Astrochronology for the Early Cretaceous Jehol Biota in northeastern China

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A B S T R A C T

The Early Cretaceous Jehol Biota in northeastern China provides an evolutionary window for ‘feathered’ dinosaurs, primitive birds, insects and early flowering plants. It also provides critical information for the biodiversity changes of the Early Cretaceous terrestrial ecosystem. Here we report a time series analysis for the 11.2-m-thick, fossil-bearing lacustrine deposits at the Sihetun section in western Liaoning, northeastern China on the basis of high-resolution magnetic susceptibility (MS) and anhysteretic remanent magnetization (ARM) measurements. A hierarchy of sedimentary cycle bands of 120–260 cm, 50–67 cm and 18–42 cm was recorded in the MS and ARM series. With available radioisotope age constraints from the same section, sedimentary cycles of 120–260 cm, 50–67 cm and 18–42 cm were interpreted as Milankovitch cycles of short eccentricity (130 and 95 kyr), obliquity (36.6 and 46 kyr), and precession (22.1, 20.9 and 18 kyr), respectively. The 100 kyr-tuned ‘floating’ astronomical time scale indicates that the duration of the 11.2-m-thick section is ~0.67 Myr and the average depositional rate is ~1.70 cm/kyr. The duration of the 1.8-m-thick, main fossil-bearing interval that contains 8 beds of ‘feathered’ dinosaur/primitive bird fossils can be estimated as short as 150 kyr. The results suggest that climate fluctuations manifested in paleobotanical, sedimentological and geochemical records of the Yixian Formation may have been controlled by orbital forcing during Early Cretaceous.

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1. Introduction

The Early Cretaceous Jehol Biota, discovered from the Yixian Formation and its overlying Jiufotang Formation in northeastern China, provides a unique opportunity to address questions about the evolution of ‘feathered’ dinosaurs and primitive birds, the diversification of flowering plants, and the radiation of placental mammals (Zhou et al., 2003; He et al., 2004, 2006; Zhou and Wang, 2010) (Fig. 1). Furthermore, exceptionally well-preserved fossils of the Jehol Biota and the unique lithological contents (fine-grained siliciclastic rocks and volcanic ash beds) open a rare window for understanding the evolution of Early Cretaceous terrestrial ecosystems and reconstruction of paleoecological history (Zhang et al., 2010; Zhou and Wang, 2010). The mass mortality and remarkable fossil preservation of the Jehol Biota have been ascribed to repeative environmental crises induced by volcanic eruptions (Wang et al., 1999; Guo et al., 2003).

Obtaining high-precision radiometric ages from the Yixian and Jiufotang formations and evaluating the duration of biological events are essential for delineating the evolutionary patterns of the Jehol Biota. Enormous efforts using 40Ar/39Ar and U/Pb dating techniques have been taken to constrain the absolute age of the Jehol Biota, and the results from different sections indicate that the ages across the Jehol Biota range from ~131 Ma to 120 Ma (Barremian to Early Aptian) (Swisher et al., 1999, 2002; Wang et al., 2001; He et al., 2004, 2006; Yang et al., 2007; Chang et al., 2009). However, further refinement for the duration of fossil-bearing strata is hindered due to uncertainties inherent to radioisotope age-dating methods (Erwin, 2006), systematic discrepancies between 40Ar/39Ar and U–Pb dating methods (Min et al., 2000; Kuiper et al., 2008), and the limited number of volcanic/tuff layers amenable for precise dating.

Astrochronology provides an alternative method for fine-tuning the duration of stratigraphic units and geological events when continuous, fine-grained sedimentary records are available. Recent studies indicated that orbital-scale climate cycles were well preserved in terrestrial successions deposited from lacustrine and palustrine environments. Examples include the Late Triassic–Early Jurassic Newark Basin in eastern North America (Olsen and Kent, 1996), the Late Cretaceous Songliao Basin in northeastern China (Wu et al., 2007, 2009, 2013-this issue), the Early Eocene Green River Formation in North America (Machlus et al., 2008), and Miocene basins around the Mediterranean sea (Abdul Aziz et al., 2004; Abels et al., 2010). The preservation of orbital-scale climate cycles in terrestrial successions makes it possible to construct astronomical time scales with resolution potentially down to 0.02–0.40 Ma (e.g., Olsen and Kent, 1996; Abdul Aziz et al., 2004, 2006; Himov and Ogg, 2007; Wu et al., 2009, 2013-this issue).
It provides a tool to estimate the duration of critical stratigraphic intervals and geological events at remarkable resolution and precision that help to better understand the deep-time paleoclimatological and paleoecological changes (Hinnov and Ogg, 2007; Hinnov and Hilgen, 2012).

In this paper, we report a cyclostratigraphic study of fossil-bearing, thinly laminated and fine-grained lacustrine deposits of the Jianshangou unit, Yixian Formation, using high-resolution magnetic susceptibility (MS) and anhysteretic remanent magnetization (ARM) measurements obtained from the Sihetun section in northeastern China. The main objectives of this study are (1) to construct a ‘floating’ astronomical time scale that provides an independent age constraint for the duration of the Jehol Biota and its host strata, and (2) to discuss the possible causes of paleoenvironmental and paleoclimatic fluctuations recorded in the fossil-bearing strata.

2. Geological background

During Late Jurassic–Early Cretaceous, a series of rifted sedimentary basins were formed in northeastern China in response to crustal extension that was likely triggered by gravitational collapse of...
previously thickened crust (Meng, 2003; Wu et al., 2008). The Cretaceous strata surrounding the Shihetun area in western Liaoning Province were deposited from one of the extensional volcanic-sedimentary basins (Wang et al., 1983, 1998) (Fig. 1). The Jehol Biota in this region was excavated from the Yixian Formation and the overlying Jiujiotang Formation (Zhou et al., 2003).

One of the best fossil-preservation sites of the Jehol Biota is located in a small region surrounding the village of Shihetun, about 25 km south of the Beipiao City (Fig. 1a). The Yixian Formation in the Shihetun area consists of four units including, in ascending order, the Lujiazuon Unit, Lower Lava Unit, Jianshangou Unit and Upper Lava Unit (Jiang and Sha, 2007) (Fig. 1). Fossil-bearing strata in the Shihetun section are from the Jianshangou Unit, which is 14.4 m thick and composed of dark to light gray shale, siltstone, silty mudstone and fine-grained sandstone that were deposited from lacustrine environments (Zhu et al., 2007). Exceptionally well-preserved “feathered” dinosaurs Sinosauropteryx (Chen et al., 1998), Protarchaeopteryx and Caudipteryx (Ji et al., 1998), primitive birds Conclusisaurus (Hou et al., 1995), placental mammals Zhangheotherium (Hu et al., 1997), and the oldest flowering plant Archaeasax (Sun et al., 1998), have been reported from the Jianshangou Unit around this area.

A number of brownish to yellowish tuff layers have been found in the Jianshangou Unit (Wang et al., 1998) (Fig. 1). Radiometric age dating of a tuff layer overlying the ‘feathered’ dinosaur-bearing bed of the Jianshangou unit yielded 40Ar/39Ar ages of 124.6 ± 0.1 Ma, 124.6 ± 0.25 Ma and 125.0 ± 0.1 Ma (Swisher et al., 1999, 2002). Subsequent U–Pb ages of 125.2 ± 0.9 Ma (Wang et al., 2001), 124.7 ± 2.7 Ma (Yang et al., 2007) and 40Ar/39Ar age of 124.1 ± 0.3 Ma (Chang et al., 2009) were obtained from the same interval. The volcanic rocks underlying and overlying the fossil-bearing lacustrine deposits were dated 40Ar/39Ar as 123.7 ± 2.6 Ma and 124.2 ± 2.5 Ma, respectively (Zhu et al., 2007; Fig. 1c). These ages roughly constrain the duration of the Jianshangou unit as less than 1.6 Myr (Fig. 1), and provide a solid basis for constructing the astronomical time scale.

3. Sampling, magnetic measurement and data processing

The rock magnetic parameters are extensively used in cyclostratigraphy research because their measurements are comparatively fast, cost-effective and non-destructive, allowing analysis of large sample populations (Maher and Thompson, 1999; Himnov, 2004). The MS refers to the capacity of a substance to become magnetized when subjected to an external magnetic field. The ARM values reflect the concentration of fine-grained (< 20 μm), low-coercivity ferromagnetic minerals that have a relatively simple origin, and it has been successfully used in cyclostratigraphic research on continental and marine successions (e.g., Latta et al., 2006; Kodama et al., 2010; Wu et al., 2012). In this study, both MS and ARM series are used for cyclostratigraphic analysis.

A total of 670 samples were collected from the 11.2-m-thick fossil-bearing strata in the Shihetun section (41°35′20.2″ N, 120°47′35.7″ E) (Fig. 1b and c). Samples were crashed and placed into plastic paleoclimatic cubes. The MS was measured on KLY-4S Kappa-bridge. The ARM was acquired by applying a peak alternating field of 0.1 T and a bias field of 50 μT on the D-2000 AF demagnetizer, and the remanence intensity measurements were made on a JR6 spinner magnetometer. In order to identify the composition of magnetic minerals, rock magnetic experiments were carried out on representative samples. Temperature dependence of low-field magnetic susceptibilities (χ − T) was measured on a KLY-4S Kappa-bridge with a temperature apparatus (CS-3). Isothermal remanent magnetization (IRM) acquisition and direct field demagnetization were applied in an ASC IM-10-30 impulse demagnetizer. All measurements were performed in the Paleomagnetism and Environmental Magnetism Laboratory at China University of Geosciences (Beijing). Both MS and ARM values were normalized by mass, given in 10⁻⁶ m³/kg and 10⁻⁶ Am²/kg, respectively.

The average value of MS is 5.77 × 10⁻⁶ m³/kg, and the average value of ARM is 1.37 × 10⁻⁶ Am²/kg, with 34 ‘abnormal’ peak values (a1–a34) (Fig. 2). Samples with ‘abnormal’ high MS and ARM values are mostly brownish to yellowish, showing strongly weathered features. These layers are commonly less than 2 cm, and their lithologies are tuffs or tuffaceous siltstone/shale. High MS and ARM values from these layers may have overridden the normal depositional information. After removing these ‘abnormal’ points, the MS and ARM values show distinct and similar cyclic variability throughout the section (Fig. 3). The tuff/tuffaceous beds, which represent instantaneous volcanic eruption events, were excluded when constructing the new MS and ARM time series for cyclostratigraphy analysis. The MS and ARM data series were detrended prior to time series analysis by removing a 35% weighted mean from the data using the software KaleidaGraph™ (Fig. 3). Power spectral was calculated for the MS and ARM time series
in the depth and time domains using the SSA-MTM toolkit (Ghil et al., 2002), with robust red noise estimation reported at 90%, 95% and 99% confidence levels for the interpretation of spectral peak significance (Mann and Lees, 1996). The evolutionary fast Fourier transform (FFT) spectrograms were constructed and used to track changes in sedimentation rate. The Gauss band-pass filtering was carried out with the freeware Analyseries 2.0.4.2 (Paillard et al., 1996).

4. Results and discussion

4.1. Rock magnetism results

IRM measurement of representative samples shows rapid increases below a field of 100 mT and the remanence coercivity of the same samples is less than 50 mT (Fig. 4a, b), which indicate that low magnetic coercive minerals are the dominant magnetic minerals in the samples. Thermal magnetic experiment shows a gradual drop of magnetic susceptibility, indicating the existence of paramagnetic minerals. The susceptibilities on the heating curves decrease rapidly between 560 °C and 580 °C, indicating the dominance of titanomagnetite (Fig. 4c). The cooling curves are much higher than the heating curves, which can be interpreted as a formation of strong magnetic minerals during heating (Fig. 4c, d). The rock magnetic experiments show that the dominant magnetic mineral is most likely the low magnetic coercive titanomagnetite.

A normal paleomagnetic polarity was revealed from the Jianshangou lacustrine interval at the Sihetun section, and the remanence carriers were identified as titanomagnetite (Pan et al., 2001; Zhu et al., 2007). Major and trace elemental analyses indicated that the source of lacustrine deposits of the Sihetun section was mainly from weathering...
products of the underlying volcanic rocks (Ke et al., 2008). Thus, we interpret that variations in MS and ARM values of the Jianshangou Unit at the Sihetun section record fluctuations in the flux of fine-grained detrital titanomagnetic minerals in response to climate changes.

4.2. Cyclostratigraphic results

The MTM power spectral analysis and evolutionary FFT spectrum analysis of the ARM series in the depth domain reveals a hierarchy of cycles with 227 cm, 157 cm, 128 cm, 57 cm, 40 cm and 21 cm wavelengths above 99% confidence (Fig. 5a, b). The MTM power spectra and evolutionary spectrum of the untuned MS series show significant peaks at 255 cm, 120 cm, 21 cm and 18.3 cm above 99% confidence level (Fig. 5c, d). The evolutionary FFT spectrum of the MS and ARM shows that the dominant frequency of ~0.08 cycles/cm gradually changed to lower frequency of ~0.05 cycles/cm, which may indicate a higher sedimentary rate in the upper part of the section. Jiang et al. (2012) also proposed that the upper part of the section has a higher rate of sedimentation due to increased flooding events during the late stage of the lake deposition. The ratio of the major cycle bands of 120–260 cm:50–67 cm:18–42 cm is similar to the ratio of the Late Cretaceous astronomical parameters of short eccentricity (95 kyr and 130 kyr): obliquity (36.6 kyr and 46 kyr): precession (18 kyr, 20.9 kyr and 22.1 kyr) (Laskar et al., 2011) (Fig. 5a–e). Thus, we interpret these cycles as Milankovitch sedimentary cycles of short eccentricity, obliquity and precession according to the cycle length ratios (Hinnov, 2000; Weedon, 2003).

It has been recommended that long eccentricity (405 kyr) cycles should be used for the calibration of Mesozoic astronomical time scales (Laskar et al., 2004; Hinnov and Ogg, 2007; Hinnov and Hilgen, 2012), but examples have shown that astronomical time scales calibrated by ~100 kyr eccentricity cycles are identical to those tuned by long eccentricity cycles (e.g., Wu et al., 2009; Huang et al., 2010). Because no long eccentricity cycles are identified in this study, we use the 100 kyr eccentricity cycles to tune the ARM and MS series to construct a “floating” astronomical time scale (Fig. 3). The Gaussian band-pass filters were designed to extract the signal of short eccentricity cycles of 120–260 cm wavelength. As shown in Fig. 3, the studied succession recorded 6.7 short eccentricity cycles. The 120–260 cm cycles were then tuned by assigning 100 kyr to neighboring peaks in the filter-outputs in the depth domain (Fig. 3). The power spectral analysis reveals 102 kyr, 85 kyr, 39.4 kyr, 35.3 kyr, 20.9 kyr and 18 kyr peaks above 99% confidence in 100 kyr-tuned ARM series, and significant 100 kyr and 18 kyr periods in the 100 kyr-tuned MS series (Fig. 5f, g). These spectra match well with Early Cretaceous astronomical parameters of the La2010a solution (Fig. 5e; Laskar et al., 2011) and support our cyclostratigraphic interpretation on the MS and ARM data.

4.3. Time constraints for the Jehol Biota and geomagnetic polarity chron M3n

Based on the 100 kyr-tuned ‘floating’ astronomical time scale (Fig. 3), the duration of the 11.2-m-thick fossil-bearing strata is 0.67 Myr and the average depositional rate for the studied interval is 1.70 cm/kyr. The duration of the 14.4-m-thick Jianshangou Unit outcropped at the Sihetun section can be estimated as 0.86 Myr.
The ‘feathered’ dinosaur/primitive bird fossils in this section were discovered from eight layers in the 1.8-m-thick interval from 8.4 m to 10.2 m (Fig. 1c) (Zhang et al., 2004). The floating astronomical time scale (Fig. 3) suggests that the duration of these ‘feathered’ dinosaur/primitive bird fossil beds is ~150 kyr, with each fossil-bearing bed appearing at an average period of ~18.7 kyr (Figs. 1c and 3).

Recently, three new M-sequence geomagnetic polarity time scales were proposed, including GPTS12 (Ogg, 2012), MHCT12 and MHTC12-125 (Malinverno et al., 2012). The main difference of these new polarity time scales was the assignment of the onset age of M0r, i.e., 125 Ma (GPTS12 and MHCT12-125) or 121 Ma (MHTC12). Zhu et al. (2007) reported normal to reverse magnetic polarity changes from the fossil-bearing strata to the overlying volcanic rocks at the Sihetun section. In combination with 40Ar/39Ar ages from overlying and underlying volcanic rocks (125.7 ± 2.6 Ma and 124.2 ± 2.5 Ma), the normal and reversed polarities could correspond to geomagnetic polarity chron M3n (123.92–124.58 Ma) of MHTC12 (Malinverno et al., 2012), but could not correlate well with the polarity chron of the GPTS2012 (Ogg, 2012) and MHCT12-125 (Malinverno et al., 2012). The duration of ~0.86 Myr for the normal polarity of the Jianshangou section is consistent, in first order, with the duration of 0.66 ± 0.0929 Myr for M3n (Malinverno et al., 2012) and supports the polarity time scale of MHTC12, which was also preferred by Malinverno et al. (2012).

4.4. Orbital forcing of climate recorded in the Yixian Formation

Sedimentological, paleobotanical and geochemical studies revealed dynamic climate fluctuations during the deposition of the Yixian Formation. Wu (1999) proposed warm and arid climate alternations based on the size, root system and membranous leaves of plants. Jiang and Sha (2007) proposed that thin gypsum and calcareous mudstone layers in the succession were formed under very shallow-water and arid conditions. However, Li and Batten (2007) suggested a warm and seasonal climate (semi-arid) system with fairly short wet phases and long dry (arid) periods. Ding et al. (2003) indicated that most of sporopellets, plant, and wood fossils of the lacustrine deposits in this region recorded warm and wet habitats, and that only a few fossils such as xerophilous Gnetales, Bennettiales with membranous leaves, and Conifers with scaled leaves were representative of arid or semi-arid climatic conditions. Fürsich et al. (2007) also proposed a semi-arid climate in which dry periods with little air movements alternated with stormier wet seasons. Amiot et al. (2011) obtained the oxygen isotope composition of apatite from various reptile remains of the Jehol Biota from China, Thailand, and Japan, which shows that the climate in this period of the Early Cretaceous was cold and similar to that of today at equivalent latitude. The inferred low temperatures are in agreement with the marine records of late Barremian–Early Albian (e.g., Price, 1999; Puclat et al., 2003; Dumitrușcu et al., 2006).

The causes of climate changes recorded in the Yixian Formation still remain uncertain. It has been proposed that frequent volcanic activities around western Liaoning area played an important role in climate change by inducing ‘volcanic winters’ (e.g., Ding et al., 2003; Guo et al., 2003; Zhou et al., 2003). The Milankovitch cycles identified from the Jianshangou Unit in this study offers an alternative interpretation: climate variations were likely driven by Early Cretaceous orbital forcing, similar to the astronomical forcing recorded in Cretaceous marine systems (e.g., Fiet and Gorin, 2000; Gale et al., 2002; Miller et al., 2005). The Sihetun paleolake represents a relatively small and closed volcanic valley formed during volcanic eruptions of the Lower Lava Unit of the Yixian Formation. The depositional processes and lake level were very sensitive to climate and environmental changes (Jiang et al., 2012; Zhang and Sha, 2012). The rock magnetic cyclostratigraphy of the Jianshangou Unit suggests that climate variations are linked to orbital...
forcing climate cycles which are encoded by the concentration of fine-grained detrital titanomagnetite (Figs. 3–5). During periods of relatively cold and dry climates (precession maxima or low obliquity), decrease in weathering rate, precipitation and riverine discharge would result in less input of magnetic minerals, leading to lower MS and ARM values. In contrast, high MS and ARM values suggest increased input of magnetic minerals, which can be explained by increased precipitation, weathering and riverine input during warm and wet climates corresponding to periods of precession maxima or high obliquity.

5. Conclusion

Spectral analyses of high-resolution MS and ARM time series in the depth and time domain reveal significant orbital forcing climate cycles in the lacustrine deposits that host the Early Cretaceous Jehol Biota. A 100 kyr-tuned floating astronomical timescale of the ARM series indicates that the duration of the 11.2-m-thick fossil-bearing strata is 0.67 Myr and the average depositional rate is 1.70 cm/kyr. The duration of the 1.8-m-thick interval that contains abundant and well-preserved feathered dinosaur/primitive bird fossils is as short as 150 kyr. The climate fluctuations recorded in the Xixian Formation may have been controlled by orbital forcing during Early Cretaceous.

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References


