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Cyclostratigraphic calibration of the Famennian stage (Late Devonian, Illinois Basin, USA)

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A B S T R A C T

The Late Devonian biosphere was affected by two of the most severe biodiversity crises in Earth's history, the Kellwasser and Hangenberg events near the Frasnian–Famennian (F–F) and the Devonian–Carboniferous (D–C) boundaries, respectively. Current hypotheses for the causes of the Late Devonian extinctions are focused on climate changes and associated ocean anoxia. Testing these hypotheses has been impeded by a lack of sufficient temporal resolution in paleobiological, tectonic and climate proxy records. While there have been recent advances in astronomical calibration that have improved the accuracy of the Frasnian time scale and part of the Famennian, the time duration of the entire Famennian Stage remains poorly constrained. During the Late Devonian, a complete Late Frasnian–Early Carboniferous succession of deep-shelf deposits accumulated in the epieric sea in Illinois Basin of the central North-American mid-continent. A record of this sequence is captured in three overlapping cores (H-30, Sullivan and H-32). The H-30 core section spans the F–F boundary; the Sullivan section spans almost all of the Famennian and the H-32 section sampled spans the interval of the Upper Famennian and the D–C boundary. To have the best chance of capturing Milankovitch cycles, 2000 rock samples were collected at minimum 5-cm-interval across the entire sequence. Magnetic susceptibility (*MS*) was measured on each sample and the preservation of climatic information into the *MS* signal was verified through geochemical analyses and low-temperature magnetic susceptibility acquisition. To estimate the duration of the Famennian Stage, we applied multiple spectral techniques and tuned the *MS* signal using the highly stable 405 kyr cycle for Sullivan and the obliquity cycle for the H-30 and H-32 cores. Based on the correlation between the cores we constructed a Famennian floating astronomical time scale, which indicates a duration of 13.5 ± 0.5 myr. An uncertainty of 0.5 myr was estimated for the uncertainties arising from the errors in the stratigraphic position of the F–F and D–C boundaries, and the 405 kyr cycle counting. Interpolated from the high-resolution U–Pb radiometric ages available for the Devonian–Carboniferous boundary we recalibrated the Frasnian–Famennian boundary numerical age to 372.4 ± 0.9 Ma.

1. Introduction

The Late Devonian is a key interval in Earth's history that is marked by a dramatic drop in CO_2 concentration (Berner, 2006) and the onset of the end-Famennian glaciation associated with the Hangenberg Event during the *Bispathodus ultimus* Zone just prior to the Devonian–Carboniferous boundary (Isaacson et al., 2008). The Middle Devonian Epoch was characterized by a greenhouse climate, a relatively high sea-level and favorable environmental conditions that contributed to afforestation associated with the diversification and spread of land plants, which culminated in the development of large trees (Algeo and Scheckler, 1998), and to the greatest diversity of marine fauna in the Palaeozoic (Sepkoski, 1997).

During the Late Devonian both marine and terrestrial biodiversity collapsed as a result of the stepped Kellwasser (end-Frasnian) and the end-Famennian Hangenberg extinction events,

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ranked as the fifth and the fourth largest biodiversity crises in the Phanerozoic, respectively (McGhee et al., 2013). The significant marine $\delta^{13}C$ oscillations (Buggisch and Joachimski, 2006) and the large number of organic-rich horizons deposited during that interval also attests to important changes in global carbon cycling. In recent estimates for the durations of stages of the Devonian Period, the duration of the Famennian Stage is the best constrained of the entire Devonian Period in terms of chronostratigraphy due to a clustering of accurate and high precision zircon U–Pb dates near that D–C boundary (Becker et al., 2012; De Vleeschouwer and Parnell, 2014). However, these 8 age-points are all in the latest Famennian, and they do not fully resolve the timing, the magnitude and cause-and-effect relationships of the significant environmental perturbations that occurred during the final stage of the Late Devonian.

The recent development of advanced time-series methods for the identification of Milankovitch cycles in sedimentary records has accelerated the refinement of the Phanerozoic geological time scale. Most of the Cenozoic time scale (Hinnov, 2013) has been astronomically calibrated (Hilgen et al., 2012), and the highly stable 405 kyr long orbital eccentricity cycles have allowed the development of a floating astronomical time scale for Mesozoic and Paleozoic sequences (e.g., Da Silva et al., 2016; Huang et al., 2010).

A growing body of research is directed towards building an astronomically tuned Devonian time scale, and has led to improvements in estimates of the time duration of the Lower Devonian Lochkovian and Pragian stages (Da Silva et al., 2016); Givetian Stage of the Middle Devonian (De Vleeschouwer et al., 2015); and the Upper Devonian Frasnian Stage (De Vleeschouwer et al., 2012) and the Frasnian–Famennian boundary and uppermost Famennian (De Vleeschouwer et al., 2013; Whalen et al., 2016). The Famennian Stage is a key interval with the second longest duration in the Devonian, but still lacks a complete cyclostratigraphic calibration and calculated duration. The present study provides an astronomically calibrated duration for the Famennian Stage based on the cyclostratigraphy of a complete Late Frasnian–Early Carboniferous epeiric deep-shelf sequence from central North America.

2. Materials and methods

2.1. Sites selection

High-resolution magnetic susceptibility (*MS*) data (sampling step of maximum 5-cm) were acquired from a continuous Late Frasnian–Early Carboniferous succession of deep-shelf hemipelagic deposits that accumulated in the western sub-basin of the Illinois Basin (Day et al., 2011; Day and Witzke, 2017; Witzke and Bunker, 2002). At that time, the Illinois Basin was located at approximately 20°S latitude (e.g., Fig. 1A; Blakey, 2015), within the extensive epieric sea covering the North American mid-continent, in western Laurussia (Fig. 1A). The sequence studied was sampled in three overlapping cores (H-30, H-32, Sullivan and H-32) cored along the Iowa–Illinois border (Fig. 1C) and stored in the Iowa Geological Survey. The cores belong to four stratigraphic units (e.g. Fig. 1B) that are, in ascending order, the Grassy Creek Shale (fissile organic-rich brown shale with carbonized plant remains in its type area, but *Tasmanites*-rich in the subsurface) (Day and Witzke, 2017), the Saverton Shale (grey calcareous shales and mudstones), the English River Formation (shales and siltstones) and the Louisiana Limestone (subtidal platform carbonates) (Fig. 1). A detailed description of the Upper Devonian lithostratigraphy in the Iowa–Illinois Basin is available in Witzke and Bunker (2002). Available conodont biostratigraphy for the cores identify the positions of Stage and System boundaries and the span in terms of the conodont zonation covered in each core (Day et al., 2015; Day and Witzke, 2012, 2017). The H-30 core section sampled spans the Frasnian–Famennian boundary (from Frasnian Subzone 13b = Lower *linguiformis* to the *Palmatolepis delicatula platys zones*); the Sullivan section spans almost all of the Famennian (from *Palmatolepis delicatula platys* to lower part of the *Bispathodus ultimus* zones of Spalletta et al. (2017) and the H-32 core section is correlated with the *Bispathodus costatus* through the *Protognathodus kockeli* zones. The English River Formation and Louisiana Limestone sampled in the H-32 core section represent the thickest known record of the Hangenberg Extinction and post-extinction survivor and recovery intervals in the world (e.g., Cramer et al., 2008). The Devonian–Carboniferous boundary, as revised by Spalletta et al. (2017), is proposed at the base of the *P. kockeli* Zone that coincides with the base of the Louisiana Limestone in the H-32 core based on the First Appearance Datum (FAD) of *P. kockeli* in the basal Louisiana Limestone as reported by Chauffe and Nichols (1995). The conodont sample series (>300 samples) indicates that there are no significant discontinuities in the studied sequence.

The shale succession lithologies, the low thermal alteration values of conodont apatite (CAI: ±1) and the well preserved organic matter indicate that the sampled strata are thermally pristine. The conodont biostratigraphic control cited above, the quiet deep-shelf depositional context and the high-resolution sampling (5–10 kyr) provide an unprecedented sedimentary record of the Famennian Stage.

2.2. Magnetic susceptibility

Our study is based on *MS* values measured on ∼2000 samples across the 90 m-thick Latest Frasnian–Early Carboniferous sequence. Samples were collected at 3-cm-interval throughout the H-30 core, and at 5-cm-interval through the Sullivan and H-32 cores to ensure the best chance of capturing Milankovitch cycles. Based on the best available duration for the Famennian Stage (13.3 ± 0.9 myr, Becker et al., 2012) and a total thickness of ∼80 m for the studied Famennian succession, our 5-cm sampling step therefore represents a ∼8.3 kyr interval while the 3-cm spacing corresponds to ∼5 kyr interval. Following Martinez et al.'s (2016) recommendations our sampling rate should preserve the significance levels of the long orbital eccentricity, short orbital eccentricity and obliquity peaks. Spectral peaks within the precession band should also be observed but likely at a low significance level for the Sullivan and H-32 sections where the sampling step is 5-cm. Each sample in this dataset was measured three times with a KLY-3s (AGICO Kappabridge located at Lehigh University's paleomagnetism laboratory) and weighed with a precision of 0.01 g for mass normalization. This allowed the determination of the low-field mass-normalized magnetic susceptibility for each sample and the establishment of a high-resolution *MS* record for each studied interval. In order to determine the relative proportion of paramagnetic (e.g., clays) vs. ferromagnetic (e.g., magnetite) phases contributing to the magnetic susceptibility data for the Sullivan succession, three representative samples (lower, middle and upper portion of the Sullivan section) were measured from −196 °C (the temperature of liquid nitrogen) to ∼20 °C (room temperature) in Lehigh's KLY-3s Kappabridge. The resulting temperature-dependent magnetic susceptibility curve is fit to the Curie–Weiss law to determine the proportion of the signal carried by paramagnetic vs. ferromagnetic magnetic minerals (Hrouda, 1994; Hrouda et al., 1997).

2.3. Trace and major elements

For this study, we use a group of 131 samples (minimum 1 sample per meter) from the Sullivan core that was analyzed for trace- and major-elements concentration at the University of Kentucky in 2008. Analyses were performed by inductively coupled