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Abstract

Cyclostratigraphy is an important tool for understanding astronomical climate forcing and 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, Palaeozoic 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 palaeoenviromental 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) shortly introduces the main concepts of cyclostratigraphy and astrochronology, and particular challenges in the 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 on 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 10^4-to-10^6-year time scales (Milankovitch, 1941; Hays et al., 1976; Laskar, 2020). 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 ~100 kyr (thousand years) 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 the eccentricity will change the distance with the Earth. As such, the 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. The precession is the result of the change of the orientation of the earth axis (**Fig. 1**). The astronomical precession describes the precession of the Earth`s rotation axis, which has a present period of ~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 its closest position (perihelion). The precession determines the timing and location of the seasons with respect to Earth's orbit (e.g. short, hot versus 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 the 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 ~24-kyr, 22-kyr 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**). The 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 increases with an increasing value for the tilt. Berger (1978) determined the present main period of obliquity to be ~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 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 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 ~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 ~100 kyr duration during the Ordovician. Both the eccentricity and obliquity have so-called 'very long Milankovitch' 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 Myr (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 is receding from the Earth, but the speed with which this is happening is not constant over time as is for example evident from interpretations of various geological archives like for example 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 direction of the Earth`s rotation, and so is 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 ~16-kyr and ~19-kyr and a main obliquity period of ~31-kyr for 440 Ma (**Fig. 2**). There are several reconstructions back in time (Berger and Loutre, 1994; Laskar et al., 2004; Waltham et al., 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 ~100-kyr 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-kyr and ~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-Myr 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 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). 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 depository environments (Hilgen et al., 2015). However, it is not aways straightforward to assess if singe sections are complete at the scale of sedimentary cycles linked to orbital forcing of climate, and 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 metamorphosis 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 Sambtleben, 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). Truly, 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 **Tab. 1** and **Figs. 3 & 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 throughout the rest of this chapter. To the best of my knowledge, this compilation includes most main papers published over the last 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).

Williams (1991) was a pioneering Ordovician cyclostratigraphy study demonstrating Milankovitch-band cyclicity 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 eighties, A. Berger and colleagues (e.g. Berger et al., 1989a, 1989b) 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 2000's and nineteen in the 2010's there is a clear increase in publications focusing on Ordovician cyclostratigraphy (**Tab. 1**). In general, interest in Palaeozoic 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, like Siberia for example. **Fig. 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 evolves through time. Earlier studies often only mention one or two astronomical components, while the more recent studies identify more. The increasing use of numerical ways of analysis (e.g. spectral analysis) is also noticeable. The earlier studies often limit themselves to eccentricity cycles as well.

Over the years, stratigraphic constraints and age control might have improved which could have allowed for more precise interpretations. This is further suggested in **Fig. 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 on **Fig. 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 optimisation 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, with in the most extreme case 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 an 8.38 ± 0.4 Myr for the Darriwilian Stage. The latter is a few million years shorter compared to both GTS2020 timescales. 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 ~1.225 Myr (Zhang 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; O'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). However, from the compilation presented in **Tab. 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 region 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 stays 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 Palaeozoic. 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 depositionary age, an uncertainty that also needs to be considered when such ages would be 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 its potential to construct continuous high-resolution (~10 kyr scale) timescales 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-kyr and ~100-kyr eccentricity periods. As discussed, using ratio's involving the shorter Ordovician periods for precession and obliquity is more uncertain (Waltham, 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., 2018a). 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 **Fig. 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 centimeter- to decimeter-thick limestone-marl couplets, but the lithological variations of interest in this study are multimeter bed bundles between more carbonate versus more clay-rich intervals, as also reflected in the potassium concentration proxy as measured by gamma-ray borehole logging. Each alternation, on average ~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 recognisable (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 (P's) 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 depositionary 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 accumulations 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 developments of severe glacial episodes during the Ordovician has changed Earth's sensitivity to astronomical climate forcing, with high-latitude typically being more sensitive to obliquity forcing (e.g. Elrick et al., 2013; Ghienne et al., 2014). For the Anticosti Island example presented in **Fig. 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 versus dry climate conditions) is found in the Upper Ordovician Australian evaporite sequences of the Canning Basin (Williams et al., 1991).

From a Solar System reconstruction perspective, Zhong et al. (2020) studied Middle Ordovician strata from South China and suggested specific Late Ordovician (~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/yr), length of day (22.37 ± 0.12 h) and Earth-Moon distance (375,330 ± 722 km vs. 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 versus the current 2.4-Myr duration. These studies present some of the first Palaeozoic 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., 2018b) and applying a range of (statistical) cyclostratigraphic research approaches. It is imperative that cyclostratigraphic studies are imbedded 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 ± 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; Sinneseal 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 (Palaeozoic) stratigraphic context using a statistical Bayesian framework (De Vleeschouwer and Parnell, 2014; Ballo et al., 2019; Trayler et al., 2019; O'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) an 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 Palaeozoic 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 will 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 developments 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 timescales (~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 from the theoretical perspective of the astronomical solutions. Weedon (2003) is a time-series analysis and cyclostratigraphy handbook introducing many key concepts in an accessible way. The '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), 'QAnalySeries' (Kotov and Pälike, 2018). Useful aspects to consider before performing statistical analyses are also the importance of sampling resolutions (Martinez et al., 2016), and the implications of bandpass 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 like: evaluate the precession-eccentricty, or ~100-kyr and 405-kyr eccentricity modulation patterns and power spectrum ratio's with 'TimeOpt' (Meyers, 2015, 2019), looking at ratio fitting of power spectra with astronomical target frequencies (Meyers and Sagemann, 2007; Li et al., 2018a) 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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Figure captions

Fig. 1. The evolution of the three astronomical parameters (eccentricity, obliquity and precession) over the last 1 million year, 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 ~100 kyr for eccentricity, 41 kyr for obliquity and 24, 22 and 19 kyr for precession. ka = thousand years ago. kyr = thousand years duration. Adapted from www.cyclostratigraphy.org.

Fig. 2. Evolution of the main obliquity and precession periods between today and 500 Ma accordingly to Berger et al. (1992) and Laskar et al. (2004). Grey-shaded area indicates the Ordovician (Ord.). Adapted from www.cyclostratigraphy.org.

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

Fig. 4. Ordovician time scale based on the Geological Time Scale 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 ago (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 GTS2020 and individual studies; therefore the temporal positions and durations should be considered as approximate. The filled black circle (●) indicates cyclostratigraphy studies with direct radio-isotopic age control (Svensen et al., 2015; Ballo et al., 2019). D. = Dapingian, Hi. = Hirnantian.

Fig. 5. Example of Ordovician (Katian) precession cycles modulated by eccentricity from Sinnesael et al. (2021). 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 versus clay. P = precession cycle, P? = potential precession cycle, O? = potential obliquity cycle, 100E = short ~100-kyr eccentricity cycle and 405E = long ~405-kyr eccentricity cycle.

Table Caption

Table 1: Compilation of peer-reviewed stratigraphic publications interpreting the recording of Ordovician astronomical climate forcing, ranked by time of publication. Additional information contains the respective country, stratigraphic interval, identified astronomical cycles, used proxies and methodologies, authors and reference to the map presented on **Fig. 3**. Abbreviations: Atomic Absorption Spectrometry (AAS); Long eccentricity (LE); Magnetic susceptibility (MS); Natural Gamma Ray (NGR); Precession (P); Obliquity (OBL); Short eccentricity (SE); Total Organic Content (TOC); X-ray fluorescence (XRF).

Year	Country	Stage(s)	Cycles ID	Proxies & Methodology	Authors	N
1991	Australia	Ordovician-Silurian	SE, (OBL), P	AAS, XRF, spectral analysis	Williams	1
1998	Korea	Lower Ordovician	SE	sedimentology, stratigraphy	Kim&Lee	2
2000	Africa compilation	Hirnantian	LE	sedimentology, stratigraphy	Sutcliffe et al.	3
2001	USA, Utah	Lower-Middle Ord.	SE, OBL, P	sedimentology, stratigraphy, ratio	Gong & Droser	4
2001	Korea	Middle Ordovician	SE	sedimentology, stratigraphy	Lee et al.	5
2003	Russia, Siberia	Middle Ordovician	LE, SE, OBL, P	MS, spectral analysis	Rodionov et al.	6
2005	Jordan	Hirnantian	OBL	sedimentology, TOC, d13Corg	Armstrong et al.	7
2007	USA, Kentucky	Katian	LE, SE, OBL, P	MS, visual, spectral analysis	Ellwood et al.	8
2007	Canada, Anticosti	Katian-Aeronian	LE, SE	tempestite frequency distribution	Long	9
2010	Morocco	Katian-Hirnantian	LE, SE, P	sedimentology	Loi et al.	10
2011	South Africa	Floian-Darriwillian	L-LE, L-OBL	sedimentology, stratigraphy, sequence strat.	Turner et al.	11
2012	USA, Wyoming	Katian-Hirnantian	SE, P	sequence strat.	Holland&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 et al.	14
2013	USA, Kentucky	Katian	LE, SE, OBL, P	MS, visual, spectral analysis	Ellwood et al.	15
2013	USA-Canada	Katian	LE, SE	$\delta^{18}O_{apatite}$	Elrick et al.	16
2014	Marocco-Canada	Katian-Hirnantian	L-OBL	sedimentology, stratigraphy	Ghienne et al.	17
2015	France	Darriwilian-Sandbian	L-OBL, LE, SE, P	sedimentology, NGR, sequence strat.	Dabard et al.	18
2015	USA, W-Virginia	Katian-Hirnantian	LE, SE, OBL, P	GR, spectral analysis	Hinnov&Diecchio	19
2015	Norway, Oslo	Sandbian	SE, OBL, P	MS, spectral analysis	Svensen et al.	20
2016	China, Ordos Basin	Sandbian	LE, SE, OBL, P	MS, lithology, spectral analysis	Fang et al.	21
2016	Williston Basin	Katian	LE, SE, OBL	sequence stratigraphy	Husinec	22
2018	China, South-China	Dapingian-Darriwilian	LE, SE, OBL, P	MS, spectral analysis	Zhong et al.	23
2019	Norway, Oslo	Sandbian	SE, OBL, P	MS, spectral analysis	Ballo et al.	24

2019	China, Tarim Basin	Darriwilian-Sandbian	LE, SE, OBL, P	MS, GR, spectral analysis	Fang et al.	25
2019	China, South-China	Katian-Rhuddanian	LE, SE, OBL, P	Fe3+, spectral analysis	Lu et al.	26
2019	China	Floian	LE, SE, OBL, P	pXRF, spectral analysis	Ma et a.	27
2019	China, South-China	Sandbian-Katian	LE, SE, OBL, P	MS, spectral analysis	Zhong et al.	28
2020	USA, W-Virginia	Katian-Hirnantian	LE, SE, OBL, P	GR, spectral analysis	Hinnov&Diecchio	29
2020	Canada, Anticosti	Katian-Hirnantian	LE, SE	sedimentology, $\delta^{18}O_{carb}$, spectral analysis	Mauviel et al.	30
2020	China, South-China	Katian-Hirnantian	LE, SE, OBL, P	MS, spectral analysis	Zhong et al.	31
2021	Norway	Middle Ordovician	LE, SE, OBL, P	sedimentology, spectral analysis	Rasmussen et al.	32
2021	Canada, Anticosti	Katian	LE, SE, (OBL), P	GR, spectral analysis	Sinnesael et al.	33
2021	China, South-China	Katian-Rhuddanian	LE, SE, OBL, P	d13C, chemical index of alteration	Zhang et al.	34
2022	France	Darriwilian-Sandbian	(LE, SE, OBL, P)	sedimentology, NGR, pXRF, sequence	Sinnesael et al.	35

Table 1

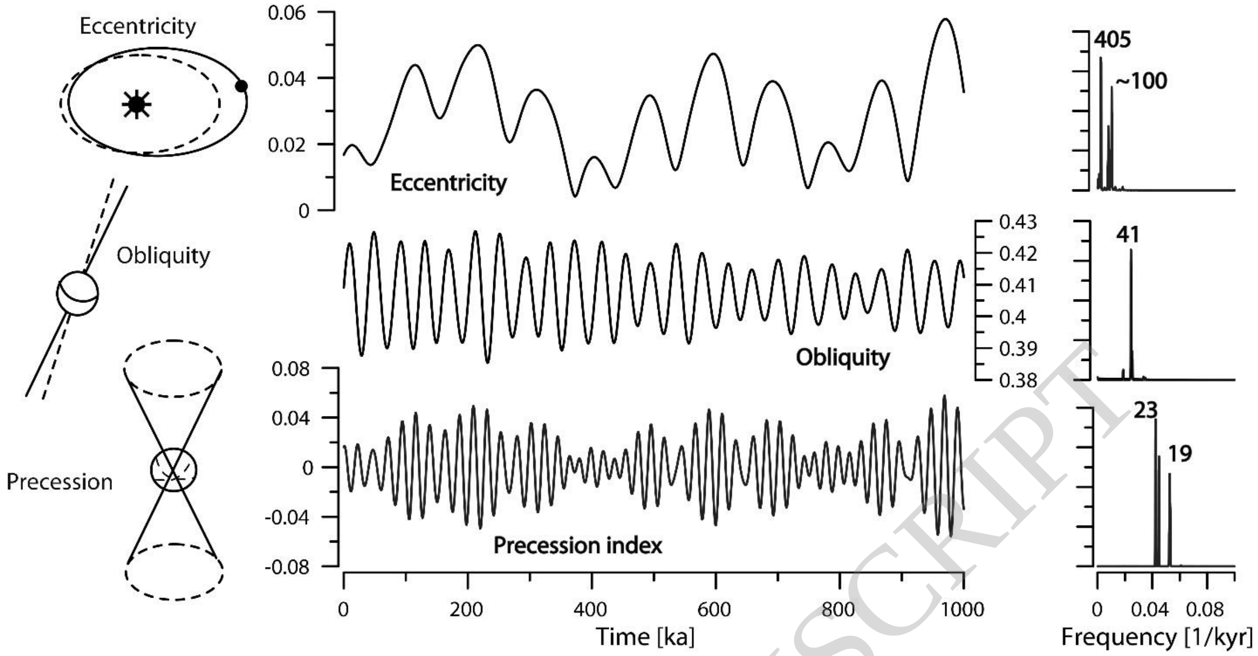

Eccentricity
Obliquity
Precession
0.06
0.04
0.02
0
Eccentricity
0.43
0.42
0.41
0.4
0.39
0.38
Obliquity
0.08
0.04
0
-0.04
-0.08
Precession index
0
200
400
600
800
1000
Time [ka]
405
~100
41
23
19
0
0.04
0.08
Frequency [1/kyr]

Figure 1

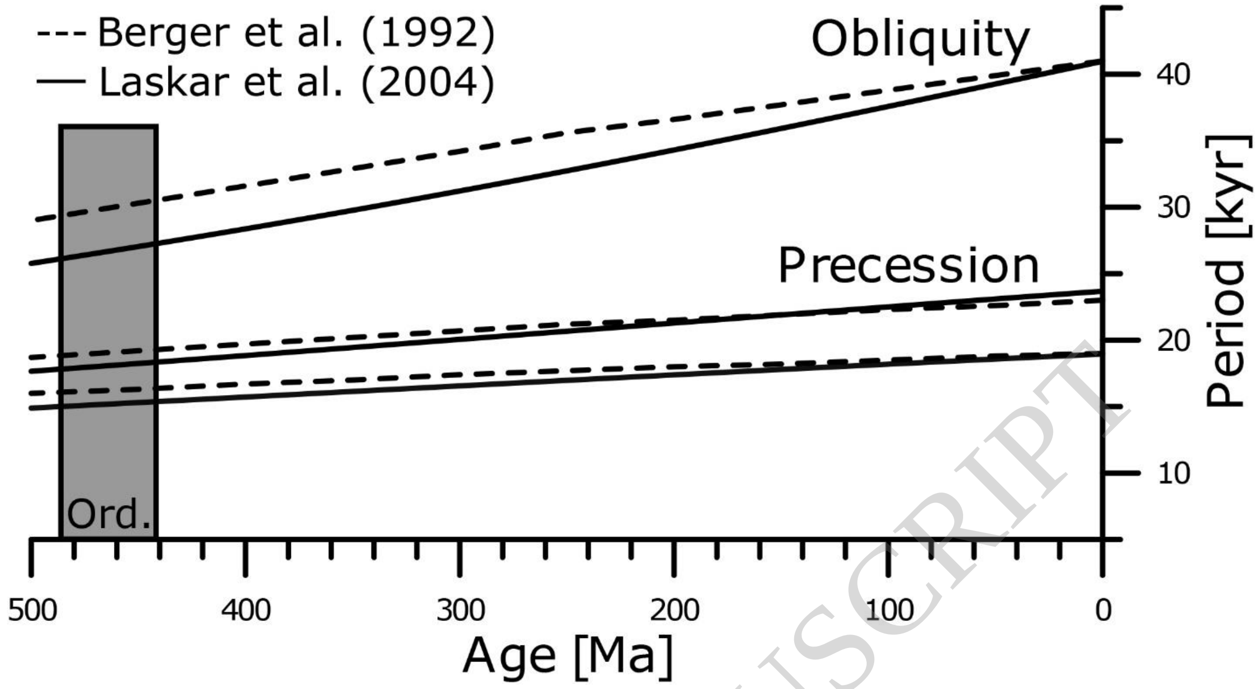

--- Berger et al. (1992)
— Laskar et al. (2004)
Obliquity
Precession
Ord.
40
30
20
10
Period [kyr]
500
400
300
200
100
0
Age [Ma]

Figure 2

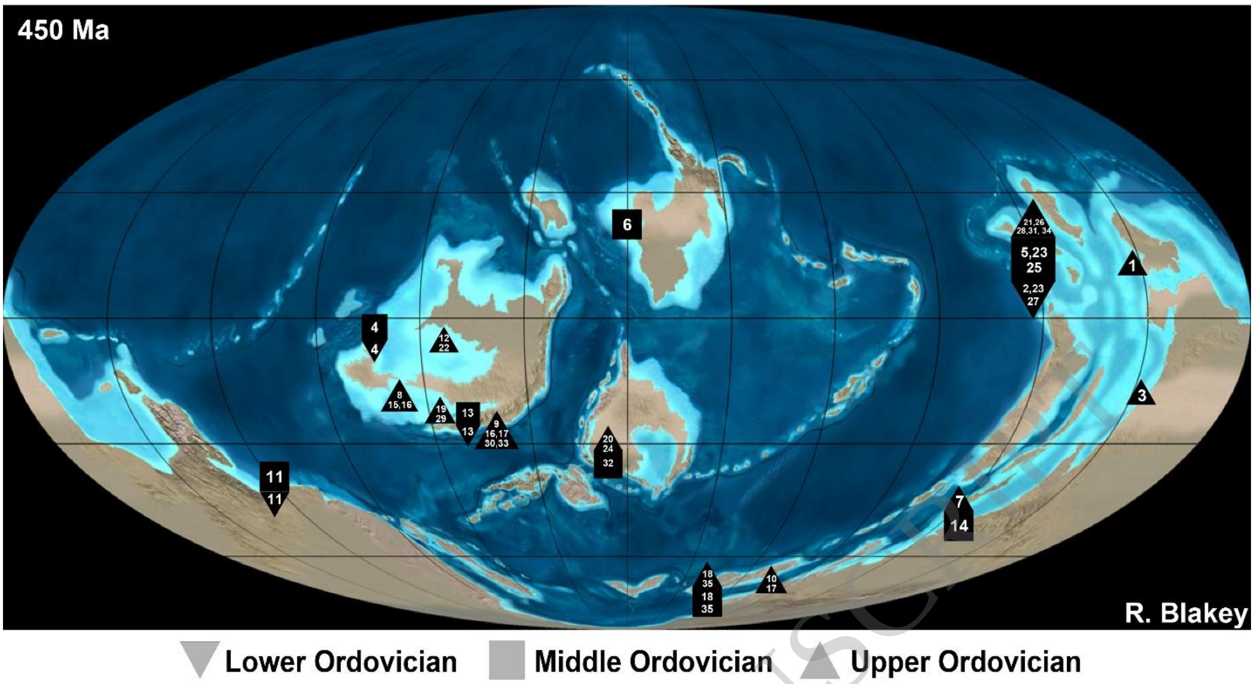
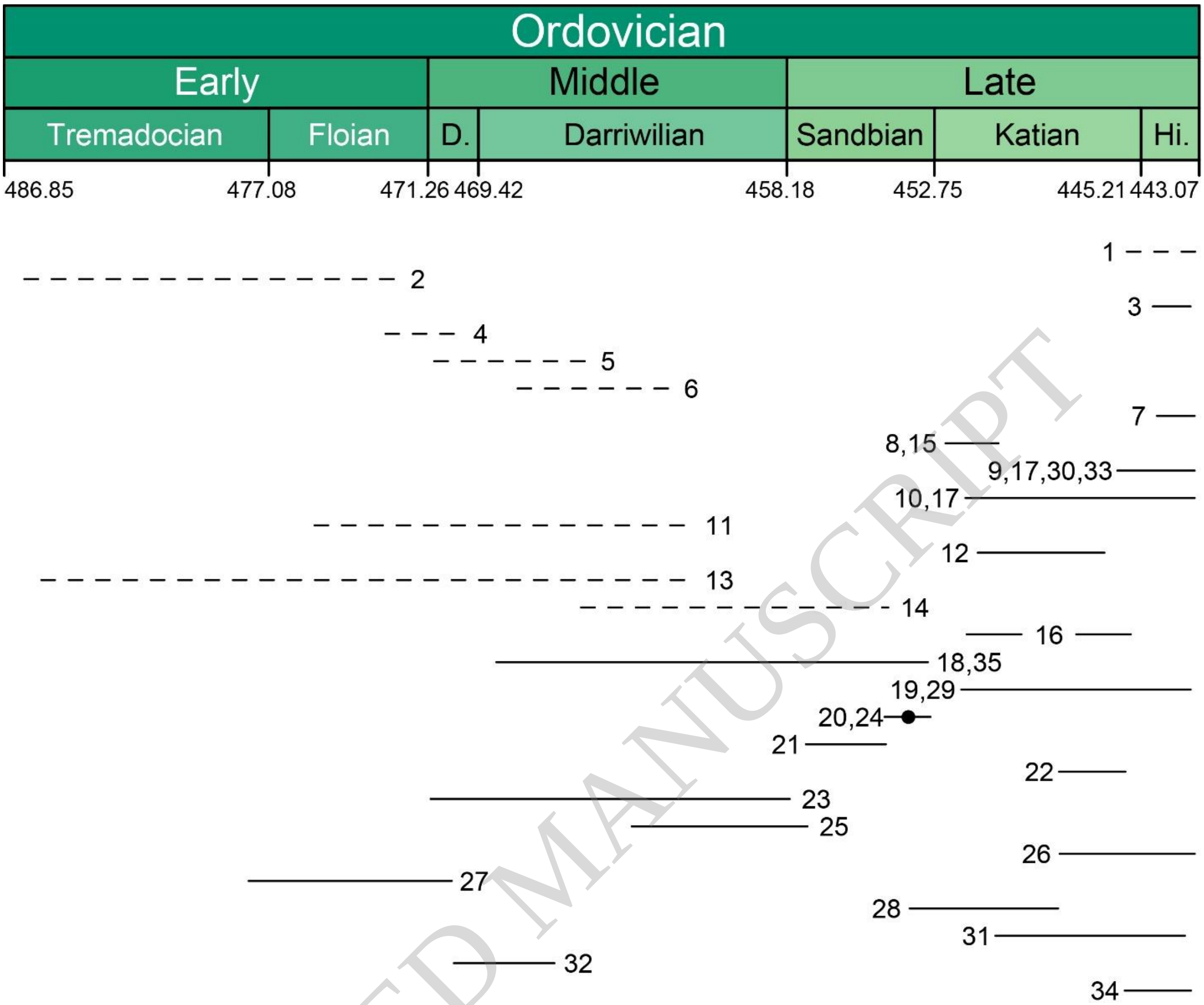

450 Ma
R. Blakey
Lower Ordovician
Middle Ordovician
Upper Ordovician

Figure 3


Ordovician
Early
Middle
Late
Tremadocian
Floian
D.
Darriwilian
Sandbian
Katian
Hi.
486.85
477.08
471.26
469.42
458.18
452.75
445.21
443.07
1
2
3
4
5
6
7
8,15
9,17,30,33
10,17
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18,35
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Figure 4

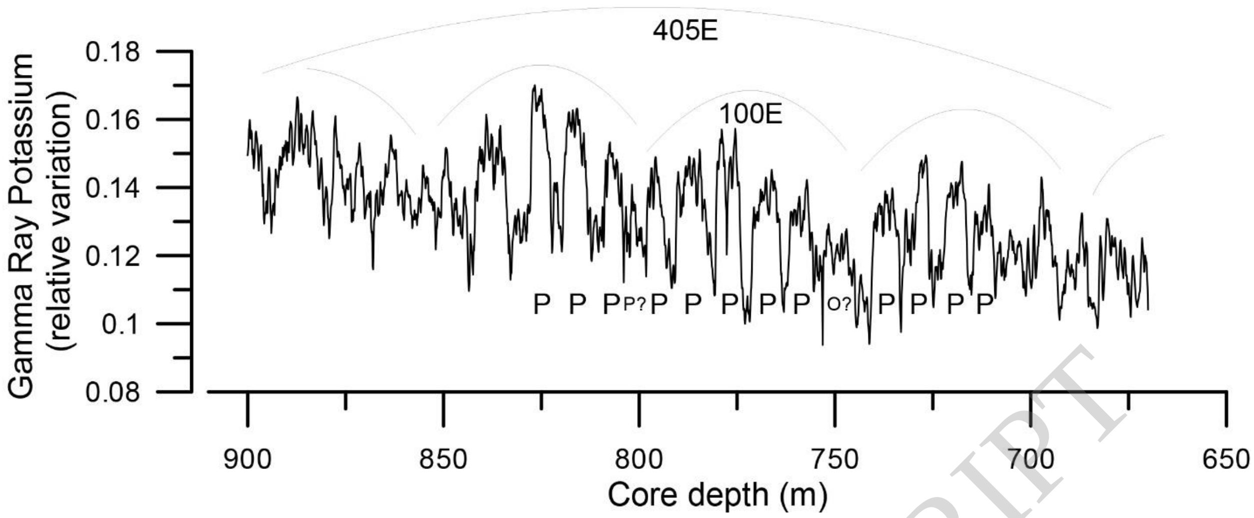
405E
100E
Gamma Ray Potassium (relative variation)
0.18
0.16
0.14
0.12
0.1
0.08
P P P P? P P P P P P O? P P P P
900
850
800
750
700
650
Core depth (m)

Figure 5