccentricity, precession and obliquity (Fig. 1). Eccentricity measures the deviation of the Earth's orbit from a perfect circle and varies rhythmically, with main periodicities around *c.* 100 and 405 kyr (Berger 1978). As the Sun is situated in one of the two focal points of the ellipse that represents the orbit of the Earth, changes in eccentricity will change the distance between the Earth and the Sun. As such, eccentricity is the only astronomical parameter that affects the total solar energy the Earth receives over a year. However, this change is very small compared to the amount of total solar energy received. Changes in eccentricity also influence the duration of the seasons. Precession is the result of the change in orientation of the Earth's axis (Fig. 1). Astronomical precession describes the precession of the Earth's rotation axis, which has a present period of *c.* 26 kyr relative to the fixed stars. The orientation of the Earth's axis is important, for example, when the Earth stands on its most distant position from the Sun (aphelion) and on its closest position (perihelion). The precession determines the timing and location of the seasons with respect to the Earth's orbit (e.g. short, hot v. long, warm summers). When the Earth's orbit is more circular (role of eccentricity), the difference between aphelion and perihelion will be smaller than when the Earth's orbit is more elliptical. So, although eccentricity is the only parameter

that directly influences the absolute amount of energy received by the Earth from the Sun, its main climatic influence is the modulation of the precession. The terms 'climatic precession' or 'precession index' consider both the influence of eccentricity and the longitude of the perihelion, and have present main periods of *c.* 24, 22 and 19 kyr (Berger 1978). It is often stated that the precession is 'amplitude-modulated' by the eccentricity, which is one of the typical characteristics of an astronomical signal. Obliquity, or tilt, is defined as the angle between the Earth's rotational axis and the normal to the plane of the Earth's orbit – at present value of 23.5° (Fig. 1). Obliquity controls the annual course of the declination, the angle of incoming solar energy and the length of the day. As such, the obliquity is the reason why the Earth has different seasons. In the Northern Hemisphere (NH) summer, the NH is orientated towards the Sun and receives relatively more energy than the Southern Hemisphere (SH). The effect of this parameter on seasonality increases towards the poles and with an increasing value for the tilt. Berger (1978) determined the present main period of obliquity to be *c.* 41 kyr, with its angle in the Quaternary varying between 22.0 and 24.5°.

The durations of the astronomical cycles vary through geological time (Berger *et al.* 1992; Berger and Loutre 1994; Laskar *et al.* 2004; Waltham 2015). The 'Astrochronology' chapter of *The Geological*

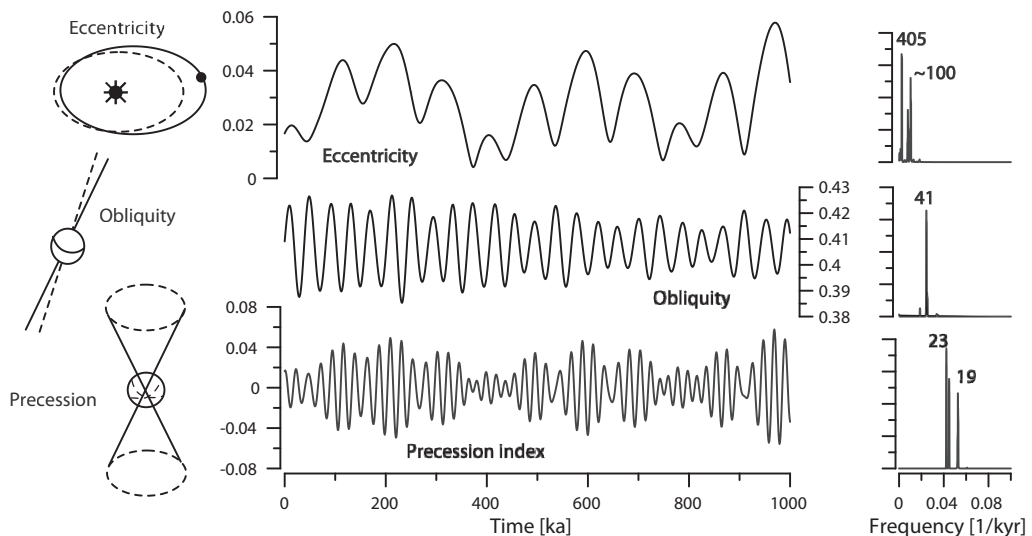


Fig. 1. Evolution of the three astronomical parameters (eccentricity, obliquity and precession) over the last million years in the time domain (middle panels) as well as in the frequency domain (right-hand panels). Their main present-day periodic components are: 405 and *c.* 100 kyr for eccentricity; 41 kyr for obliquity; and 24, 22 and 19 kyr for precession. ka, thousand years ago; kyr, thousand years duration. Source: adapted from <http://www.cyclostratigraphy.org>.

Time Scale 2020 (GTS2020) provides a detailed state-of-the-art overview on various aspects of these variations through time (Laskar 2020). The eccentricity largely depends on the motion of the planetary bodies in the Solar System and their stable or chaotic behaviour (Laskar 1989; Laskar *et al.* 2004, 2011; Zeebe 2017; Zeebe and Lourens 2019; Laskar 2020; Hoang *et al.* 2021). The g_i s and s_i s represent the secular frequencies of the planets (i ; $i = 1$ for Mercury, etc.) in our Solar System and are related to the deformation and inclination of the respective planets' orbital planes by gravitational forces (Laskar *et al.* 2004). The main eccentricity period of 405 kyr depends on the g_2 – g_5 term (Venus and Jupiter) and is the most stable one. Because of its stability, the 405 kyr eccentricity cycle is also called a 'metronome' and is even suggested as a basis for defining formal 'astrochronozones' (Hilgen *et al.* 2020). Looking at different eccentricity solutions, there is only a small drift of less than one 405 kyr period over the last 250 myr or from the present time to the end of the Permian (Laskar 2020). Thus, for the Ordovician, we do not know from the astronomical solutions what the precise eccentricity configuration is for a specific moment in time, but the period of the 405 kyr cycle seems to have been very stable. Based on more recent observations, it seems that also the obliquity has a longer relatively stable period of *c.* 173 kyr (e.g. Huang *et al.* 2021), which could be an additional 'metronome' to consider. What is often referred to as the '100 kyr eccentricity cycle' actually consists of many different eccentricity periods, with durations around 100 kyr, that are thought to have had a similar average *c.* 100 kyr duration during the Ordovician. Both eccentricity and obliquity have so-called 'very long Milankovitch cycles' or 'grand cycles' that correspond to their main long-term modulation terms, and for the last 50 million years have respective periods of 2.4 (g_4 – g_3) and 1.2 myr (s_4 – s_3) (Laskar 2020). An important note is that these 2.4 myr eccentricity and 1.2 myr obliquity cycles did not necessarily have the same durations during the Ordovician due to the chaotic behaviour of the Solar System (Laskar 1989; Ma *et al.* 2017; Olsen *et al.* 2019; Hoang *et al.* 2021).

A major cause for changes in periods of precession and obliquity is the dynamics of the Earth–Moon system (Berger and Loutre 1994; Laskar *et al.* 2004; Waltham 2015). The Moon recedes from the Earth, but the speed with which this happens is not constant over time, as is evident from interpretations of various geological archives such as corals and tidalites (Williams 2000). The gravitational force exerted by the Moon on the Earth's tidal bulge produces a torque in the opposite direction of the Earth's rotation, and so it slows down the rotation of the Earth. This slowing down of the Earth's rotation causes the length of day on Earth to increase

through time. The shorter Earth–Moon distance in the past was also important for the duration of the precession and obliquity periods. For example, Berger and Loutre (1994) predicted main precession periods of *c.* 16 and *c.* 19 kyr, and a main obliquity period of *c.* 31 kyr for 440 Ma (Fig. 2). There are several reconstructions back in time (Berger and Loutre 1994; Laskar *et al.* 2004; Waltham 2015) that in general show the same trends but have some differences in precise numbers and uncertainties. An important application of cyclostratigraphic research is now to reconstruct this Earth–Moon history using geological observations based on, for example, corals, bivalves, tidalites and astronomical cycles (e.g. Williams 2000; Meyers and Malinverno 2018). One consequence of having relatively stable eccentricity cycle periods and shorter Ordovician precession and obliquity cycles is the changed expected ratios between the various astronomical components (e.g. Waltham 2015). The respective current day precession to eccentricity ratio is about 1:5, while for the Ordovician it was closer to 1:6. On the other hand, if both the *c.* 100 and 405 kyr eccentricity cycles remained relatively stable, they maintained their 1:4 ratio.

From an astronomical theoretical perspective, we thus have reason to assume that an astronomical forcing existed during the Ordovician, with the eccentricity period durations of 405 and *c.* 100 kyr probably being similar to today (but with unknown phases), while the periods of obliquity and precession were shorter, with some uncertainty according to the different available models (Fig. 2). The Ordovician duration of the very long 2.4 and 1.2 myr cycles is uncertain because of the chaotic behaviour of the Solar System. Not knowing the exact astronomical configuration at a certain moment in time makes it impossible to derive an absolute age for an Ordovician record by solely matching geological observations to an astronomical solution (i.e. astronomical tuning). It is, however, possible to identify

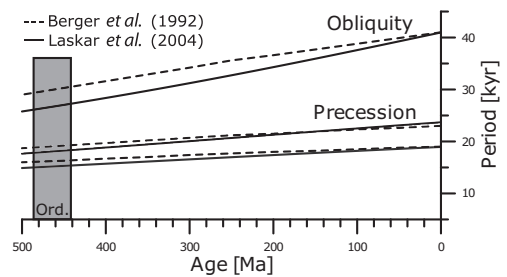


Fig. 2. Evolution of the main obliquity and precession periods in the last 500 myr according to Berger *et al.* (1992) and Laskar *et al.* (2004). Grey shaded area indicates Ordovician Period. Source: adapted from <http://www.cyclostratigraphy.org>.

and count cycles, construct floating astrochronologies and make duration estimates for intervals of strata. Floating astrochronologies can be anchored in absolute time if they can be reliably integrated with radio-isotopic ages, ideally state-of-the-art chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA–ID–TIMS) dates of volcanic zircons (see [McLaughlin *et al.* this volume, in press](#)). The relative paucity of such absolute age constraints is a challenge for the Ordovician.

Another challenge is the nature of the Ordovician stratigraphic archive. Classical cyclostratigraphy studies are typically conducted using open marine pelagic deposits (e.g. [Westerhold *et al.* 2020](#)), which are virtually absent in the Ordovician stratigraphic record. Many of the preserved sections are shallow-marine, and are more prone to be less complete and show larger variations in, for example, accumulation rates. Most numerical cyclostratigraphic analysis techniques assume complete continuous records without major changes in accumulation rates or depositional environments ([Hilgen *et al.* 2015](#)). However, it is not always straightforward to assess if single sections are complete at the scale of sedimentary cycles linked to orbital forcing of climate; [Weedon \(2003\)](#) addresses some of the consequences of this unknown information in the context of spectral analysis. Therefore, there is a need to explore new ways of identifying astronomical cycles in less traditional archives using a broader range of analysis techniques ([Noorbergen *et al.* 2018](#); [Lantink *et al.* 2019](#); [Montanez 2021](#); [Sinnesael *et al.* 2022](#)). In general, the preservation of many Ordovician records is also potentially affected by long histories of metamorphism or diagenesis. A particular lithofacies within the context of cyclostratigraphy and diagenesis are limestone–marl alternations ([Amberg *et al.* 2016](#); [Cho and Hong 2021](#)). These are often used for cyclostratigraphic interpretations, assuming a primary control of astronomical climate forcing, but it has also been demonstrated that these alternations can be the result of purely diagenetic processes (e.g. [Hallam 1964](#); [Munnecke and Samtleben 1996](#); [Westphal 2006](#)). Several types of analyses are suggested to evaluate a potential diagenetic origin of limestone–marl alternations ([Hallam 1964](#); [Westphal *et al.* 2010](#); [Amberg *et al.* 2016](#); [Nohl *et al.* 2021](#)). In reality, any lithology can be affected by diagenesis and, whenever possible, testing various proxies with different diagenetic paths can increase confidence in demonstrating a primary origin of the investigated signal. Thus, not all cyclic sedimentary features are necessarily linked to Milankovitch scale astronomical cycles. Some might also be the result of autocyclic processes (e.g. [Pratt and James 1986](#); [Goldhammer *et al.* 1993](#)), or find their origin in periodic forcing on a different temporal scale (e.g. millennial; [Elrick and Hinnov 2007](#)).

Existing Ordovician studies and the Ordovician time scale

A compilation of the Ordovician stratigraphic record of the expression of astronomical climate forcing is presented in [Table 1](#) and [Figures 3](#) and [4](#). This list focuses on original peer-reviewed publications that interpret certain changes in lithology or stratigraphic sequences explicitly in a cyclostratigraphic way. As many as possible other references touching on all aspects of Ordovician astronomical climate forcing are incorporated in the remainder of this chapter. To the best of my knowledge, this compilation includes most main papers published over the last three decades and provides a comprehensive overview on how cyclostratigraphic thinking evolved through time and space for the Ordovician. Some studies investigated sedimentary cyclicity without explicitly mentioning, or assertively ascribing the cyclicity to, the astronomical cycles (e.g. [Pope and Read 1997, 1998](#); [Amberg *et al.* 2016](#); [Brett *et al.* 2020](#); [Cho and Hong 2021](#); [Husinec and Harvey 2021](#)). Others considered the effects of astronomical climate forcing on the palaeoclimate, palaeoenvironmental or palaeontological records without looking at concrete sections but by using it as a model parameter or considering compiled records. For example, as obliquity is important for high-latitude climate and ice-sheet dynamics, previous studies have used variations in the angle of obliquity ([Herrmann *et al.* 2003](#)) or a periodic forcing corresponding with the estimated period of Ordovician obliquity ([Pohl *et al.* 2016](#)) as model parameters while studying Late Ordovician glacial dynamics using numerical models. [Armstrong *et al.* \(2009\)](#) make a conceptual link between Late Ordovician climate dynamics related to the position of the Intertropical Convergence Zone and changes in insolation, and therefore with the astronomical parameters. From a palaeoenvironmental perspective, the very long Milankovitch cycles have been suggested to pace Ordovician–Silurian organic carbon burial rates linked to weathering feedbacks and the occurrence of glaciations ([Cherns *et al.* 2013](#); [Sproson *et al.* 2021](#)). Orbital cycles have been suggested to exert an environmental control on the development of certain minerals that favour the exceptional preservation of fossils of the Lower Ordovician Fezouata biota from southern Morocco ([Saleh *et al.* 2019](#)). Not only the preservation of fossils themselves but even their evolutionary dynamics might have been influenced by astronomical climate forcing when looking at macroevolutionary rates derived from graptoloids ([Crampton *et al.* 2018](#)), or a change in the expression of astronomical environmental forcing linked to the start of the Great Ordovician Biodiversification Event ([Rasmussen *et al.* 2021](#)).

Table 1. Compilation of peer-reviewed stratigraphic publications interpreting the recording of Ordovician astronomical climate forcing, ranked by time of publication

Year	Country	Stage(s)	Cycles ID	Proxies and methodology	Authors	No.
1991	Australia	Ordovician–Silurian	SE, (OBL), P	AAS, XRF, spectral analysis	Williams	1
1998	Korea	Lower Ordovician	SE	Sedimentology, stratigraphy	Kim and Lee	2
2000	Africa compilation	Hirnantian	LE	Sedimentology, stratigraphy	Sutcliffe <i>et al.</i>	3
2001	USA, Utah	Lower–Middle Ord.	SE, OBL, P	Sedimentology, stratigraphy, ratio	Gong and Droser	4
2001	Korea	Middle Ordovician	SE	Sedimentology, stratigraphy	Lee <i>et al.</i>	5
2003	Russia, Siberia	Middle Ordovician	LE, SE, OBL, P	MS, spectral analysis	Rodionov <i>et al.</i>	6
2005	Jordan	Hirnantian	OBL	Sedimentology, TOC, $\delta^{13}\text{C}_{\text{org}}$	Armstrong <i>et al.</i>	7
2007	USA, Kentucky	Katian	LE, SE, OBL, P	MS, visual, spectral analysis	Ellwood <i>et al.</i>	8
2007	Canada, Anticosti	Katian–Aeronian	LE, SE	Tempestite frequency distribution	Long	9
2010	Morocco	Katian–Hirnantian	LE, SE, P	Sedimentology	Loi <i>et al.</i>	10
2011	South Africa	Floian–Darriwillian	L-LE, L-OBL	Sedimentology, stratigraphy, sequence strat.	Turner <i>et al.</i>	11
2012	USA, Wyoming	Katian–Hirnantian	SE, P	Sequence strat.	Holland and Patzkowsky	12
2012	USA, Appalachians	Lower–Middle Ord.	SE	Sedimentology, stratigraphy	Landing	13
2012	Jordan	Darriwillian–Sandbian	L-LE, L-OBL, LE	Sedimentology, stratigraphy, sequence strat.	Turner <i>et al.</i>	14
2013	USA, Kentucky	Katian	LE, SE, OBL, P	MS, visual, spectral analysis	Ellwood <i>et al.</i>	15
2013	USA–Canada	Katian	LE, SE	$\delta^{18}\text{O}_{\text{apatite}}$	Elrick <i>et al.</i>	16
2014	Morocco–Canada	Katian–Hirnantian	L-OBL	Sedimentology, stratigraphy	Ghienne <i>et al.</i>	17
2015	France	Darriwillian–Sandbian	L-OBL, LE, SE, P	Sedimentology, NGR, sequence strat.	Dabard <i>et al.</i>	18
2015	USA, West Virginia	Katian–Hirnantian	LE, SE, OBL, P	GR, spectral analysis	Hinnov and Diecchio	19
2015	Norway, Oslo	Sandbian	SE, OBL, P	MS, spectral analysis	Svensen <i>et al.</i>	20
2016	China, Ordos Basin	Sandbian	LE, SE, OBL, P	MS, lithology, spectral analysis	Fang <i>et al.</i>	21
2016	Williston Basin	Katian	LE, SE, OBL	Sequence stratigraphy	Husinec	22
2018	China, South China	Dapingian–Darriwillian	LE, SE, OBL, P	MS, spectral analysis	Zhong <i>et al.</i>	23
2019	Norway, Oslo	Sandbian	SE, OBL, P	MS, spectral analysis	Ballo <i>et al.</i>	24
2019	China, Tarim Basin	Darriwillian–Sandbian	LE, SE, OBL, P	MS, GR, spectral analysis	Fang <i>et al.</i>	25
2019	China, South China	Katian–Rhuddanian	LE, SE, OBL, P	Fe^{3+} , spectral analysis	Lu <i>et al.</i>	26
2019	China	Floian	LE, SE, OBL, P	pXRF, spectral analysis	Ma <i>et al.</i>	27
2019	China, South China	Sandbian–Katian	LE, SE, OBL, P	MS, spectral analysis	Zhong <i>et al.</i>	28
2020	USA, W-Virginia	Katian–Hirnantian	LE, SE, OBL, P	GR, spectral analysis	Hinnov and Diecchio	29
2020	Canada, Anticosti	Katian–Hirnantian	LE, SE	Sedimentology, $\delta^{18}\text{O}_{\text{carb}}$, spectral analysis	Mauviel <i>et al.</i>	30
2020	China, South China	Katian–Hirnantian	LE, SE, OBL, P	MS, spectral analysis	Zhong <i>et al.</i>	31
2021	Norway	Middle Ordovician	LE, SE, OBL, P	Sedimentology, spectral analysis	Rasmussen <i>et al.</i>	32
2021	Canada, Anticosti	Katian	LE, SE, (OBL), P	GR, spectral analysis	Sinnesael <i>et al.</i>	33
2021	China, South China	Katian–Rhuddanian	LE, SE, OBL, P	$\delta^{13}\text{C}$, chemical index of alteration	Zhang <i>et al.</i>	34
2022	France	Darriwillian–Sandbian	(LE, SE, OBL, P)	Sedimentology, NGR, pXRF, sequence, spectral analysis	Sinnesael <i>et al.</i>	35

This table shows respective country, stratigraphic interval, identified astronomical cycles, used proxies and methodologies, authors and reference numbers to the map presented in Figure 3.

Abbreviations: AAS, atomic absorption spectrometry; GR, gamma ray; L-LE, very long eccentricity; L-OBL, very long obliquity; LE, long eccentricity; MS, magnetic susceptibility; NGR, natural gamma ray; P, precession; pXRF: portable X-ray fluorescence; OBL, obliquity; SE, short eccentricity; TOC, total organic content; XRF, X-ray fluorescence; $\delta^{13}\text{C}_{\text{org}}$, Organic carbon stable isotope ratio; $\delta^{13}\text{C}$, carbon stable isotope ratio; $\delta^{18}\text{O}_{\text{apatite}}$, apatite oxygen stable isotope ratio; $\delta^{18}\text{O}_{\text{carb}}$, carbonate oxygen stable isotope ratio.

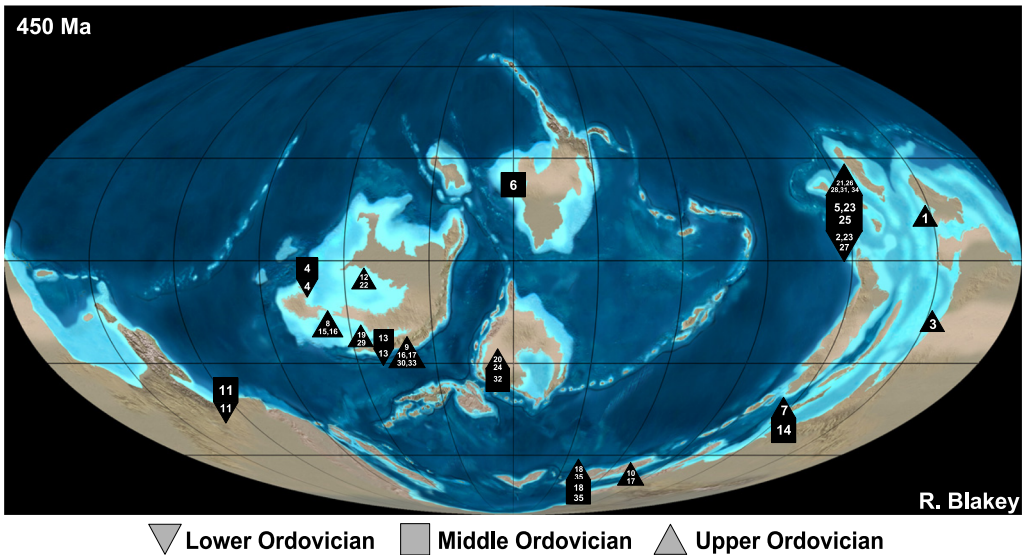


Fig. 3. Late Ordovician palaeogeographical reconstruction with palaeolocations of studied sections used previously in cyclostratigraphy (see Table 1). Source: Blakey (2013).

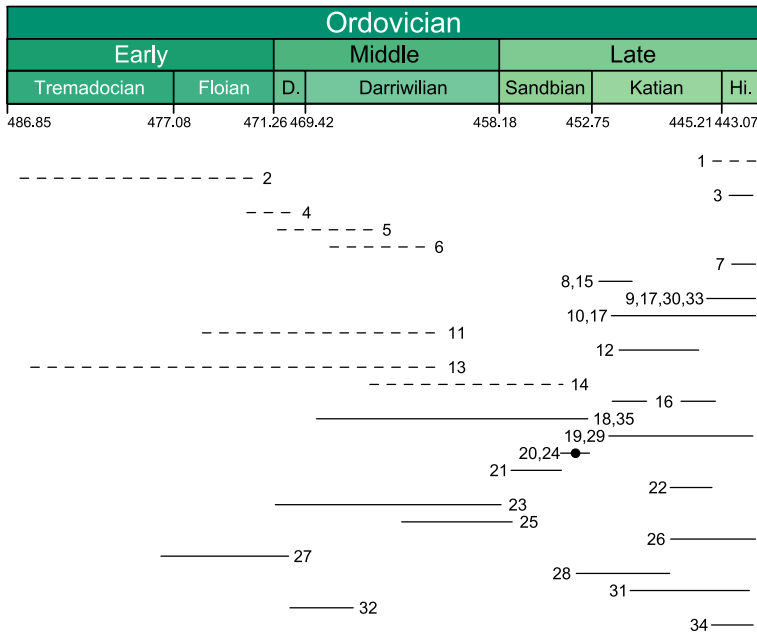


Fig. 4. Ordovician time scale based on the Geological Time Scale (GTS) 2020 (Goldman *et al.* 2020) with temporal positions of studied sections used previously in cyclostratigraphy (see Table 1). Ages are expressed in millions of years (Ma). Dashed lines represent studies with imprecise age models. Stratigraphic position and length of bars have uncertainties, for example, those originating from different temporal estimates between the GTS 2020 and individual studies; therefore, the temporal positions and durations should be considered as approximations. The black circle indicates cyclostratigraphy studies with direct radio-isotopic age control (Svensen *et al.* 2015; Ballo *et al.* 2019). D., Dapingian; Hi., Hirnantian.

Williams (1991) was a pioneering Ordovician cyclostratigraphy study demonstrating Milankovitch-band cyclicality in the Australian Upper Ordovician–lower Silurian evaporite sequences of the Canning Basin. It was long known that astronomical climate forcing could be traceable in sedimentary successions (e.g. Gilbert 1895; Schwarzacher 1964), but it was only with the landmark paper by Hays *et al.* (1976) that the wide application in the field of stratigraphy took off. In a series of papers starting in the late 1980s, A. Berger and colleagues (e.g. Berger *et al.* 1989*a, b*) computed pre-Quaternary astronomical frequencies and, by doing so, formed a theoretical basis that could be tested against the Phanerozoic sedimentary record.

With seven studies published in the 2000s and 19 in the 2010s, there is a clear increase in publications focusing on Ordovician cyclostratigraphy (Table 1). In general, interest in Paleozoic cyclostratigraphic research is growing (e.g. ‘Paleozoic cyclostratigraphy represents the next great “frontier” in the study of astronomical forcing’; Hinnov 2013, p. 1719). Additionally, the Chinese stratigraphic community has become increasingly active in this research field (review by Dai *et al.* 2019), resulting in an increase in data production, publications and a geographical shift in study areas. The best represented Ordovician palaeocontinents in terms of cyclostratigraphic research are Laurentia and, more recently, the various Chinese palaeo-terrains (Fig. 3). Other regions are understudied, Siberia, for example. Figure 4 further shows that the Early Ordovician is much less studied in terms of cyclostratigraphy compared to the Middle and Late Ordovician. The number and nature of identified astronomical cycles also evolve through time. Earlier studies often mention only one or two astronomical components, while more recent studies identify more. The increasing use of numerical ways of analysis (e.g. spectral analysis) is also noticeable. Earlier studies often limit themselves to eccentricity cycles as well.

Over the years, stratigraphic constraints and age control may have improved, which could have allowed for more precise interpretations. This is further suggested in Figure 4, showing the temporal positions of Ordovician cyclostratigraphy studies, where many of the older studies have less precise age models, making it more difficult to assign precise temporal positions. Therefore, the length of the studies as indicated in Figure 4 does not necessarily correspond exactly with the true duration estimates, but also reflects age assignment uncertainties. Another challenge is potential discrepancies in duration estimates between individual studies and the GTS2020 time scale. Only two out of the 35 listed studies have direct independent radio-isotopic age control coming from the same section as the cyclostratigraphic analysis (Svensen *et al.* 2015; Ballo *et al.*

2019). These challenges illustrate both the difficulties and opportunities for using cyclostratigraphy for constructing an Ordovician astronomical time scale. A major difficulty is robustly correlating and integrating various astrochronological interpretations of individual studies, certainly at the relative high temporal resolution astrochronology can provide. Ghobadi Pour *et al.* (2020) reviewed several Mid to Late Ordovician astrochronological studies, demonstrating that the integration of individual Ordovician cyclostratigraphy studies is not straightforward, mainly due to the lack of robust independent age control. On the other hand, astrochronological interpretations are directly related to time estimations and form an independent way of testing time scales constructed in different ways. For example, the GTS2020 Ordovician time scale has now two versions, one based on graptolite stratigraphy and another one based on conodont stratigraphy. Both time scales are based on a spline curve fitted through radio-isotopic ages that are scaled to their respective composite sequences using a constrained optimization approach named CONOP (Goldman *et al.* 2020). Both time scales have the advantage that they synthesize information coming from a large number of different sections and therefore reduce the dependency on single section interpretations. The graptolite and conodont time scales resulted respectively in different age and duration estimates for the various Ordovician stages, in the most extreme case with almost a double duration estimate for the Dapingian Stage in the conodont time scale (3.5 myr) compared the graptolite time scale (1.9 myr). This is an example of how astrochronological duration estimates can provide additional information. Zhong *et al.* (2018), for example, provide a Dapingian duration estimate of 1.97 ± 0.7 myr, and of 8.38 ± 0.4 myr for the Darriwilian Stage. The latter is a few million years shorter compared to both GTS2020 time scales. Only a few other studies report Ordovician stage duration estimates, with a 7.08 ± 0.405 myr estimation for the Floian Stage (Ma *et al.* 2019) and two duration estimations for the Hirnantian Stage of 1.74 ± 0.4 myr (Lu *et al.* 2019) and *c.* 1.225 myr (Zhong *et al.* 2020). The reasons for different interpretations for the same intervals of time can be multiple, and the issue of cyclostratigraphic uncertainty formulation is expanded upon further in the text, as well as the use of certain tools for the combined use of radio-isotopic dating and cyclostratigraphy for time scale construction (e.g. De Vleeschouwer and Parnell 2014; Harrigan *et al.* 2021).

Examples and opportunities

As it is currently not possible to astronomically tune an Ordovician record to a robust astronomical

solution in the absolute age domain, an Ordovician cyclostratigraphic interpretation can ideally be verified by means of independent radio-isotopic dating constraints (e.g. zircons from volcanic ash layers dated using CA-ID-TIMS; McLaughlin *et al.* this volume, in press). However, from the compilation presented in Table 1, only two out of 35 studies have such direct independent numerical age control coming from the same section as the cyclostratigraphic analysis. Both studies were performed in the Norwegian Oslo–Asker district by Svensen *et al.* (2015) and Ballo *et al.* (2019). Even when radio-isotopic ages are available, these too come with their uncertainties and potential complications in interpretations (e.g. complex zircon populations; Ballo *et al.* 2019), and it is equally important to critically assess the quality of the cyclostratigraphic records (e.g. sampling resolution, length of the record or the presence of clearly identifiable cycles). The lack of studies with combined radio-isotopic and cyclostratigraphic data coming from the same section is not unique for the Ordovician, with only a handful of such studies currently existing for the entire Paleozoic. A single radio-isotopic age might serve to anchor a floating astrochronology, but to assess duration estimates one needs at least two, ideally clearly stratigraphically separated, dated horizons. When the obvious classical datable material is not available, it might be worth considering other ways of obtaining numerical age constraints. One upcoming avenue is the dating of detrital zircons. Even though detrital zircons do not give a depositional age, recent technological advances make it possible to, for example, date a large number of detrital zircons (with laser ablation–inductively coupled plasma–mass spectrometry, LA–ICP–MS) after which the youngest zircons can be very precisely dated using CA–ID–TIMS to come to an informative ‘maximal depositional age’ (e.g. Karlstrom *et al.* 2019; Landing *et al.* 2021). Alternatively, Lindskog *et al.* (2017) dated prismatic zircons found by dissolving a limestone bed in Sweden (see also discussion in Liao *et al.* 2020). This age was then used, via biostratigraphic correlation, to anchor a cyclostratigraphic study in Norway (Rasmussen *et al.* 2021). For both the detrital zircon and non-bentonite associated prismatic zircon dating approaches it is crucial to keep in mind that the numerical age from the dating comes with an additional (larger) uncertainty on its depositional age, an uncertainty that also needs to be considered when such ages are used for the construction of the Ordovician time scale. Even when such uncertainties would be in the order of millions of years, they can still be valuable in such cases where there are tens of millions of years worth of stratigraphy with poor chronological constraints.

Most Ordovician cyclostratigraphic studies will thus be carried out without the availability of direct

independent age control via radio-isotopic dating. Two other aspects then become increasingly important: the availability of other sources of stratigraphic constraints (e.g. biostratigraphy or chemostratigraphy) and the quality of the signal that is analysed in terms of astronomical cycles. Both aspects are of course important too when radio-isotopic constraints are available. Thanks to integrative synthetic efforts like the ‘The Ordovician Period’ chapter from the *Geological Times Scale 2020* book (Goldman *et al.* 2020), that bring together information acquired from many individual sections, also biostratigraphic and chemostratigraphic information can provide some indirect rough first-order temporal constraints, besides being tools for stratigraphic correlation. Sometimes, there are seemingly cyclic features in a record, but the stratigraphic constraints are not precise enough to serve as an independent test for a potential astronomical origin (see discussion in Sinnesael *et al.* 2022).

One of the key advantages of cyclostratigraphy and astrochronology is their potential to construct continuous high-resolution (*c.* 10 kyr scale) time scales that are crucial for a better understanding of the rates of many processes, investigating cause-and-effect or lead–lag relationships. A first step in evaluating a potential astronomical signal is thus evaluating potential durations’ estimates in an integrated stratigraphic framework, also considering the degree of continuity of the investigated section (e.g. Hilgen *et al.* 2015; Sinnesael *et al.* 2021). Although the presence of ‘missing time’ in the stratigraphic record is a challenge for cyclostratigraphic work, well-constrained cyclostratigraphic frameworks can at the same time be used to estimate the amount of missing time in stratigraphic gaps and be a basis for the construction of (more complete) composite sections (e.g. Weedon *et al.* 2019). Once the integrated stratigraphic context is considered, and regular alternations are observed in a record, a first basic approach to evaluate a potential presence of an astronomical signal is looking at the ratio between different periodicities in a signal, if more than one is identified. Various periods can be identified both visually while investigating a record or by considering peaks of elevated power identified by spectral analysis of a numerical proxy series. The topic of statistical significance testing of power spectra for cyclostratigraphic purposes is subject of discussion (e.g. Vaughan *et al.* 2011; Meyers 2015). A classic example of the ratio approach is the (stable) 4:1 ratio between the 405 and *c.* 100 kyr eccentricity periods. As discussed, using ratios involving the shorter Ordovician periods for precession and obliquity is more uncertain (Walsham 2015), but is being done (e.g. Gong and Droser 2001; Svensen *et al.* 2015; Fang *et al.* 2016). There are also several statistical approaches available that

are based on the evaluation of the ratio between various astronomical frequencies (e.g. Meyers and Sageman 2007; Li *et al.* 2018b). An additional diagnostic feature can be the typical amplitude modulation patterns between, for example, precession and eccentricity (e.g. Svensen *et al.* 2015; Sinnesael *et al.* 2021), which can be statistically evaluated in combination with ratio fitting of spectral power peaks (Meyers 2015, 2019).

This characteristic precession–eccentricity amplitude modulation pattern is illustrated in Figure 5 using a Katian example from Anticosti Island (Canada) as interpreted by Sinnesael *et al.* (2021). The basic lithological units in this mixed carbonate–siliciclastic tempestitic setting are centimetre–decimetre-thick limestone–marl couplets, but the lithological variations of interest in this study are multimetre bed bundles between more carbonate v. more clay-rich intervals, as also reflected in the potassium concentration proxy as measured by gamma-ray borehole logging. Each alternation, on average *c.* 10 m thick, represents something in the order of a few tens of thousands of years based on the available bio- and chemostratigraphic information. Recognition of the precession–eccentricity amplitude modulation patterns was used as an argument to interpret these lithological cycles as precession (P) cycles (Fig. 5). Some of the alternations are very clearly recognizable (P), some are harder to distinguish, for example, because they are much shorter (P?) or longer (O?) compared to the average cycle thickness (Fig. 5). In this interval, there are often three to four clearly distinguishable cycles (Ps) followed by slightly less clear intervals. One interpretation is that the less clear intervals represent the

eccentricity minima where the precession cycles are less strongly developed and, for example, the relative power of obliquity might become more important (O?); or, alternatively, the astronomical control on the palaeoclimatological or depositional mechanisms might be reduced. These types of uncertainties are important to consider when reporting estimates on durations and precise timings of events. These visual observations were confirmed by a series of statistical and spectral analysis tests in Sinnesael *et al.* (2021). When performing certain statistical tests, one needs to keep in mind to check if basic assumptions, like the relative continuity of the record, underlying such tests are valid (see discussion in Sinnesael *et al.* 2022). Another such important assumption is often having a relatively stable accumulation rate throughout the record, which is often not the case. This is a crucial motivation for the application of evolutionary, or sliding window, approaches to try to detect and accommodate changes in accumulation rates.

Once a cyclostratigraphic interpretation is considered to be robust, several types of information can be retrieved. High-resolution duration estimations, with meaningful uncertainty estimations, can come from multiple analyses and detailed descriptions. The combination of duration estimates with anchoring in absolute time can further constrain the timing of particular events and constitute an additional tool for correlation exercises (e.g. Ballo *et al.* 2019; Rasmussen *et al.* 2021). An astronomical origin of a certain signal equally contains information on potential palaeoclimatological and sedimentary processes. It is, for example, reasonable to believe that the development of severe glacial

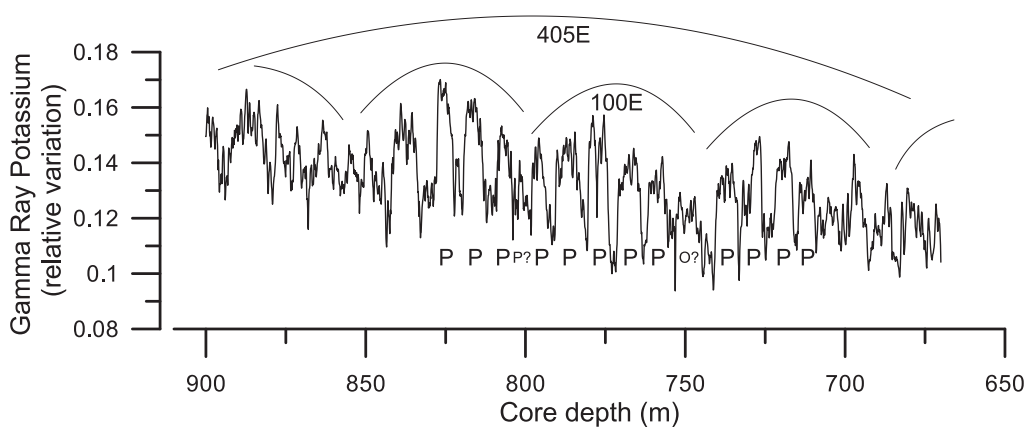


Fig. 5. Example of Ordovician (Katian) precession cycles modulated by eccentricity. The variations in the gamma ray potassium record as measured in the LaLoutre no. 1 borehole on Anticosti Island (Canada) reflect lithological alternations between intervals that are richer in carbonate v. clay. P, precession cycle; P?, potential precession cycle; O?, potential obliquity cycle; 100E, short *c.* 100 kyr eccentricity cycle; 405E, long 405 kyr eccentricity cycle. Source: Sinnesael *et al.* (2021).

episodes during the Ordovician changed Earth's sensitivity to astronomical climate forcing, with high-latitudes typically being more sensitive to obliquity forcing (e.g. Elrick *et al.* 2013; Ghienne *et al.* 2014). For the Anticosti Island example presented in Figure 5, the suggested hypothesis is a precession influence on the monsoon intensity controlling the amount of transported detrital material into the basin (Sinnesael *et al.* 2021). Another example of a low-latitude precession–eccentricity influence (wet v. dry climate conditions) is found in the Upper Ordovician Australian evaporite sequences of the Canning Basin (Williams 1991).

From a Solar System reconstruction perspective, Zhong *et al.* (2020) studied Middle Ordovician strata from South China and suggested specific Late Ordovician (c. 445 Ma) values for the duration of the main obliquity period (33.8 ± 0.46 kyr), various climatic precession periods (17–22 kyr), the value of the precession constant (57.19 ± 0.53 arcsec/years), length of day (22.37 ± 0.12 h) and Earth–Moon distance ($375\,330 \pm 722$ km v. $384\,000$ km today). Zhong *et al.* (2018) and Ma *et al.* (2019) suggest a shorter duration for the very long Milankovitch cycle related to the g_4 – g_3 term, closer to 1.9 myr v. the current 2.4 myr duration. These studies present some of the first Paleozoic cyclostratigraphic work starting to document these features based on geological observations. The occurrence of, for example, chaotic transitions, or the estimation of the Earth–Moon distance, are features that should have global synchronous signatures, and as such will have to be confirmed by the study of more time-equivalent sections.

Future work and conclusions

The broad variety of archives in the sedimentary record makes it difficult to formulate strict rules on how every section could be studied, but the community-based Cyclostratigraphy Intercomparison Project formulated a set of flexible guidelines that should be applicable to any cyclostratigraphic study (see Sinnesael *et al.* 2019). Whenever possible, the robustness of a cyclostratigraphic study can be improved by comparing different (independent) proxies from the same section (Li *et al.* 2018a) and applying a range of (statistical) cyclostratigraphic research approaches. It is imperative that cyclostratigraphic studies are embedded in an integrated stratigraphic approach, considering all available sources of stratigraphic information. Ideally, cyclostratigraphic studies of contemporaneous stratigraphic intervals should be consistent with each other. This does not necessarily mean they have the same cyclic record. For example, a low-latitude record might be dominated by a precession signal, while a high-latitude section might rather be dominated by an

obliquity signal; but if they are temporally equivalent, they should have the same duration. An important aspect of evaluating consistency between different studies is the concept of uncertainty. Currently, there is no (uniform) approach for the expression of uncertainty of cyclostratigraphic results (Sinnesael *et al.* 2019). The most common way to assign an uncertainty on a cyclostratigraphic duration estimate is \pm a few cycles, but these formulations are often quite arbitrary. One could consider analysing different proxies or using different methodologies to see how consistent the various options are (e.g. Da Silva *et al.* 2020; Sinnesael *et al.* 2021). Alternatively, one can describe specific intervals where one might be more, or less, confident in an interpretation, which could be valuable information for potential future research. Considering that there always might be missing cycles in a single section, one could treat those as minimum duration estimates. Besides formulating an uncertainty for an individual section, uncertainty formulations are also important for the numerical integration of the stratigraphic record, for example, with radio-isotopic ages. Such an integrated stratigraphic approach is crucial to make it possible to compare and verify astrochronological duration estimates coming from contemporaneous single sections. Several promising studies explore the combined use of cyclostratigraphic and radio-isotopic age constraints in a (Paleozoic) stratigraphic context using a statistical Bayesian framework (De Vleeschouwer and Parnell 2014; Ballo *et al.* 2019; Trayler *et al.* 2019; Harrigan *et al.* 2021). Another important aspect besides age model construction is understanding the origin of a potential astronomical signal. What was the pathway between the insolation forcing, climate and sedimentary recording. Even though it might be hard to prove, an important question to consider is, ‘Can I formulate (and test) a hypothesis on why I see this particular astronomical cycle in this archive using this proxy?’. There would be a large benefit in more sedimentological and climate model studies that explicitly focus on the expression of astronomical cycles, something that is currently quite rare in the Paleozoic context (e.g. Read *et al.* 1991; De Vleeschouwer *et al.* 2014).

Despite an increase in the number of Ordovician astrochronological studies, several challenges remain to be resolved before constructing a robust integrated Ordovician astronomical time scale. Ordovician cyclostratigraphy is a relatively young field of research and will benefit from a growing awareness of the principles and application of deep-time cyclostratigraphy. As more researchers learn about and apply cyclostratigraphic methodologies, the amount and level of detail of astrochronological information will increase. Integrative efforts will have to be made to compare individual

astrochronological interpretations in a robust integrated stratigraphic framework that considers the multiple sources of uncertainty (e.g. Ghobadi Pour *et al.* 2020). This exercise will need to go hand in hand with developing new approaches that are more suited to investigate less traditional archives for cyclostratigraphy like shallow-marine palaeoenvironments (Montanez 2021; Sinnesael *et al.* 2022). The development of these approaches should go in parallel with both sedimentological and palaeoclimatological modelling efforts to further improve our understanding of the underlying mechanisms behind the recording of astronomical signals. The first target for an Ordovician astronomical time scale can be based on the stable 405 kyr eccentricity cycle, that can then be refined by identifying individual short eccentricity, precession and obliquity cycles. This process can then lead to unprecedented high-resolution time scales (c. 10 kyr resolution) and fascinating new constraints on the dynamics of the Ordovician world and the history of the Solar System during the Ordovician Period.

Available resources

Here, a summary overview of main references and suggestions for practical tools is provided. Reference review papers on cyclostratigraphy and astrochronology are: Strasser *et al.* (2006); Hinnov (2013, 2018); Meyers (2019); Sinnesael *et al.* (2019); Laskar (2020). Laskar (2020), in particular, gives an overview of the astronomical solutions from the theoretical perspective. Weedon (2003) is a time-series analysis and cyclostratigraphy handbook introducing many key concepts in an accessible way. The <http://www.cyclostratigraphy.org> website is designed to be an educational online platform providing cyclostratigraphy training by experts for the broader stratigraphic community, and hosts a cyclostratigraphy figure repository, cyclo-podcast and newsletter. Often used software packages for spectral and time-series analyses are ‘ACycle’ (Li *et al.* 2019), ‘Astrochron’ (Meyers 2014), ‘PAST’ (Hammer *et al.* 2001) and ‘QAnalySeries’ (Kotov and Pålík 2018). Useful aspects to consider before performing statistical analyses are also the importance of sampling resolutions (Martinez *et al.* 2016) and the implications of band-pass filter settings (Zeeden *et al.* 2018). There are several statistical tools available that might be useful in an Ordovician context to test for specific aspects such as evaluating the precession–eccentricity, or c. 100 and 405 kyr eccentricity modulation patterns and power spectrum ratios with ‘TimeOpt’ (Meyers 2015, 2019), looking at ratio fitting of power spectra with astronomical target frequencies (Meyers and Sageman 2007; Li *et al.* 2018b) or considering

(evolutionary) whole spectrum characteristics instead of only looking at individual components (Sinnesael *et al.* 2018; Duesing *et al.* 2021). Non-Fourier based approaches to time-series are also in development, e.g. astronomical component estimation as an alternative to band-pass filtering for the extraction of astronomical components in a signal (Sinnesael *et al.* 2016) or the use of a signal decomposition approach (Wouters *et al.* 2022).

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