Early Cretaceous Terrestrial Milankovitch Cycles in the Luanping Basin, North China and Time Constraints on Early Stage Jehol Biota Evolution

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This research analyzes the cyclostratigraphy of the lacustrine Dabeigou Formation (DBG) of early Jehol Biota age (~130–135 Ma) in the Luanping Basin, northern China. A high-resolution (2 cm interval), 117.82-m-long magnetic susceptibility (MS) stratigraphic series was measured along the Yushuxia section. MS is positively correlated with thorium, potassium and uranium concentrations associated with gamma ray intensity, and represents a proxy for detrital influx to the Luanping Basin. Power spectral analysis identifies a hierarchy of sedimentary cycles with wavelengths of 16.38 m, 5.85–3.28 m, 1.88–1.33 m, and 0.98–0.7 m, which are interpreted to represent Earth’s orbital eccentricity, obliquity and precession index cycles. Objective testing of the MS series supports the interpretation of Milankovitch cycles, indicating an average sedimentation rate of 4.642–4.723 cm/kyr. A floating astronomical time scale with a duration of 2478 kyr is established from interpreted 405 kyr long orbital eccentricity cycles along the MS series. The 405-kyr tuned DBG MS time series closely matches the predicted orbital eccentricity of the La2004 astronomical solution from 130.787 to 133.265 Ma, providing independent temporal constraints on early stage Jehol Biota evolution. Finally, this estimated time interval for the DBG MS time series indicates that it occurred entirely within the Weissert Event.

Keywords: Early Cretaceous, Dabeigou Formation, magnetic susceptibility, astrochronology, Jehol Biota, Weissert Event

INTRODUCTION

The Early Cretaceous terrestrial Jehol Biota in East Asia is well-known for its exceptionally well-preserved feathered dinosaurs, early birds, mammals, pterosaurs, amphibians, insects and early flowering plants, and provides a unique window for understanding the evolution of Early Cretaceous terrestrial ecosystems (Zhou et al., 2003; Zhou, 2014). Geographically, the Jehol Biota is found in the Liaoning Province and adjacent areas in northeastern China. Stratigraphically, it is preserved mainly in the Dabeigou/Huajiying, Dadianzi, Yixian, and Jiufotang formations in ascending order in the Liaoning and Hebei
provinces (Figure 1; Xu et al., 2019), with an age range of \( \sim 135-120 \) Ma (Swisher et al., 1999, 2002; He et al., 2006; Yang et al., 2007; Chang et al., 2009).

It has been increasingly recognized that the biota preserved in the Dabeigou Formation (DBG) reflect the origin and early stage Jehol Biota evolution (e.g., Tian et al., 2004; Ji et al., 2006; Wang and Ji, 2009; Zhou et al., 2009; Huang et al., 2015; Niu et al., 2015; Wang et al., 2015). The discovery of the earliest occurrence of the insect *Ephemeroptes tristialis* and ostracods in the DBG, together with other fossils, suggests that the earliest Jehol Biota might already have appeared at the time when the lowermost part of Member 2 of the DBG was deposited (Zhou, 2014; Xu et al., 2019). The geochronology of the DBG indicates a range from \(~135\) to \(~130\) Ma (Liu et al., 2003; Zhang et al., 2005; He et al., 2006; Gao et al., 2018), but has large uncertainties, which impedes further progress in understanding early stage Jehol Biota evolution.

Cyclostratigraphy has been instrumental in establishing a 405-kyr-scale astronomical time scale (ATS) for the Cretaceous Period from well-preserved marine and continental successions (Hinnov, 2018; Huang, 2018). This has been possible due to the stability of the 405-kyr orbital eccentricity cycle over hundreds of millions of years (Laskar et al., 2004, 2011a; Kent et al., 2018). Cyclostratigraphy of the Cretaceous terrestrial strata from the Songliao Basin in northeastern China was interpreted with Milankovitch cycles, and established a \( \sim 28 \) Myr-long ATS for the upper Turonian-Maastrichtian stages (Wu et al., 2004, 2013b; Liu et al., 2003; Zhang et al., 2005; He et al., 2006; Gao et al., 2018), which has been possible due to the stability of the 405-kyr orbital eccentricity cycle over hundreds of millions of years (Laskar et al., 2004, 2011a; Kent et al., 2018). Subsequently, Wu et al. (2013b) analyzed cyclostratigraphy of the Lower Cretaceous Yixian Formation in the Sihetun Basin, northeastern China, estimating an average sedimentation rate of \( \sim 1.70 \) cm/kyr for the Jianshangou Beds that host “feathered” dinosaur/primitive bird fossils of the Jehol Biota. Most recently, Liu et al. (2020) found that the cyclic alluvial-fluvial synrift deposits of the Lower Cretaceous (Valanginian-Hauterivian) Shahezi Formation in Songliao Basin were controlled by astronomical forcing, and reconstructed an \( \sim 11.14 \) Myr-long floating astrochronology based on interpreted 405-kyr cycles.

The Lower Cretaceous DBG in the Yushuxia section, Luanping Basin (LPB), Hebei Province, the focus of this study, consists of 213 m of dominantly cyclic continental strata in well-exposed outcrops with abundant fossils (Liu et al., 2002; Tian et al., 2004; Wu et al., 2004; Zhang et al., 2007; Zhou et al., 2009; Niu et al., 2010). It provides a unique opportunity to develop an astrochronology to enable characterization of terrestrial climate change and environmental evolution of the Early Cretaceous Period. In this study, we conducted detailed time series analysis and modeling of the high-resolution (2 cm interval) magnetic susceptibility (MS) series of the DBG. The objectives were to search for and identify astronomical signals in the DBG, to develop an astrochronology for the early stage Jehol Biota, and to test the reliability of the astronomical solutions for early Cretaceous time.

**GEOLOGICAL SETTING**

The Luanping Basin (LPB) is located in northeastern Hebei Province, northern China, near the northern margin of the Yanshan orogenic belt (Figure 1). The paleo-latitude of LPB was \( \sim 40^\circ \) N during the Cretaceous Period, i.e., approximately the same as today (Wang, 2013; Wang C. S. et al., 2013). Here, the Volcanic Sedimentary Basin Group was formed by the active tectonics and frequent volcanic eruptions during the Late Jurassic to Early Cretaceous (Tian et al., 2004). The LPB is one of the small, terrestrial extensional basins in the Yanshan structural belt with a complete sedimentary sequence (Wu et al., 2004; Zhang et al., 2007). Its sedimentary evolution involved three successive stages: (1) “vigorous volcanic eruptions,” (2) “extensional subsidence,” and (3) “sedimentary infilling” (Zhang et al., 2007). The Jurassic and Cretaceous terrestrial strata in LPB are divided into six lithologic formations (in descending order): Jiufotang, Xiguayuan, Dadianzi, DBG, Zhangjiakou and Houcheng formations (Tian et al., 2008; Wang and Ji, 2009; Wang S. E. et al., 2013).

The DBG of the 213 meter-thick Yushuxia section (Figure 1) is well-known for its continuous non-marine Lower Cretaceous deposits and preservation of early stage Jehol Biota, including plants, pollen, spores, spinicaudatans, gastropods, bivalves, ostracods, insects, and fishes (Liu et al., 2002; Tian et al., 2004; Li et al., 2004; Zhou et al., 2009; Wang et al., 2015). The stratigraphy is characterized by alternating deposition of mudstones, shales, and siltstones, interbedded with sandstones and conglomerates of semi-deep lake facies in the lower part and deep lake facies in front of fan deltas in the upper part (Figure 2; Liu et al., 2001; Wang and Ji, 2009).

The DBG is divided into 3 members and 46 layers according to a detailed description of sedimentology and stratigraphy (Li et al., 2004; Qin et al., 2018). Member 1 (49.39 m) consists of tuffaceous, pebbly and coarse-grained sandstones, and medium to fine-grained sandstones intercalated with tuffaceous siltstone, sedimentary tuff and thin volcanic ashes. Member 2 (98.44 m) consists of siliceous mudstones and shales, interlayered with siltstones, fine to medium-grained sandstones; abundant fossils occur in this member. Member 3 (76.68 m) consists of mudstones, silty mudstones, calcareous mudstones and pelitic siltstones, and abundant fossils. The DBG represents shoreline-shallow lake to fan delta front-semi-deep lake facies in the lower part, and deep lake to fan delta front facies in the upper part (Liu et al., 2001).

The age of the DBG has been disputed for a long time. The paleontological data, including ostracods, spinicaudatans, palynotaxa, and plant macrofossils indicate that the DBG ranges from Late Jurassic to Early Cretaceous (e.g., Wan et al., 2016; Qin et al., 2018; Xi et al., 2019). Radioisotopic dating provides further constraints: in the Yushuxia section, SHRIMP zircon U-Pb dating of the tuffs in Layers 34 and 21, and the volcanic rocks of the underlying Zhangjiakou Formation indicates ages of 133.9 ± 2.5 Ma, 129.9 ± 1.2 Ma, and 135.4 ± 1.6 Ma, respectively (Figure 2; Liu et al., 2003; Gao et al., 2018). Zhang et al. (2005) obtained a LA-ICP-MS zircon U-Pb age of 135.2 ± 2.3 Ma from the Zhangjiakou Formation in the same section (Figure 2). \(^{39}\)Ar/\(^{40}\)Ar dating of a tuff layer in the upper DBG of the Jiecaiqou section, near LPB, yielded an age of 130.7 ± 1.2 Ma (He et al., 2006). Thus, the DBG can be constrained roughly from \(~135\) to \(~130\) Ma. The most recent constraints for Valanginian-Hauterivian time
FIGURE 1 | Left: Map of northeastern China, Songliao Basin (SLB), and Luanping Basin (LPB), modified from Qin et al. (2018). The location of the Yushuxia section is indicated with the red star, at GPS coordinates 40°47′ N, 117°12′ E. Right: Lower Cretaceous stratigraphic column of northern China indicating the evolution stages of the Jehol Biota. The Dabeigou Formation is highlighted with bold lines; the stratigraphic coverage of this study is shown by the vertical red line at the far right.

are: 126.08 ± 0.19 Ma (top Hauterivian) 131.29 ± 0.19 Ma (top Valanginian); and 137.05 ± 1.0 Ma (top Berriasian) (Martinez et al., 2015; Aguirre-Urreta et al., 2019), which indicates that the DBG corresponds to late Valanginian to early Hauterivian time.

DATA

Magnetic susceptibility (MS) is a measure of the degree of magnetization of a material when subject to an external magnetic field. In sediments and sedimentary rocks, MS is affected by the concentration, grain size and shape of magnetic minerals (Kodama, 2012). Many studies have shown that MS is an effective indicator for Milankovitch-scale signals in stratigraphy, and it has been extensively used to characterize both marine and terrestrial sediments (e.g., Wu et al., 2013b; Zhong et al., 2018; Kodama, 2019).

MS was measured at 0.02 m intervals (on average) along the recently exposed Yushuxia section using a portable SM-30 MS detector. A total of 117.82 meters was measured, for a total of
FIGURE 2 | MS series of the DBG section. (A) The detailed measured section with numbered beds and U-Pb ages (modified from Qin et al., 2018). (B) The MS series with interpreted long orbital eccentricity (E0-E6) cycles. (C) Detrended MS series. (D) Long (blue) and short (red) orbital eccentricity Gaussian filter outputs with passbands of 0.053 ± 0.01 and 0.2 ± 0.05 cycles/m, respectively. (E) Biostratigraphy from Qin et al. (2018). O, ostracods; S, spinacaudatans; P, palynotaxa; B, bivalves; I, insects; F, fishes.
FIGURE 3 | (A) Comparison of lithology, MS, gamma ray (GR) intensity, and percent (%) of Th, K and U contributions in Layer 19. (B) Outcrop photo of Layers 17–20 with in situ measured data from Layer 19.
TABLE 1 | Orbital eccentricity, obliquity, and precession index periodicities from the periodogram of the La2004 astronomical solution (Laskar et al., 2004), between 129.55 and 134.55 Ma, i.e., a 5 Myr-long interval with a median age 132.05 Ma, calculated by Aycycle for the TimeOpt astronomical target (orbital eccentricity and precession index) and for the ASM and COCO astronomical frequency targets (all three astronomical parameters).

| Astronomical parameter | Periodicity (kyr) |
|------------------------|------------------|
| Orbital eccentricity   | 409.6000         |
|                        | 132.1290         |
|                        | 124.1212         |
|                        | 99.9024          |
|                        | 94.1609          |
| Obliquity              | 36.6000          |
| Precession index       | 21.1405          |
|                        | 20.9514          |
|                        | 18.0839          |
|                        | 17.9256          |

Frequency in cycles/kyr is obtained by 1/periodicity.

5892 data points. This MS stratigraphic series covers from the top part of Member 1 (Layers 4–7; 16.54 m), Member 2 (Layers 8–33; 99.39 m) and the lower part of Member 3 (Layer 34; 1.89 m) (Figure 2B). Gamma ray intensity was measured at 0.1 m intervals along the section using a portable RS-230 GR detector; in this study measurements are presented for Layer 19 only for comparison (Figure 3).

MATERIALS AND METHODS

Pre-processing
The Prior to analysis, the data of 16 ash beds was removed, and MS series was interpolated to the average sample rate of 0.02 m. A low-pass filter was applied to the MS stratigraphic series using tanerfiller.m to retain astronomical frequencies while removing the very high frequencies. A cut-off frequency of 5 cycles/m and roll-off rate of 10^{-12} were defined to reject wavelengths shorter than 0.2 m. The low-pass filtered MS series was then smoothed with a 40-meter-long window with the Matlab function smooth.m with the “lowess” option to estimate irregular long-term trends that could interfere with the detection of low frequency orbital eccentricity cycles. This smoothed curve was then subtracted from the MS series (Figure 2C).

Spectral Analysis
Multi-taper method (MTM) power spectral analysis (Thomson, 1982) with pmtm.m, and the evolutionary Fast Fourier Transform (FFT) spectrogram with evoft.m (Kodama and Hinnov, 2015) were used to characterize the frequency content of the processed MS series. The MTM F-ratio test was used to determine significant harmonic lines. The MTM harmonic F-test used in the average spectral misfit analysis (see below) was performed using the “eha” function of the Astrochrono package in R (Meyers, 2014); otherwise F-test significance values were computed with Aycycle (Li et al., 2019). The application of frequency ratios, e.g., 20:5:2:1 for long orbital eccentricity (405 kyr), short orbital eccentricity (100 kyr), obliquity (36.6 kyr), and precession (20 kyr) served as a preliminary test for astronomical frequencies in the MS stratigraphic series (Huang et al., 1992; Mayer and Appel, 1999; Laskar et al., 2004).

Sedimentation Rate Modeling
Three objective methods were used to test jointly for the presence of astronomical frequencies and the most probable sedimentation rate for the DBG MS stratigraphic series:

1. Average spectral misfit (ASM) analysis (Meyers and Sageman, 2007) estimates an optimal sedimentation rate given a set of astronomical target frequencies that is compared with the set of statistically significant frequencies of the stratigraphic data series for a specified range of sedimentation rates. The sedimentation rate with the lowest misfit between data and target frequencies is the “optimal sedimentation rate” (Supplementary Material).

2. Time Optimization (TimeOpt) analysis evaluates orbital eccentricity-like variations in the data, together with supporting evidence from amplitude modulations of the precession index band, across a test range of 100 m (Meyers, 2015, 2019). TimeOptSim performs Monte Carlo AR1 model simulations to evaluate significance of TimeOpt results (Meyers and Malinverno, 2018; Supplementary Material).

3. Correlation coefficient (COCO) analysis (Li et al., 2018) estimates the correlation coefficient between power spectra of a stratigraphic proxy series and an astronomical solution in the time domain for a range of sedimentation rates. The evolutionary correlation coefficient (eCOCO) procedure was used to investigate changes in sedimentation rate along the stratigraphic series (Li et al., 2018). COCO and eCOCO analysis with 5000 Monte Carlo simulations was performed on test sedimentation rates ranging from 1 to 10 cm/kyr (Supplementary Material).

The ASM procedure was carried out using the Astrochron package in R (Meyers, 2014); TimeOpt, TimeOptSim, COCO, and eCOCO procedures were performed using the software ACycle v 2.1 (Li et al., 2019). The astronomical target frequencies used in these three procedures are based the La2004 astronomical solution periodogram for the 5-my, long interval 129.55–34.55 Ma (median age of 132.05 Ma) (Table 1; Laskar et al., 2004).

The La2004 Astronomical Solution
The accuracy of astronomical solutions declines rapidly prior to 50 Ma, and solutions other than the well-known La2004, e.g., La2010 and La2011, are thought to incorporate parameterizations and initial conditions that are superior to those used in La2004 (Laskar et al., 2011a,b), and more closely fit geological data around and prior to 50 Ma, e.g., La2010c and ZB18a (Zeebe and Lourens, 2019). The main issue centers on modeling the fundamental frequencies that involve the orbits of Earth (g_3, s_3) and Mars (g_4, s_4), and the expectation for chaotic interactions...
between these two planetary orbits through deep time. For example, La2004 from 92 to 90 Ma and 87 to 85 Ma, predicts chaotic transitions between the Earth and Mars orbits. Recently, it was discovered that these two transitions closely fit Late Cretaceous cyclostratigraphic patterns from the Western Interior Seaway (Ma et al., 2017, 2019). Here we will test whether the La2004 solution also fits cyclostratigraphic patterns of the Early Cretaceous time represented by the DBG.

RESULTS

MS Variations

MS values range from $-2.4 \times 10^{-8}$ SI to $4.2 \times 10^{-7}$ SI, with an average of $7.02 \times 10^{-8}$ SI (Figure 2B). The MS stratigraphic series shows a sustained cyclic pattern that is consistent with the decimeter- to meter-scale lithological cycles (Figures 2, 3). MS is positively correlated with gamma ray intensity and elevated $^{232}$Th, $^{40}$K, and $^{238}$U (Figure 3). Th contributes ~60% of the GR signal, which identifies GR as a primarily clay proxy (“shale log”) (Crain, 2019) that tracks the detrital influx from surrounding terrestrial source areas (Ohta et al., 2011). Recently, Pei et al. (2019) identified primary magnetic remanence and constructed a magnetostratigraphic framework for the upper DBG in LPB, further supporting the validity of the MS series as an important paleoenvironmental and paleoclimatic proxy. We propose that DBG MS is a proxy for the terrestrial hydrologic cycle, weathering and fluvial intensity, and if these processes were forced by insolation, represent Milankovitch cycles.

The DBG Stratigraphic Spectrum

$2\pi$ MTM power spectral analysis of the MS stratigraphic series indicates spectral peaks at wavelengths of 16.38 m, 5.85–4.82 m, 3.28–1.42 m, and 0.98–0.7 m above the 90% $F$-test value (Figures 4A,B). The ratio of the major cycle bands of 20.5–16.4 m: 5.85–4.82 m: 3.28–1.42 m: 0.98–0.7 m is similar to the ratio of the Early Cretaceous astronomical periodicities of long orbital eccentricity (405 kyr) : short orbital eccentricity (132, 124, 99, and...
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FIGURE 5 | ASM analysis of the DBG MS series, applied over a range of sedimentation rates from 1 to 10 cm/kyr by 0.0225 cm/kyr steps, using the La2004 astronomical target frequencies for 129.55–134.55 Ma (Table 1). All harmonics in the MS series exceeding 85% significance level, a total of 42, are evaluated. The astronomical target used is based on the list in Table 1, but has reduced the number of short eccentricity terms from four (1/132.129, 1/124.1212, 1/99.9024, 1/94.1609) to two (1/132.129, 1/95.25), which was found to yield a significantly lower $H_0$ (see Supplementary Material for ASM analysis with all 10 terms). (A) The ASM statistic between data and target spectrum. (B) The results of null hypothesis testing: $H_0$ is the probability of no target astronomical frequencies in the data. The optimal sedimentation rate occurs at the first joint lowest value ASM statistic and statistically significant $H_0$ minimum in the tested sedimentation rate range. (C) The number of astronomical terms used in the statistic; a total of 8 terms (frequencies) are included in the target (see above). (D) Comparison of significant spectral lines (dotted black lines) evaluated at the optimal sedimentation rate identified in (C) and the astronomical target lines (solid red lines). Vertical dash-dot red lines indicate solutions for optimal sedimentation rates.

95 kyr) : obliquity (37 kyr) : precession (23.0, 22.5, 21.8, 18.7, and 18.5 kyr) (Laskar et al., 2004). These cycles may be correlated with Milankovitch cycles of short orbital eccentricity, obliquity and precession according to the cycle length ratios. The evolutionary FFT spectrogram of the MS stratigraphic series (Figure 4A) indicates a sudden shift of power to higher frequencies in the 35–65 m interval, followed at $\sim$65 m by an equally sudden shift back to the lower frequencies that is then maintained to the base of the series. The question is whether these shifts indicate sudden changes in sedimentation rate, or evolution of the astronomical frequencies.

Sedimentation Rate Optimization

ASM Analysis

ASM analysis indicates a statistically significant ($H_0 \sim 1\%$) solution at 4.723 cm/kyr (Figure 5). However, only five of the total of eight astronomical target frequencies were evaluated for this result, with the long orbital eccentricity at 409.6 kyr, and short precession index terms at 18.08 and 17.9256 kyr not successfully fitted to within the half-Rayleigh spacing required by the ASM statistic (Equation 1 in Meyers and Sageman, 2007), as indicated by three vertical red lines that do not coincide with any of the black vertical dashed lines in Figure 5D.

TimeOpt/TimeOptSim Analysis

TimeOpt analysis (Figure 6) indicates a $r^2_{\text{opt}}$ maximum at a sedimentation rate of 4.642 cm/kyr, for which TimeOptSim analysis estimates a $p$-value of 0.119 (Figure 6I). This is close to the 4.723 cm/kyr sedimentation rate solution obtained by ASM (see above). The $r^2_{\text{envelope}}$ assessment (Figure 6A) indicates a much faster 9.224 cm/kyr with a very low $p$-value of 0.05348 (Figure 6G); $r^2_{\text{power}}$ (Figure 6A) indicates 6.339 cm/kyr, and
a much higher p-value of 0.47128 (Figure 6H). Adopting 4.642 cm/kyr as the optimal sedimentation rate, the MS series has a periodogram with a strong orbital eccentricity signature (Figure 6F).

**COCO/eCOCO Analysis**

COCO analysis indicates three maxima at 3.32, 4.72, and 6.34 cm/kyr, the largest at 4.72 cm/kyr with a correlation coefficient value exceeding 0.4 (Figure 7A). All three...
FIGURE 7 | Correlation coefficient (COCO) and evolutionary correlation coefficient (eCOCO) analysis of the DBG MS stratigraphic series. (A) Correlation coefficient vs. test sedimentation rate estimation of the correlation coefficient between the power spectra of astronomical solutions and the DBG MS series indicating an optimal sedimentation rate of 4.72 cm/kyr (top), and a sliding stratigraphic window to track variable sedimentation rates through the MS series (bottom). The vertical black lines indicate sedimentation rates according to the 405-kyr tuning (Table 2); the vertical dashed lines highlight the higher COCO values along the section. (B) The null hypothesis ($H_0$) significance level test (top) and evolutionary null hypothesis ($H_0$) significance level (bottom). For both the COCO and eCOCO, tested sedimentation rates range from 1 to 10 cm/kyr with a step of 0.02 cm/kyr, and the number of Monte Carlo simulations is 5000. For eCOCO analysis, the sliding window size is 38 m; the sliding window step is 0.02 m. In the top graph: the dashed horizontal line indicates $H_0 = 0.01$; the horizontal dotted lines, from top to bottom, indicate $H_0 = 0.001, 0.05$, and 0.1.
sedimentation rates have $H_0$ significance levels lower than 0.01 (Figure 7B). The results of eCOCO analysis shows that the sedimentation rates vary from 4.72 to 6.3 cm/kyr (Figure 7A).

**DISCUSSION**

**Sedimentation Rate Variations in the DBG MS Series**

The optimal sedimentation rates indicated by the ASM, TimeOpt and COCO methods are summarized in Table 3. Only one sedimentation rate is shared by all three methods: 4.642 cm/kyr (TimeOpt) to 4.72 cm/kyr (ASM, COCO). Other sedimentation rates arising at 3.4 and 6.34 cm/kyr can be explained as the result of sedimentation rate variations, as revealed by eCOCO (Figure 6A). The TimeOpt precession index amplitude envelope model result indicating 9.224 cm/kyr (red circles, Figure 6A) with an extremely low $P$-value of 0.05348 (Figure 6G), is twice the joint optimal sedimentation rate of 4.642 cm/kyr that has a higher $P$-value of 0.11902, but shows an excellent fit of orbital eccentricity model frequencies in the periodogram (from 0 to 0.12 cycles/kyr) (Figure 6F). It is worth further considering this periodogram, and rescaling the frequencies by a factor of 2 (for 9.224 cm/kyr). This would shift the data spectral peaks that are currently at $\sim$100 kyr (0.01 cycles/kyr) to $\sim$50 kyr, and $\sim$400 kyr (0.0025 cycles/kyr) to $\sim$200 kyr, which do not coincide with the orbital eccentricity terms. Indeed, $r_{2_{\text{opt}}}$, which compares the orbital eccentricity model and sedimentation rate-calibrated data, records a low value at 9.224 cm/kyr (Figure 6A). The joint modeling by $r_{2_{\text{opt}}}$ steers the TimeOpt solution toward the sedimentation rate (4.642 cm/kyr) that produces a data periodogram with credible orbital eccentricity frequencies, and it is comparable to the sedimentation rate (4.72 cm/kyr) estimated by the other methods.

**Astrochronology of the DBG MS Series**

The astronomical frequencies identified in the DBG are supported by coeval evidence for astronomical forcing in the Valanginian–Hauterivian marine systems (e.g., Fiet et al., 2006; Martinez et al., 2015; Aguirre-Urreta et al., 2019). The optimization procedures reveal that the 20.5–16.4 m, 5.85–4.82 m, 3.28–1.42 m, and 0.98–0.75 m wavelengths in the MS stratigraphic series are associated with the periodicities of the long and short orbital eccentricity, obliquity and precession index, respectively.

Notably, assuming that the 16–20 m thick MS cycles along the section are 405 kyr cycles indicates sedimentation rates that are closely aligned with the objective testing (Figure 7: vertical dashed and solid black lines in the eCOCO color maps). The recognition of 405-kyr cycles is important for the ongoing initiative to define cyclostratigraphy in terms of the 405-kyr g2-g5 orbital eccentricity metronome for the geologic time scale (Kent et al., 2018; Hinnov, 2018). Applying the 405-kyr-based chronology model (Table 2) to convert the DBG MS stratigraphic series to a time series results in a spectrum with power concentrated in the short orbital eccentricity (influenced in part by three 100-kyr scale time points in Table 2), obliquity [1/(40.9 kyr), 1/(36.9 kyr) and 1/(27.6 kyr)] and precession index [1/(22.1 kyr) and 1/(18.9 kyr)] bands (Figure 4C). The spectrogram of the 405-kyr tuned MS series also indicates that the long and short orbital eccentricity trade positions in dominance at $\sim$400–500 kyr intervals along the section (Figure 4D).

The DBG MS cyclostratigraphy and the La2004 astronomical solution from 135 to 130 Ma are shown together in Figure 8. The yellow shading indicates a proposed correlation interval between data and model, from 133.265 to 130.787 Ma. This specific correlation was selected according to the singular coincidence at 131.538 Ma of an obliquity maximum and an orbital eccentricity minimum in both the La2004 astronomical solution and the 405-kyr tuned DBG time series (green vertical line in Figure 8). The obliquity-filtered DBG series (Figure 8D) also shows a pronounced amplitude modulation cycle that repeats every 6–7 cycles, which could be evidence for the recently described 173-kyr $83\sim\delta_8$ metronome, that is also present in the La2004 obliquity (Figure 8B; Boulila et al., 2018; Hinnov, 2018).

**Paleoclimate Implications: The Weissert Event**

The Weissert Event, characterized by a positive marine d$^{13}$C excursion and global cooling, is the first major Early Cretaceous Earth system perturbation in the geologic record (Erba et al., 2004; Gröcke et al., 2005; Gréselle et al., 2011; Föllmi, 2012; Bajnai et al., 2017; Price et al., 2018). It is thought to span as much as 5.85 Myr (135.22–129.37 Ma) from the start of the Late Valanginian to the end of the Early Hauterivian (Martinez et al., 2015).
By this measure, the DBG, from 133.265 to 130.787 Ma (Figure 8), falls entirely within the Weissert Event. Geochemical analysis of the DBG indicates that the formation was deposited under relatively low-intensity hinterland weathering related to the boreal or semiarid regions; the upper unit of the DBG records hinterland weathering that is comparable to that in temperate and humid mid-latitude regions (Ohta et al., 2011). Palynoflora data also indicate that the paleoclimate changed from semi-humid to relatively temperate and humid conditions during DBG time (Wang et al., 2016).

The change toward more humid conditions during the late Berriasian and intensification during the Valanginian Weissert Event evidently influenced terrestrial biota, and especially the evolution of herbivore vertebrates. A study of oxygen isotope composition of vertebrate apatite in Liaoning Province, China, indicates global cooling during Jehol Biota time, demonstrated by an estimated air temperature of $10 \pm 4^\circ$C (Amiot et al., 2011). Zhou (2014) also found temperate-to-cool-temperate fossil wood genus *Xenoxylon* in the Jehol Lagerstätte and an absence of crocodilians in northeastern China.

**CONCLUSION**

The DBG in the LPB, Hebei Province, northeastern China represents the prelude to the Jehol Biota, the spectacular Lagerstätte in the Lower Cretaceous. However, the DBG also occurs in a geologic interval that is chronostratigraphically very
poorly constrained. This state of affairs motivated measuring the DBG for MS to search for astronomical signals during DBG time, with the larger goal of developing an astrochronology for the formation. The results are as follows:

- A high-resolution (2 cm measuring interval) MS stratigraphic series was collected from the predominantly cyclic continental (lacustrine) DBG of the Yushuxia section in Luanping Basin, NE China.
- Gamma ray (GR) data indicate that MS increases with detrital content of the sediment, linking MS to fluvial delivery of sediment to the LPB, the hydrologic cycle, and climate forcing.
- Spectral analysis of the DBG MS stratigraphic series indicates that cyclicity occurs at wavelengths of 16.38 m, 5.85–4.82 m, 3.28–1.42 m, and 0.98–0.75 m. These are proposed to represent long orbital eccentricity, short orbital eccentricity, obliquity and precession index cycles.
- Objective testing using ASM, TimeOpt/TimeOptSim and COCO/eCOCO indicates the presence of Early Cretaceous (∼132.05 Ma) astronomical frequencies predicted by the La2004 astronomical solution. The testing identifies common optimal sedimentation rates of 4.64–4.72 cm/kyr measured by all three methods.
- Correlation between the 405-kyr-tuned DBG MS time series and the La2004 astronomical solution, generally constrained by radioisotope dating, suggests that the DBG was deposited from 133.265 to 130.787 Ma with a duration of 2478 kyr.
- Strong correlation between the DBG MS-La2004 astronomical solution raises the possibility that the La2004 solution is valid much further back in time than is currently recognized.
- The global cooling Weissert Event lasted from 135.22 to 129.37 Ma, indicating that DBG deposition, and hence, early stage Jehol Biota, occurred entirely within the Weissert Event.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation, to any qualified researcher.

AUTHOR CONTRIBUTIONS

HW designed the study. WL measured the data and performed the analysis and modeling. WL, LH, and HW wrote the manuscript. All authors contributed to data interpretation and provided significant input to the final manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2020.00178/full#supplementary-material

REFERENCES

Aguirre-Urreta, B., Martinez, M., Schmitz, M., Lescano, M., Omarini, J., Tunik, M., et al. (2019). Interhemispheric radio-astrochronological calibration of the time scales from the andean and the tethyan areas in the valanginian-hauterivian (Early Cretaceous). *Gondwana Res.* 70, 104–132. doi: 10.1016/j.gr.2019.01.006

Amiot, R., Wang, X., Zhou, Z. H., Wang, X. L., Buffetaut, E., Lécuyer, C., et al. (2011). Oxygen isotopes of East Asian dinosaurs reveal exceptionally cold Early Cretaceous climates. *Proc. Natl. Acad. Sci. U.S.A.* 108, 5179–5183. doi: 10.1073/pnas.1013691018

Bajnai, D., Pálfy, J., Martinez, M., Price, G. D., Nyerges, A., and Fõzy, I. (2017). Multi-proxy record of orbital-scale changes in climate and sedimentation during the weissert event in the valanginian bierek marl formation (Gerecse Mts., Hungary). *Cretaceous Res.* 75, 45–60. doi: 10.1016/j.cretres.2017.02.021

Bouilla, S., Vahlenkamp, M., De Vleeschouwer, D., Laskar, J., Yamamoto, Y., Pülke, H., et al. (2018). Towards a robust and consistent middle Eocene astronomical timescale. *Earth Planet. Sci. Lett.* 486, 94–107. doi: 10.1016/j.epsl.2018.01.003

Chang, S. C., Zhang, H. C., Renne, P. R., and Fang, Y. (2009). High-precision 40Ar/39Ar age for Jehol Biota. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 280, 94–104. doi: 10.1016/j.palaeo.2009.06.021

Crain, E. R. (2019). Available at: www.spec2000.net. (accessed December 31, 2019).

Erba, E., Bartolini, A., and Larson, R. (2004). Valanginian Weissert oceanic anoxic event. *Geology* 32, 149–152. doi: 10.1130/G20008.1

Fiet, N., Quideleur, X., Parize, O., Bulot, L. G., and Gillot, P. Y. (2006). Lower Cretaceous stage durations combining radiometric data and orbital chronology: towards a more stable relative time scale? *Earth Planet. Sci. Lett.* 246, 407–417. doi: 10.1016/j.epsl.2006.04.014

Föllmi, K. B. (2012). Early Cretaceous life, climate and anoxia. *Cretaceous Res.* 35, 230–257. doi: 10.1016/j.cretes.2011.12.005

Gao, L. Z., Wang, Y. S., and Zhang, H. (2018). A discussion on Jurassic and Cretaceous boundary based on the SHRIMP zircon U-Pb dating of Mesozoic holotype section in Luanping basin. *Geol. Bull. China* 37, 1186–1192.

Grésille, B., Pittet, B., Mattioli, E., Joachimski, M., Barzarin, N., Riquier, L., et al. (2011). The Valanginian isotope event: a complex suite of palaeoenvironmental perturbations. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 306, 41–57. doi: 10.1016/j.palaeo.2011.03.027

Gröcke, D. R., Price, G. D., Robinson, S. A., Baraboshkin, E. Y., Mutterlose, J., and Ruffell, A. H. (2005). The upper valanginian (Early Cretaceous) positive carbon-isotope event recorded in terrestrial plants. *Earth Planet. Sci. Lett.* 240, 495–509. doi: 10.1016/j.palaeo.2005.09.001
Ma, C., Meyers, S. R., and Sageman, B. B. (2019). Testing late Cretaceous astronomical solutions in a 15 million year astrochronologic record from North America. *Earth Planet. Sci. Lett.* 513, 1–11. doi: 10.1016/j.epsl.2019.01.053

Meyers, M., Deconinck, J. F., Pellenard, P., Riquier, L., Company, M., Reboulet, S., et al. (2015). Astrochronology of the valanginian-hauterivian stages (Early Cretaceous): chronological relationships between the Paraná-Eldeńka large igneous province and the Weissett and the Faraoi events. *Global Planet. Change* 131, 158–173. doi: 10.1016/j.gloplacha.2015.06.001

Mayer, H., and Appel, E. (1999). Milanovich cyclicity and rock-magnetic signatures of palaeoclimatic changes in the Early Cretaceous Bacnone Formation of the Southern Alps. *Italy. Cretaceous Res.* 20, 189–214. doi: 10.1016/cres.1999.0145

Meyers, S. R. (2014). *Astrochron: An R Package for Astrochronology*. Available at: https://cran.r-project.org/package=astrochron

Meyers, S. R. (2015). The evaluation of eccentricity-related amplitude modulation and bundling in paleoclimate data: an inverse approach for astrochronological testing and time scale optimization. *Paleoceanography* 30, 1625–1640. doi: 10.1002/2015PA002850

Meyers, S. R. (2019). Cyclostratigraphy and the problem of astrochronologic testing. *Earth Sci. Rev.* 190, 190–223. doi: 10.1016/j.earscirev.2018.11.015

Meyers, S. R., and Malinverno, A. (2018). Proterozoic milankovich cycles and the history of the solar system. *Proc. Natl. Acad. Sci. U.S.A.* 115, 6363–6368. doi: 10.1073/pnas.1717891115

Ni, S. W., Tian, S. G., and Pang, Q. Q. (2010). Conchostracan biostratigraphy of the dadianzi formation in the luanping basin, northern Hebei, China and the boundary of continental Jurassic and Cretaceous strata. *Geol. Bull. China* 29, 961–979.

Ohta, T., Li, G., Hirano, H., Sakai, T., Kozai, T., Yoshikawa, T., et al. (2011). Early Cretaceous terrestrial weathering in Northern China: relationship between palaeoclimatic change and the phased evolution of the Jehol biota. *J. Geol.* 119, 81–96. doi: 10.1086/657341

Pe, I. L., Yang, Z. Y., Sun, Z. M., Tong, Y. B., Cai, Y. H., Wang, X. R., et al. (2019). Magnetostatigraphic dating of the early Jehol biota. *Acta Geosci. Sin.* 40, 393–404.

Price, G. D., Jansen, N. M. M., Meyers, M., Company, M., Vandeveld, J. H., and Grimes, S. T. (2018). A High-Resolution belemnite geochemical analysis of early Cretaceous (Valanginian-Hauterivian) environmental and climatic perturbations. *Geochim. Geophys. Geosyst.* 19, 3832–3843. doi: 10.1002/2018GC007676

Qin, Z. H., Xi, D. P., Sames, B., Do Carmo, D. A., Wang, X. R., Xu, K. K., et al. (2018). Ostracods of the non-marine lower Cretaceous dabeigou formation at yushuxia (Luanping basin, North China): implications for the early Jehol Biota age. *Cretaceous Res.* 86, 199–218. doi: 10.1016/j.cretres.2018.03.010

Swisher, C. C., Wang, X. L., Zhou, Z. H., Wang, Y. Q., Jing, F., Zhang, J. Y., et al. (2002). Further support for a Cretaceous age for featured dinosaur beds of liaoning province, China: new 40Ar/39Ar dating of the Yixian and Tuchengzi formations. *Chin. Sci. Bull.* 47, 135–138.

Swisher, C. C., Wang, Y. Q., Wang, X. L., Xu, X., and Wang, Y. (1999). Cretaceous age for the feathered dinosaurs of Liaoning, China. *Nature* 400, 59–61. doi: 10.1038/21872

Thomson, D. (1982). Spectrum estimation and harmonic analysis. *Proc. IEEE* 70, 1055–1096. doi: 10.1109/PROC.1982.12433

Tian, S. G., Ni, S. W., and Pang, Q. Q. (2008). Redefinition of the lower Cretaceous terrestrial Yixianian Stage and its stratotype candidate in the Luoping basin, northern Hebei. *Geol. Bull. China* 27, 739–752. doi: 10.3969/j.issn.1671-2552.2008.06.003

Tian, S. G., Pang, Q. Q., Ni, S. W., Li, P. X., and Liu, Y. Q. (2004). Terrestrial Jurassic-Cretaceous boundary candidate in Luoping basin, northern Hebei. *Geol. Bull. China* 23, 1170–1179. doi: 10.3969/j.issn.1671-2552.2004.12.002

Wan, X. Q., Gao, F. L., Qin, Z. H., Cui, C., and Xi, D. P. (2016). The Jurassic-Cretaceous boundary problem and the discussion on continental boundary of northern China. *Geosci. Front.* 23, 1–6.
Wang, C. S. (2013). Environmental/climate change in the Cretaceous greenhouse world: records from Terrestrial scientific drilling of songliao basin and adjacent areas of China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 385, 1–5. doi: 10.1016/j.palaeo.2013.05.006

Wang, C. S., Feng, Z. Q., Zhang, L. M., Huang, Y. J., Cao, K., Wang, P. J., et al. (2013). Cretaceous paleogeography and paleoclimate and the setting of SKI borehole sites in Songliao Basin, northeast China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 385, 17–30. doi: 10.1016/j.palaeo.2012.01.030

Wang, S. E., Gao, L. Z., Wan, X. Q., and Song, B. (2013). Ages of Tuchengzi Formation in western Liaoning-northern Hebei area in correlation with those of international strata. *Geol. Bull. China* 32, 1673–1690. doi: 10.3969/j.issn.1671-2552.2013.11.001

Wang, D. N., Wang, X. R., and Ji, Q. (2016). The Palynoflora alternation and the paleoclimate change at the turning time between Late Jurassic and Early Cretaceous in Northern Hebei and Western Liaoning. *Acta Geosci.* Sin. 37, 449–459. doi: 10.3975/cagshb.2016.04.07

Wang, S. E., and Ji, Q. (2009). Lithostratigraphy and biostratigraphy features of Zhangjiakou formation and dabeigou formation and its significance for stratigraphic subdivision and correlation in the Northeast Asia. *Geol. Bull. China* 28, 821–828.

Wang, Y. Q., Sha, J. G., Pan, Y. H., and Zhang, X. L. (2015). Early Cretaceous nonmarine ostracide biostratigraphy of western Liaoning area. NE China. *Micropaleontology* 61, 135–145. doi: 10.1002/rcm.2049

Wu, F. D., Chen, Y. J., Hou, Y. A., Zhang, F., and Li, U. (2004). Characteristics of sedimentary tectonic evolution and high-resolution sequence stratigraphy in luoping basin. *Earth Sci. J. China Univ. Geosci.* 29, 625–630.

Wu, H. C., Zhang, S. H., Hinnov, L. A., Jiang, G. Q., Yang, T. S., Li, H. Y., et al. (2014). Cyclostratigraphy and orbital tuning of the terrestrial upper Santonian-Lower Danian in Songliao Basin, northeastern China. *Earth Planet. Sci. Lett.* 407, 82–95. doi: 10.1016/j.epsl.2014.09.038

Wu, H. C., Zhang, S. H., Jiang, G. Q., Hinnov, L. A., Yang, T. S., Li, H. Y., et al. (2013a). Astrochronology of the early turonian-early campanian terrestrial succession in the songliao basin, northeastern China and its implication for long-period behavior of the Solar System. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 385, 55–70. doi: 10.1016/j.palaeo.2012.09.004

Wu, H. C., Zhang, S. H., Jiang, G. Q., Yang, T. S., Guo, J. H., and Li, H. Y. (2013b). Astrochronology for the Early Cretaceous Jehol Biota in Northeastern China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 385, 221–228. doi: 10.1016/j.palaeo.2013.05.017

Wu, H. C., Zhang, S. H., Jiang, G. Q., and Huang, Q. H. (2009). The floating astronomical time scale for the terrestrial late Cretaceous Qingshankou formation from the Songliao Basin of Northeast China and its stratigraphic and paleoclimate implications. *Earth Planet. Sci. Lett.* 278, 308–323. doi: 10.1016/j.epsl.2008.12.016

Xi, D. P., Wang, X. Q., Li, G. B., and Li, G. (2019). Cretaceous integrative stratigraphy and timescale of China. *Sci. China: Earth Sci.* 62, 256–286. doi: 10.1007/s11430-017-9262-y

Xu, X., Zhou, Z., Wang, Y., and Wang, M. (2019). Study on Jehol Biota: recent advances and future prospects. *Sci. China: Earth Sci.* 49, 1491–1511. doi: 10.1360/SSr-2019-0121

Yang, W., Li, S. G., and Jiang, B. Y. (2007). New evidence for Cretaceous age of the feathered dinosaurs of Liaoning: zircon U-Pb SHRIMP dating of the Yixian Formation in Sihetun, northeast China. *Cretaceous Res.* 28, 177–182. doi: 10.1016/j.cretres.2006.05.011

Zeebe, R. E., and Lourens, L. (2019). Solar System chaos and the Paleocene-Eocene boundary age constrained by geology and astronomy. *Nature* 365, 926–929. doi: 10.1126/science.aax0612

Zhang, H., Liu, X. M., Zhang, Y. Q., Yuan, H. L., and Hu, Z. C. (2005). Zircon U-Pb ages and significance of bottom and top beds of Zhangjiakou Formation in Liaoning and Hebei Provinces. *Earth Science-Journal of China University of Geosciences* 30, 387–401.

Zhang, Y. L., Qu, H. J., and Meng, Q. R. (2007). Depositional process and evolution of Luanping Early Cretaceous basin in the Yanshan structural belt. *Acta Petrol. Sin.* 23, 667–678. doi: 10.3321/j.issn:1000-0569.2007.03.013

Zhong, Y. Y., Wu, H. C., Zhang, Y. D., Zhang, S. H., Yang, T. S., Li, H. Y., et al. (2018). Astronomical calibration of the middle ordovician of the yangtze block, South China. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 505, 86–99. doi: 10.1016/j.palaeo.2018.05.030

Zhou, Z. H. (2014). The Jehol biota, an early Cretaceous terrestrial Lagerstätte: new discoveries and implications. *Natl. Sci. Rev.* 1, 543–559. doi: 10.1093/nsr/nwu055

Zhou, Z. H., Barrett, P. M., and Hilton, J. (2003). An exceptionally preserved lower Cretaceous ecosystem. *Nature* 421, 807–814. doi: 10.1038/nature01420

Zhou, Z. H., He, H. Y., and Jiang, X. L. (2009). The continental Jurassic–Cretaceous boundary in China. *Acta Palaeontol. Sin.* 48, 541–555.

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