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The astronomical rhythm of Late-Devonian climate change (Kowala section, Holy Cross Mountains, Poland)

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ABSTRACT

Rhythmical alternations between limestone and shales or marls characterize the famous Kowala section, Holy Cross Mountains, Poland. Two intervals of this section were studied for evidence of orbital cyclostratigraphy. The oldest interval spans the Frasnian–Famennian boundary, deposited under one of the hottest greenhouse climates of the Phanerozoic. The youngest interval encompasses the Devonian–Carboniferous (D–C) boundary, a pivotal moment in Earth's climatic history that saw a transition from greenhouse to icehouse. For the Frasnian–Famennian sequence, lithological variations are consistent with 405-kyr and 100-kyr eccentricity forcing and a cyclostratigraphic floating time-scale is presented. The interpretation of observed lithological rhythms as eccentricity cycles is confirmed by amplitude modulation patterns in agreement with astronomical theory and by the recognition of precession cycles in high-resolution stable isotope records. The resulting relative time-scale suggests that ~800 kyr separate the Lower and Upper Kellwasser Events (LKE and UKE, respectively), two periods of anoxia that culminated in massive biodiversity loss at the end of the Frasnian. Th/U and pyrite framboid analyses indicate that during the UKE, oxygen levels remained low for 400 kyr and $\delta^{13}C_{org}$ measurements demonstrate that more than 600 kyr elapsed before the carbon cycle reached a steady state after a +3‰ UKE excursion. The Famennian–Tournaisian (D–C) interval also reveals eccentricity and precession-related lithological variations. Precession-related alternations clearly demonstrate grouping into 100-kyr bundles. The Famennian part of this interval is characterized by several distinctive anoxic black shales, including the Annulata, Dasberg and Hangenberg shales. Our high-resolution cyclostratigraphic framework indicates that those shales were deposited at 2.2 and 2.4 Myr intervals respectively. These durations strongly suggest a link between the long-period (~2.4 Myr) eccentricity cycle and the development of the Annulata, Dasberg and Hangenberg anoxic shales. It is assumed that these black shales form under transgressive conditions, when extremely high eccentricity promoted the collapse of small continental ice-sheets at the most austral latitudes of western Gondwana.

1. Introduction

Throughout the Phanerozoic, the imprint of Milanković's astronomical cycles is recognized in lithological rhythms, as well as in many geochemical and paleoecological proxies (e.g. Boulila et al., 2011; Fischer and Bottjer, 1991; House and Gale, 1995; Tyszka, 2009). The study of cyclical change in sedimentary archives provides a better insight in the sensitivity of the Earth's climate system to cyclic variations in the orbital parameters of the Earth (e.g. Lourens et al., 2010; Verschuren et al., 2009) and demonstrates that climatic setting strongly influences the response of climate to orbital forcing (Boulila et al., 2011; Giorgioni et al., 2012). As a geo-chronometer, astronomical rhythms observed in a sedimentary archive provide insight into absolute and relative timing questions (Ghil et al., 2002; Kuiper et al., 2008; Muller and MacDonald, 2000).

A relevant astronomical imprint into climatic proxies has been successfully demonstrated in diverse cyclostratigraphic studies of Devonian carbonate-shelf archives, exemplified by Chen and Tucker (2003), Crick et al. (2002), De Vleeschouwer et al. (2012a, 2012b), Elrick and Hinnov (2007), Elrick et al. (2009), Garcia-Alcalde et al. (2012) and House (1991, 1995). The Devonian system is poorly constrained by radiometric dating (see recent chronologies by Becker et al., 2012; Kaufmann,

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2006), and the refined analysis of sedimentary rhythmicity in stratigraphically extended and relatively continuous sequences remains an overall unexploited field and an urgent research aim, as stressed by House (2002) and Racki (2005). This study focuses on the conodont-dated and widely studied Late Devonian shelf-basin successions at Kowala, Holy Cross Mountains (central Poland; see regional geological setting in Chapter 2 and Supplementary material) characterized by distinct limestone-shale rhythmites (Bond and Zatoń, 2003; Fig. 2 in Marynowski and Filipiak, 2007; Fig. 2 in Marynowski et al., 2010; Fig. 3 in Racka et al., 2010; Fig. 3 in Racki et al., 2002; Fig. 1A and B in Racki, 2005; marly facies of Szulczewski, 1971; 1995). We test whether or not this rhythmicity is the result of astronomical forcing, within a climate on the eve of the transition from the Devonian greenhouse to the Carboniferous icehouse (Racki, 2005, p. 15; Streel et al., 2000). In addition, a comprehensive set of other environmental proxies, such as stable isotopes, magnetic susceptibility and gamma-ray spectrometry, which record only minor diagenetic/thermal overprint (Belka, 1990; Joachimski et al., 2001; Marynowski et al., 2011), serve as indispensable tools for the correct interpretation of the observed lithological variations in terms of paleoenvironmental change.

2. Regional and stratigraphic setting

Extensive outcrops of Middle to Upper Devonian reefal and basinal systems are exposed in the Holy Cross Mountains (see Supplementary material), that formed a fragment of the once vast equatorial carbonate shelves of south-eastern Laurussia (Racki, 1993; Racki et al., 2002; Szulczewski, 1995). The centrally located Frasnian Dyminy Reef evolved into a Famennian pelagic ridge, and this shoal was surrounded by drowned, oxygen-depleted deeper-shelf areas (i.e. intrashelf basins): Chęciny–Zbrza to the south, and Łysogóry–Kostomłoty to the north (Racki, 1993; Szulczewski, 1971, 1995).

The large, still active Kowala quarry near Kielce is well established as a major reference site for multifaceted Late Devonian studies. This more than 350 m thick, generally deepening-upward and continuous succession from the Chęciny–Zbrza basin is relatively well-dated using conodonts (Fig. 1), and comprehensively investigated from event-stratigraphical, paleontological and geochemical perspectives (summarized in Racki, 2005). The intensely studied distinctive Frasnian–Famennian and late Famennian bituminous horizons record several recurrent anoxic pulses that are known to be of global extent (Filipiak and Racki, 2010; Kazmierczak et al., 2012; Marynowski and Filipiak, 2007; Marynowski et al., 2010; 2012; Racka et al., 2010).

Within the largely dark to black rhythmically bedded marly series, late Frasnian to basal Carboniferous lithologic units H–N (Fig. 1; Bond and Zatoń, 2003; Szulczewski, 1996) record the post-reef phase of shelf evolution. In this study, two rhythmite-bearing successions were analyzed for cyclostratigraphy (Fig. 1):

(1) The upper Frasnian to lower Famennian interval (sets H-1 to H-4) encompasses the Frasnian–Famennian (F–F) boundary beds and records one of the greatest biodiversity crises of the Phanerozoic, the Late Devonian mass extinction (Bond et al., 2004; Joachimski et al., 2002; Racki et al., 2002). Graded bioclastic limestones (with redeposited reef-builders and brachiopod coquinas) and/or thick (up to 1 m) slump layers occur in the basal (H-1) unit only. An abrupt lithologic change from wavy- and thin-bedded marly deposits, which are highly fossiliferous in places (unit H-2), to cherty limestone strata (H-3), is particularly significant for the F-F passage (Racki et al., 2002). These relatively thick-layered calcareous sets, 6 to 8 m thick, with thin (up to 5 cm) shale breaks, constitute the main lithologic peculiarity within the otherwise uniform marly rhythmic succession of set H. In fact, the succeeding monotonous fossil-impoverished unit H-4, which is more than 100 m thick, includes regularly alternating marly limestones and shales, here analyzed in the lower part only (see also Filipiak, 2009; Marynowski et al., 2011).

(2) The highest exposed interval contains the latest Devonian thicker-layered dark platy limestone-shale couplets, interrupted by the Annulata and Dasberg black shales (set K; details in Marynowski et al., 2010; Racka et al., 2010) and the grey to brownish fossil-rich wavy-bedded to (sub)nodular calcareous set with thin shale partings (Woclumeria limestone, set L, see Supplementary material; Marynowski and Filipiak, 2007; Rakocinski, 2011). The Hangenberg bituminous shale (90 cm thick, total organic carbon (TOC) up to 22.5 wt%), that also records a major biotic crisis, albeit of less significance than the F–F event, occurs above this interval. It is succeeded by a 120 cm thick grey-greenish clayey/tuffite succession with several interbedded limestone layers (the newly proposed set M = sets B and C sensu Malec, 1995; see also Marynowski and Filipiak, 2007, Fig. 2 therein). The Devonian–Carboniferous (D–C) boundary occurs within the upper part of this unit. The Lower Carboniferous comprises a greenish clayey/tuffite interval with four thin black shale intercalations (5 to 15 cm thick) and some nodular carbonate horizons. This recently exposed succession is named herein as set *N* (= lower part set D sensu Malec, 1995, Fig. 8).

The middle segment of the Famennian succession remains unexplored due to frequent diagenetic nodular lithologies that obscure the depositional rhythmicity (Fig. 1; Marynowski et al., 2007), as well as some fault disturbances and/or covered intervals (Fig. 2 in Bond and Zatoń, 2003).

3. Materials and methods

3.1. Time-series analysis procedure

The frequency composition of lithological variations (shales, marls, micrites, sparites, calcarenites and nodular limestones) were analyzed via spectral analysis. To carry out time-series analysis of lithological variations, each lithology was assigned a different code and a quantified litholog was obtained. Spectral analysis of proxy data, like the isotopic, magnetic susceptibility and gamma-ray spectrometry records, was carried out after detrending and interpolating the records to equally-spaced intervals. Proxy data and quantified logs were analyzed using the multitaper method (MTM; Thomson, 1982) as implemented in the SSA-MTM Toolkit (Ghil et al., 2002).

The MTM-method was performed using 3 discrete prolate spheroidal sequences (DPSS) as data tapers to compromise between spectral resolution and sidelobe reduction. Small variations in accumulation rate behave like phase modulations, and introduce multiple spurious spectral peaks (Muller and MacDonald, 2000). We chose the MTM because it averages these sidelobes into the main peak and thereby gives a superior estimate of the true spectral power. To assess whether or not the strongest spectral peaks are statistically different from the red noise spectrum, the 95% confidence level (CL) is calculated (robust AR(1) estimation, median smoothing window width $=(10\Delta t)^{-1}$, Log Fit, $f_{\mathrm{Nyquist}}=2/\Delta t$).

The Continuous Wavelet Transform is used to decompose the one-dimensional time-series into their two-dimensional