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Refining the Early Devonian time scale using Milankovitch cyclicity in Lochkovian–Pragian sediments (Prague Synform, Czech Republic)

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ABSTRACT

The Early Devonian geological time scale (base of the Devonian at 418.8 ± 2.9 Myr, Becker et al., 2012) suffers from poor age control, with associated large uncertainties between 2.5 and 4.2 Myr on the stage boundaries. Identifying orbital cycles from sedimentary successions can serve as a very powerful chronometer to test and, where appropriate, improve age models. Here, we focus on the Lochkovian and Pragian, the two lowermost Devonian stages. High-resolution magnetic susceptibility (χ_{in} – 5 to 10 cm sampling interval) and gamma ray spectrometry (GRS – 25 to 50 cm sampling interval) records were gathered from two main limestone sections, Požár-CS (118 m, spanning the Lochkov and Praha Formations) and Pod Barrandovem (174 m; Praha Formation), both in the Czech Republic. An additional section (Branžovy, 65 m, Praha Formation) was sampled for GRS (every 50 cm). The χ_{in} and GRS records are very similar, so χ_{in} variations are driven by variations in the samples' paramagnetic clay mineral content, reflecting changes in detrital input. Therefore, climatic variations are very likely captured in our records.

Multiple spectral analysis and statistical techniques such as: Continuous Wavelet Transform, Evolutive Harmonic Analysis, Multi-taper method and Average Spectral Misfit, were used in concert to reach an optimal astronomical interpretation. The Požár-CS section shows distinctly varying sediment accumulation rates. The Lochkovian (essentially equivalent to the Lochkov Formation (Fm.)) is interpreted to include a total of nineteen 405 kyr eccentricity cycles, constraining its duration to 7.7 ± 2.8 Myr. The Praha Fm. includes fourteen 405 kyr eccentricity cycles in the three sampled sections, while the Pragian Stage only includes about four 405 kyr eccentricity cycles, thus exhibiting durations of 5.7 ± 0.6 Myr and 1.7 ± 0.7 Myr respectively. Because the Lochkov Fm. contains an interval with very low sediment accumulation rate and because the Praha Fm. was cross-validated in three different sections, the uncertainty in the duration of the Lochkov Fm. and the Lochkovian is larger than that of the Praha Fm. and Pragian. The new floating time scales for the Lochkovian and Pragian stages have an unprecedented precision, with reduction in the uncertainty by a factor of 1.7 for the Lochkovian and of ∼6 for the Pragian. Furthermore, longer orbital modulation cycles are also identified with periodicities of ∼1000 kyr and 2000–2500 kyr.

1. Introduction

A major challenge for improvement of the Devonian Time scale is the limited number of good quality and chronostratigraphically fixed radiometric ages within this period (synthesis in Becker et al., 2012). The error bars of Early Devonian stage boundaries range from 2.5 to 4.2 Myr, and are among the highest of the entire Phanerozoic Geological Time Scale (De Vleeschouwer and Parnell, 2014). An useful approach to improve the Devonian Time scale

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would be to identify Milankovich cycles in the sedimentological record, which can be used as powerful chronometers (e.g. Hinnov and Ogg, 2007). The complete interference pattern of these cycles, the astronomical solution, has been theoretically calculated for the Cenozoic (Laskar et al., 2011) and most of the Cenozoic has now been astronomically age calibrated (e.g. Hilgen et al., 2012). These precise orbital solutions are not available for the Paleozoic. However, the 405 kyr eccentricity cycle is known to be very stable (Laskar et al., 2011) and has been used to build floating astronomical time scales for Mesozoic and Palaeozoic successions (e.g. Boulila et al., 2010; De Vleeschouwer et al., 2015). Furthermore, the basic periods of obliquity and precession cycles as a function of age become shorter back in time. This is a consequence of secular deceleration of the Earth's rotation rate, the increase of the distance between Earth and Moon, and the dynamical ellipticity of the Earth (Berger et al., 1992). These eccentricity, obliquity and precession periodicities serve as a template for the identification of orbital frequencies in target sections using spectral analysis. Following pioneering work on Devonian cyclostratigraphy (e.g. Chlupáč, 2000) in which robust spectral techniques are largely absent. More recent efforts in constructing precise floating astronomical time scales have been carried out for the Eifelian (Ellwood et al., 2015), Givetian (De Vleeschouwer et al., 2015), Frasnian (De Vleeschouwer et al., 2012) and the Frasnian–Famennian boundary and topmost Famennian (De Vleeschouwer et al., 2013), leaving the Early Devonian presently uncharted.

The Prague Synform (Czech Republic) is a perfect target for applying cyclostratigraphy to improve the geological time scale of the Early Devonian. It includes the historical stratotypes for the Lochkovian and Pragian stages in continuous deep marine records having not only a well-established biostratigraphy and sedimentological context but also an extensive database of high resolution magnetic susceptibility (χ_{in}) and gamma ray spectrometry (GRS) records (see Table 1A for references). χ_{in} and GRS have classically been used as proxies for detrital input and therefore, as a proxy for climatic changes (e.g. Mayer and Appel, 1999; Kodama and Hinnov, 2015; Kodama et al., 2010; Boulila et al., 2010; Hinnov et al., 2013; Da Silva et al., 2013; De Vleeschouwer et al., 2015). In this paper, we search for orbital cyclicity in different target sections, using χ_{in} and GRS records, with the aim to improve the Lochkovian and Pragian time scale.

2. Geological setting and target sections

The selected sections (Požár-CS, Pod Barrandovem and Branžovy) are all from the Prague Synform, formed during the Variscan orogeny. The original sedimentary basin was located at about 20° to 35° southern latitude (Fig. 1A), within the Rheic Ocean, and was part of the North Gondwana Province (Plusquellec and Hladil, 1998). The Lochkovian was characterized by extreme greenhouse climate, with average low latitude sea surface water temperatures (SST) around 30–32 °C calculated from oxygen isotopes in apatite from conodonts (Joachimski et al., 2009). Average SSTs start to decrease in the early Pragian and show minimum values around 22 °C in the late Emsian to Givetian (Joachimski et al., 2009). Early Pragian times were still relatively hot and humid while major climatic instability characterized mid to late Pragian times (Slavík et al., 2016).

The historical stratotypes for the Lochkovian and Pragian were defined in the Czech Republic, in the Prague Synform. The Lochkovian, in its most recent definition (Becker et al., 2012) is equivalent to its historical definition and roughly corresponds to the Lochkov Formation (Fig. 2). The historical Pragian is more or less equivalent to the Praha Fm, but the Pragian has been redefined a few decades ago (based on the basal Emsian GSSP in Kitab, Uzbekistan). It has become significantly shorter: it now corresponds only to a relatively small portion of the lower Praha Fm. (Fig. 2). However, this definition has been strongly criticized (Slavík et al., 2007; Carls et al., 2008) and a new definition of the Pragian is in progress (SDS Newsletter, 2014, p. 14). For this reason we also consider the duration of the Lochkov and Praha Fms., because their biostratigraphy is very well documented and they are still used as references (e.g. Becker et al., 2012).

During the Devonian, the Prague Basin was affected by active faulting, leading to the creation of local submarine highs, and thus to substantial difference in sediment thickness between relatively closely spaced sections (Chlupáč et al., 1998). Indeed, the Praha Fm. in the Požár-CS section is much shorter than in Pod Barrandovem, which is located only 5 km east of Požár-CS (Praha Fm. is 40.4 m thick in Požár-CS, while the same formation reaches ∼174 m thickness in the Pod Barrandovem section, to which ∼10 m missing at the base should be added to complete the Praha Fm.). However, facies in both sections are relatively similar, being dominated by carbonate distal off-shore facies. The rhythmically deposited, slightly clayey off-shore limestones are mostly hemipelagites and calciturbidites, deposited in an oxygenated water column (Hladil et al., 2010).

The continuity – crucial for a meaningful application of spectral methodology – of the different sections studied has been assessed in the literature, through biostratigraphy, sedimentary petrology and geophysical methods. The Lochkov and Praha Fms. in the Požár-CS section are partly condensed, but also considered as essentially complete without significant gaps (Koptíková et al., 2010a; Slavík, 2004a; Slavík et al., 2012). In the Branžovy section, a similar lithological succession as at Požár-CS is observed, but with a different thickness and with potential sedimentary reworking (Slavík, 2004a). The Praha Fm. at Pod Barrandovem is considered as nearly complete and undisturbed (Chlupáč, 2000), with the exception of a relatively short interval at the very base of the Praha Fm., where ∼10 m of the Slivenec limestones is missing (Fig. 2). Furthermore, there is potentially a gap at the contact with the overlying Zlichov Fm.; where the duration of this gap is unknown but very likely short as all conodont zones are present (Slavík, 2004a).

The cyclicity of these deposits has already been studied by Chlupáč (2000), who identified ∼410–450 bedding couplets within the Lochkovian and estimated about 350 to 380 couplets within the historical Pragian, pointing to a longer duration of the Lochkovian compared to the historical Pragian.

3. Materials and methods

3.1. Selected sections and sampling intervals

Two main sections Požár-CS and Pod Barrandovem were selected, with the highest sampling rate and with both χ_{in} and GRS records, complemented by one extra section (Branžovy) with a lower sampling rate GRS record. The locations of the different sections are shown on Fig. 1; Požár-CS is a composite section of Požár-1 and Požár-3 (Fig. 1E, Table A1). Sampling intervals vary between one sample every 5, 10, 25 and 50 cm (Table A1).

3.2. Magnetic measurements

Magnetic susceptibility (χ_{in}) measurements have been carried out in different laboratories but all on similar devices, using a KLY-2 at the Czech Academy of Sciences, a KLY-3 at Liège University, and a MFK-1 at Utrecht University, which are essentially different generations of the same type of Kappabridge device, manufactured by AGICO (Brno, Czech Republic). χ_{in} is mass-specific, in m^3/kg. Some hysteresis data were also gathered to get insight into the origin of the magnetic minerals carrying the magnetic susceptibility signal (detailed methodology in Appendix 1).