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

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Abstract

The first complete Early Turonian–Early Campanian lacustrine succession has been recovered from the SK-I borehole in the Songliao Basin (SLB), northeastern China. We conducted a detailed cyclostratigraphic study of natural gamma-ray (GR) log, thorium (Th) log, and magnetic susceptibility (MS) data from this core. Spectral analysis of the upper Quantou Formation (K 2q 3+4 ), Qingshankou Formation (K 2q 3), Yaojia Formation (K 2y), and lower Nenjiang Formation (K 2n1+2 ) reveals a hierarchy of meter- to decameter-scale cycling in the data. The wavelength ratios of the cycles in these stratigraphic units are ~20:5:2:1, corresponding with those of Milankovitch cycle periods of 405 kyr (long eccentricity):100 kyr (short eccentricity):37 kyr (obliquity):20 kyr (precession), indicating astronomical control on sedimentation. An astronomical time scale (ATS) was established by tuning interpreted 405 kyr cycles to a 405 kyr orbital eccentricity target curve, and to four SIMS U–Pb zircon isotope ages. This ‘absolute’ ATS provides precise numerical ages for stratigraphic boundaries, biozones, geological and geophysical events, and serves as a basis for correlation of strata and events between marine and terrestrial systems. The ages of the C33r/ C34n geomagnetic polarity boundary in K 2n2 and three short reversal events in K 2y are estimated as 83.633 Ma, 84.819–84.862 Ma, 84.982–85.092 Ma and 85.240–85.629 Ma, respectively. Long-period amplitude modulations in the obliquity and eccentricity bands of the 405-kyr-tuned GR-Th series provide strong evidence that long-period orbital forcing influenced climate change and depositional processes in the SLB. The extracted amplitude modulations provide evidence that the orbits of Earth and Mars were not in secular resonance, and were undergoing chaotic interactions during this time, although the modulations do not match those of recent astronomical models.

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1. Introduction

The Cretaceous Period is characterized by greenhouse climates and a sequence of remarkable geological and geophysical events that includes widespread oceanic anoxic events (OAES), intense volcanic activity, high sea level and the Cretaceous normal superchron (CNS). The evidence for these conditions and events mostly originates from marine stratigraphy. To improve our understanding of changes in terrestrial environments of the Cretaceous, two boreholes (SK-I South and North) with a total length of 2485.89 m, recovering strata from Early Turonian to Early Paleogene, were drilled in the Songliao Basin (SLB), northeastern China (Fig. 1) (Wang et al., 2009a).

Establishing a precise age framework for the drill cores has been a critical task for the SK-I Drilling Project. Recently, a new time framework was established for the SK-I boreholes with a complete geomagnetic polarity chron sequence from upper C34n to C29n and four SIMS U–Pb zircon ages (Deng et al., 2013–this issue; He et al., 2012). The SK-I core contains the four U–Pb ages; the uppermost age confirms that the polarity reversal at 985.95 m is the C33r/C34n boundary (Fig. 2). Despite this important advance, the time resolution for the SK-I core (Early Turonian–Early Campanian) remains too low to accurately estimate the ages and durations of geological and geophysical events.

It is well known that the Earth’s astronomical parameters influence the global climate (e.g., Hinnov and Ogg, 2007). Astronomical time calibration through cyclostratigraphic studies provides a tool to establish an ultra-high resolution (0.02–0.4 Myr) astronomical time
The SLB is one of the largest and long-lived Cretaceous continental basins in the world. It is 750 km long, 330–370 km wide with an area of 260,000 km². It is surrounded by the Great Xing’an Mountains to the west, the Lesser Xing’an Mountains to the north and the Zhangguangcun Mountains to the east (Fig. 1). The basin was formed and filled during four tectonic episodes: mantle upwelling, rifting, post-rift thermal subsidence and structural inversion (Wang et al., 2007). The basement of the SLB is composed of Precambrian to Paleozoic metamorphic and igneous rocks and Paleozoic to Mesozoic granites (Wang et al., 2006; Pei et al., 2007). The formation and sediment fill of the SLB were closely related to the tectonic evolution stages, and was broadly controlled by the Mongolia–Okhotsk collision belt, and the westward subduction of the Pacific Plate underneath the Asia continent (Wang et al., 2007; Feng et al., 2010).

Borehole SK-Is is located at the central depression zone of the SLB (Fig. 1). A total of 944.23 m of core was collected with a recovery ratio of 99.73% (Wang et al., 2009a). The drill core covers four sedimentary formations, from lower member 2 of the Neijiang Formation (K2n2) to upper member 3 of the Quantou Formation (K2q3), that were deposited during the post-rift thermal subsidence stage (Wang et al., 2007; Feng et al., 2010) (Fig. 2). The K2n1+2 (960 m to 1128.17 m) consists of dark mudstones intercalated with thin carbonates, black shales and oil shales that were deposited in deep lake environments (Gao et al., 2011). The Yaojia Formation (K2y) (1128.17 m to 1285.91 m) is composed of brownish, greenish and grayish mudstone and greenish muddy siltstone that formed in deltaic and shallow lacustrine environments (Cheng et al., 2009). The Qingshankou Formation (K2q1) (1285.91 m to 1782.93 m) consists of gray, dark gray and black mudstone inter-bedded with marlstone, with oil shale in the lower and thin bedded gray siltstone in the upper part. It has a shallowing-upward trend from deep lacustrine deposits in K2q1 (Gao et al., 2009) to moderately deep and shallow lacustrine deposits in K2q2+3 (Wang et al., 2009b). Finally, K2q3+4 (1782.93 m to 1915.0 m) is characterized by grayish green or brown mudstone, siltstone and sandstone interpreted as meandering river and deltaic deposits (Wang et al., 2009c).

Detailed core descriptions indicate that meter-scale sedimentary cycles are well developed throughout the SK-Is borehole (Cheng et al., 2008, 2009; Gao et al., 2009; Wang et al., 2009b). The meter-scale cycles are expressed by variations in rock color, lithology and composition, with sedimentary structures that include cross-bedding and normal grading (indicative of shallow lake and meandering river facies), reverse grading (primarily deltaic facies) and non-graded, fine-grained deposits (deep lacustrine facies) (Cheng et al., 2008). Cycle thicknesses range from 0.5 m to 1.5 m, and in K2q3+4 are up to 6.51 m. Fischer plots indicate that the cycles are bundled into fifth and fourth order cycles with 1:3 to 1:4 and 1:6 to 1:12 ratios, respectively (Cheng et al., 2008). These lower order cycles were attributed to Milankovitch cycles of precession and eccentricity. This interpretation is consistent with spectral analysis of the natural gamma-ray logs of K2n1 and K2q3+4 throughout the SLB (Wu et al., 2007, 2009).

Recently, He et al. (2012) obtained four SIMS zircon U–Pb radioisotope ages for bentonite beds in the SK-Is borehole, providing ages of 83.7 ± 0.5 Ma at 1019 m, 90.4 ± 0.4 Ma at 1673 m, 90.1 ± 0.6 Ma at 1705 m, and 91.4 ± 0.5 Ma at 1780 m (Fig. 2). On the basis of these ages, they interpreted the magnetic reversal at 985.95 m as the boundary of C33r/C34n, and three magnetic reversals (1144.4 m–1149.8 m, 1163.85 m–1175.9 m and 1193.15 m–1239.9 m) as short reversal events (Fig. 2). This age framework of SK-Is provides a solid basis for establishing the ATS in this study.
3. Data and methods

3.1. Magnetic susceptibility

Magnetic susceptibility (MS) refers to the capacity of a substance to become magnetized when subjected to an external magnetic field. It has been proven to be an effective paleoenvironmental proxy and has been used in cyclostratigraphic research of both marine and continental sequences (e.g., Heller et al., 1991; Nádor et al., 2003; Bouilla et al., 2008; Weber et al., 2010; Wu et al., 2012). In this study, a total of 2870 samples were collected with an average spacing of ~0.3 m from the SK-Is core. MS was measured on a Kappabridge KLY-3 in the Paleomagnetism and Geochronology Laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences. The SK-Is core is characterized by relatively high MS values ranging from $0.5 \times 10^{-8}$ m$^3$/kg to $28 \times 10^{-8}$ m$^3$/kg. Rock magnetic studies indicate a mix of magnetite, hematite and goethite contributing to the core sediment (He et al., 2012). The MS series is strongly cyclic throughout the core (Figs. 2 and 3).

3.2. Natural gamma-ray (GR) and thorium (Th) logging data

GR logging data, which records the intensity of gamma rays emitted during the decay of radioactive atomic nuclei, additionally relates to the amount of $^{40}$K, $^{232}$Th and $^{238}$U in the rock, and reflects the amount of clay and organic material in sediment (ten Veen and Postma, 1996; Schnyder et al., 2006). The GR logging data of the SK-Is were collected at a 0.125 m resolution in the borehole (Figs. 2 and 3). Eight sandstone beds in K$_2y$ have abnormally high GR values, which is due to an unusually high concentration of U (Cheng et al., 2009; Wu et al., 2011). This may lead to misinterpretation of cyclicity in K$_2y$, and so the GR series in K$_2y$ was not used for Milankovitch cycle analysis. In contrast, the thorium (Th) logging data of K$_2y$ was found to closely and consistently track lithological change, with high Th in the mudstones and low Th in the sandstones (Fig. 2). In this study, the GR series was chosen for cyclostratigraphic analysis of the K$_2n$, K$_2qn$ and K$_2q$, and the Th series for K$_2y$. The GR and Th series were standardized and joined into a single “composite” series for the astronomical calibration (Fig. 2).

3.3. Time-series methods

The multitaper method (MTM) of spectral analysis and harmonic analysis (Thomson, 1982) and wavelet analysis (Torrence and Compo, 1998) were conducted on the MS and GR-Th series to search for Milankovitch cycles. Prior to analysis, the series were pre-whitened in Kaleidagraph™ by subtracting a 35% weighted average (Cleveland, 1979). The cycle length ratio method (Mayer and Appel, 1999; Weedon, 2003) was applied to investigate the link between the sequence of sedimentary cycles and theoretical astronomical cycles. MTM power spectral analysis was conducted using the SSA-MTM toolkit (Ghil et al., 2002), with robust red noise estimation reported at the 90%, 95% and 99% confidence levels for interpretation of spectral peak significance (Mann and Lees, 1996). Wavelet analysis was used to compute evolutionary spectra, for tracking changes in cycle frequencies due to changes in sedimentation rate.

The interpreted Milankovitch cycles were extracted using Gaussian (e.g., Dziewonski et al., 1969) as implemented in the freeware Analysers 2.0.4.2 (Paillard et al., 1996), and Taner bandpass filtering (Taner, 2000). Amplitude modulation envelopes of the filtered series were obtained using Hilbert transformation (Hinnov, 2000), in order to isolate long-period components of the interpreted eccentricity and obliquity.
3.4. Late Cretaceous astronomical solutions

The calibration of cyclostratigraphy to astronomical models has become a fundamental tool for refining the geologic time scale (Hinnov and Hilgen, 2012). La2004 was compiled by numerical integration of the equations of motion of the Solar System’s planetary orbits, and includes a model of the Earth’s precession that accounts for tidal dissipation of the Earth–Moon system (Laskar et al., 2004). Recently, Laskar et al. (2011) formulated a new astronomical solution, La2010, which has an improved precision in the initial conditions provided by a special version of the ephemeris INPOP08. La2010a provides the Earth’s orbital elements only; precession and obliquity must be reconstructed using the precession model given in Laskar et al. (1993) (details in the Appendix). While there are four solutions (La2010a-d), Laskar et al. (2011) recommend La2010a, with its small integration step ($1 \times 10^{-3}$ yr) and low error through 60 Ma.

The La2004 and La2010a solutions are considered to be valid over ~42 Ma and 60 Ma, respectively (Laskar et al., 2004, 2011). Beyond this time, the precision of both solutions decrease rapidly due to chaotic behavior of Solar System and an inability of the models to predict this behavior accurately. However, the 405 kyr eccentricity variation is stable over much longer times, and is reliable for astronomical calibration of Mesozoic stratigraphy.

Spectral analysis of ETP realizations of La2004 and La2010a for the 82–93 Ma interval (Fig. 4) shows small differences in the short eccentricity band; both solutions include a faster Cretaceous Earth rotation rate according to the tidal model in Laskar et al. (2004). We will compare these astronomical periodicities and their long-term modulations with those in the MS, GR and Th series to confirm astronomical drivers in SLB sedimentary cyclicity.

4. Cyclostratigraphy

4.1. Cycle analysis and interpretation

Spectral analysis of the untuned MS stratigraphic series of the $K_{n+2}$ reveals significant wavelengths at 20 m, 15 m and 3.1 m (Fig. 5a). The $K_{n+2}$ GR spectrum shows prominent peaks at 65 m, 16 m, 6.7 m, 4.5 m, 3.3 m and 3 m above 95% confidence (Fig. 6a); wavelet analysis indicates relatively continuous cycles with wavelengths of 50 m, 16 m, 6.7 m, 4.5 m and 3 m (Fig. 6b). The ratios of the major wavelengths at 65 m, 20–16 m, 6.7 m, 3.3 m = 20:5:2:1, which matches well with those of the Late Cretaceous astronomical parameters shown in Fig. 4. Thus we interpret the 65 m, 16 m, 6.7 m, 4.5 m, 3.3 m and 3 m lithological cycles as corresponding to the eccentricity (405 kyr and 100 kyr), obliquity (42 kyr and 28 kyr), and precession (21 kyr and 19 kyr), respectively.

The power spectra of the untuned MS and Th series of $K_n$ indicate significant peaks with 46 m, 34 m, 11.6 m, ~4.8 m, 3.3 m, 2.6 m and 1.9 m wavelengths (Figs. 5b and 6c). The presence of parallel bands

Fig. 4. MTM (multitaper method) power spectra of (a) ETP signal of the La2010a solution (Laskar et al., 2011), and (b) ETP signal of the La2004 solution (Laskar et al., 2004), both over the interval 83–93 Ma. Peaks are labeled in kyr. Taner filter passbands used in Figs. 8 and 9 are shown as shaded areas and dashed lines, defined as follows, from left to right ($f_{low}$, $f_{center}$, $f_{high}$ in cycles/kyr): wide-band long eccentricity at 405 kyr (0.00146858, 0.00246858, 0.00346858), wide-band short eccentricity (0.0065, 0.0090, 0.0115) (dashed line), narrow-band short eccentricity at 95 kyr (0.0095, 0.01025, 0.0110), and obliquity at 37.4 kyr (0.0259, 0.0267, 0.0275).
in the wavelet spectra indicates that spectral power is confined to the distinct frequency bands shown in the power spectrum (Figs. 5c and 6d). Spectral wavelength ratios of 46 m, 11.6 m, 4.8 m, 3.3 m, 2.6 m and 1.9 m are very close to orbital period ratios (Figs. 5b and 6c), and they may represent eccentricity (405 kyr and 100 kyr), obliquity (41 kyr and 31 kyr), and the precession index (22.5 kyr and 16.5 kyr).
A hierarchy of significant peaks is present in the power spectrum of the untuned MS and GR series of K2qn with wavelengths of 195 m, 107 m, 73 m, 60 m, 36 m, 10.8 m, 8.8 m, 4.8 m, 4 m, 3.2 m, 2.56 m, 2.1 m, 1.8 m, 1.6 m and 1.54 m (Figs. 5da and 6e). Wavelet analysis shows significant power in the same frequency bands as the power spectrum (Figs. 5e and 6f). According to the cycle length ratio method, these sedimentary cycles may correspond to ~2.2 Myr, 1.2 Myr, 824 kyr, 680 kyr, 123 kyr, 100 kyr, 54 kyr, 45 kyr, 36 kyr, 29 kyr, 24 kyr, 21 kyr, 18 kyr and 17.5 kyr Milankovitch cycles (Figs. 5d and 6e).

Fig. 6. The 2π MTM (multitaper method) power spectra and wavelet scalograms of (a, b) the GR logging data of first and second members of the Nenjiang Formation (K2n1+2), (c, d) the Th logging data of Yaojia Formation (K2y), (e, f) the GR logging data of Qingshankou Formation (K2qn) and (g, h) the GR logging data of third and fourth members of the Quantou Formation (K2q3+4) in the depth domain. See legends and notes in Fig. 5.
Fig. 7. MTM power spectra and wavelet scalograms of the normalized 405 kyr-tuned GR (a, b) and MS (c, d) time series of the SK-IIs borehole. Significant peaks are labeled in kyr. See legends and notes in Fig. 5. In (a) Taner filter passbands used in Figs. 8 and 9 are shown as shaded areas and dashed lines, defined as follows, from left to right (flow, f center, f high, in cycles/kyr): wide-band long eccentricity at 405 kyr (0.00146858, 0.00246858, 0.00346858), wide-band short eccentricity (0.0065, 0.0090, 0.0115) (dashed line), narrow band eccentricity at 95 kyr (0.009, 0.010, 0.011), and obliquity at 37.4 kyr (0.0259, 0.0267, 0.0275).
The peaks of E405 cycles in the GR (Th for the K2y) series of the SK-Is. The centricity maxima of the La2010a solution to corresponding positive tuning was done in this study by assigning ages of 405 kyr (long eccentricity, obliquity and the deposition of sediments with higher eccentricity. Therefore, weathering, clay mineral input, nutrient input and higher productivity were enhanced. Chemical events. The astronomically calibrated boundary ages of K2n2/K2n1, K2n1/K2y2+3, K2y2+3/K2y1, K2y1/K2qn2+3, K2qn2+3/Kqn2, Kqn2/K2q4 and K2q4/Kq3 are 83.882 Ma, 84.673 Ma, 85.748 Ma, 86.010 Ma, 90.435 Ma, 91.371 Ma and 91.867 Ma, respectively (Fig. 8b). On the basis of these age constraints, the Campanian/Santonian, Santonian/Coniacian and Coniacian/Turonian boundaries are assigned to 971.1 m, 1259.6 m and 1542.0 m (Figs. 2 and 8a), respectively, in the SK-Is borehole. This ATS also serves as a basis for correlating the major Late Cretaceous geological events between marine and continental sequences.

A successful astronomical calibration is further based on interpretation of the phase relationship between sedimentary cycles and astronomical target curves. The identification of long and short eccentricity, obliquity and precession cycles in the untuned GR, Th and MS series of the SK-Is core suggests strong astronomical climate forcing in the development of the SLB sedimentary cycles. Higher GR (Th) values in lacustrine sediments in the SK-Is core are related to higher content of clay minerals and organic carbon, which may have resulted from wetter and warmer climate conditions (Wu et al., 2011). Wetter and warmer periods could have enhanced chemical weathering, clay mineral input, nutrient input and higher productivity in the paleolake, resulting in positive GR excursions. Thus, it is anticipated that wetter and warmer climate conditions prevailed during the deposition of sediments with higher eccentricity. Therefore, tuning was done in this study by assigning ages of 405 kyr (long eccentricity) maxima of the La2010a solution to corresponding positive peaks of E405 cycles in the GR (Th for the K2y) series of the SK-Is. The tuning was conducted using the Linage function in Analysies series 2.0.4.2 (Paillard et al., 1996).

Power spectra of the untuned MS and GR series of Kq4 indicate the presence of significant peaks of 20.5 m, 16 m, 8.3 m, 7.9 m, 3.8 m, 3.2 m and 2.6 m (Figs. 5f and 6g). Wavelet analysis reveals continuous cycles with periods of 16–24 m, 6.5–8 m and 2.5–4 m (Figs. 5g and 6h), which may represent short eccentricity, obliquity and the precession index.

4.2. Astronomical calibration of the SK-I south core

Direct cycle counting method was used to establish SK-Is core cyclostratigraphic framework following the method of Westerhold et al. (2007). Bandpass filters were designed to isolate the 405 kyr (“long”) and ~100 kyr (“short”) eccentricity cycles in sedimentary records based on our interpretation in Section 4.1. The filtered long and short eccentricity cycles are numbered according to their position relative to the top of the SK-Is core in K2n2 (Fig. 2). The 405 kyr (long eccentricity) cycles are referred to as E4050, E4051, E4052, etc., while the 100 kyr (short eccentricity) cycles were labeled as e0, e1, e2, etc.

The untuned MS, GR and Th series display similar E405 cycles (Fig. 2). The K2n1+2 member records ~12 e cycles and ~3 E405 cycles. The K2y member has 15 e cycles and ~3.5 E405 cycles. For K2qn and K2qn+1 members records ~12 e cycles and ~3 E405 cycles. For K2q4 and Kq4+1, ~5.5 and ~7 e cycles, 13.5 and ~1.7 E405 cycles were identified, respectively.

A major objective of this study is to establish an ATS for the SK-Is core so that the durations of major geological events can be precisely estimated and their correlation with events in marine sequences can be fine-tuned. The short eccentricity cycles are unstable due to the chaotic motion of planets in the inner Solar System during the Mesozoic, and are not suitable for astronomical calibration. Therefore, we tuned the interpreted 405 kyr eccentricity cycles to the La2010a solution.

A successful astronomical calibration is further based on interpretation of the phase relationship between sedimentary cycles and astronomical target curves. The identification of long and short eccentricity, obliquity and precession cycles in the untuned GR, Th and MS series of the SK-Is core suggests strong astronomical climate forcing in the development of the SLB sedimentary cycles. Higher GR (Th) values in lacustrine sediments in the SK-Is core are related to higher content of clay minerals and organic carbon, which may have resulted from wetter and warmer climate conditions (Wu et al., 2011). Wetter and warmer periods could have enhanced chemical weathering, clay mineral input, nutrient input and higher productivity in the paleolake, resulting in positive GR excursions. Thus, it is anticipated that wetter and warmer climate conditions prevailed during the deposition of sediments with higher eccentricity. Therefore, tuning was done in this study by assigning ages of 405 kyr (long eccentricity) maxima of the La2010a solution to corresponding positive peaks of E405 cycles in the GR (Th for the K2y) series of the SK-Is. The tuning was conducted using the Linage function in Analysies series 2.0.4.2 (Paillard et al., 1996).

Spectral and wavelet analysis of the 405 kyr-tuned GR (Th for K2y) series shows significant spectral peaks with periodicities of ~2340 kyr, 1360 kyr, 960 kyr, 680 kyr, 405 kyr (tuned), 140 kyr, 131 kyr, 107 kyr, 99 kyr, 44 kyr, 40 kyr, 37.4 kyr, 33 kyr, 26.8 kyr, 23.5 kyr, 22.2 kyr, 21 kyr and 17.6 kyr above the 99% confidence level (Fig. 7a). The power spectrum of the 405 kyr-tuned MS series has significant peaks at 1200 kyr, 680 kyr, 405 kyr (tuned), 250 kyr, 227 kyr, 101 kyr, 95 kyr, 37.4 kyr, 28 kyr, 25.5 kyr, 20.5 kyr and 18.4 kyr (Fig. 7c). Wavelet analysis of the 405 kyr-tuned GR (Th for K2y) and MS series show comparable spectral bands (Fig. 7b, d).

These spectra compare well with those of the La2010a and La2004 solutions (Fig. 4) and support our cyclostratigraphic interpretation and proposed ATS for the SK-Is core. The long-period components in the spectra, especially those at 2340 kyr and 1200 kyr, may be manifestations of eccentricity and obliquity amplitude modulation cycles, and are discussed further below (Section 5.5.).

5. Discussion

5.1. Astrochronology of the SK-Is core

The new ATS provides a continuous ‘absolute time framework’ from 83.40 Ma–92.08 Ma (Early Turonian–Early Campanian) and age assignments for stratigraphic units and biological and geological events. The astronomically calibrated boundary ages of K2n2/K2n1, K2n1/K2y2+3, K2y2+3/K2y1, K2y1/K2qn2+3, K2qn2+3/Kqn2, Kqn2/K2q4 and K2q4/Kq3 are 83.882 Ma, 84.673 Ma, 85.748 Ma, 86.010 Ma, 90.435 Ma, 91.371 Ma and 91.867 Ma, respectively (Fig. 8b). On the basis of these age constraints, the Campanian/Santonian, Santonian/Coniacian and Coniacian/Turonian boundaries are assigned to 971.1 m, 1259.6 m and 1542.0 m (Figs. 2 and 8a), respectively, in the SK-Is borehole. This ATS also serves as a basis for correlating the major Late Cretaceous geological events between marine and continental sequences.

Fifteen ostracode biotozones were identified in the SK-Is borehole (Wan et al., 2013–this issue). The age of the top boundary and durations of these biotozones were estimated using the ATS as shown in Table 1. For example, the durations of ~0.22–0.27 Ma for four ostracode biotozones are consistent with the 0.22–0.25 Ma cycles in the MS series from 85 to 86 Ma (visible in the scalogram, Fig. 7d), suggesting that long-period components of obliquity forcing affected ostracode evolution. Previously, van Dam et al. (2006) found that long-period astronomical climate forcing during the Cenozoic was a major determinant of species turnover in small mammals in Central Spain. Our results may indicate that ostracode turnover in the Songliao paleolake was also related to long-period astronomical climate forcing.

5.2. Age and duration of magnetic polarity events

The C-sequence of marine magnetic anomalies was assembled by Cande and Kent (1992, 1995) from a composite of South Atlantic profiles with additional resolution from selected Pacific surveys (Gradstein et al., 2004). They calculated absolute ages for their synthetic magnetic anomaly pattern by applying a cubic-spline fit to selected radiometric ages. Gradstein et al. (2004) recalibrated the Late Cretaceous C-sequence with a spline fit of revised and additional radiometric ages. Recently, Husson et al. (2011) estimated the ages and durations of each magnetochron from C23r.2r to C29n through cyclostratigraphic study of Late Campanian–Maastrichtian sedimentary successions from four ODP (Ocean Drilling Program) and DSDP (Deep Sea Drilling Program) holes.

The age of the end of chron C4n was assigned as 83.0 Ma by Cande and Kent (1992, 1995), 84.0 Ma by Gradstein et al. (2004), 83.3 Ma by Ogg et al. (2008), ~83.4 Ma by He et al. (2012), and 83.64 Ma by Ogg (2012). According to our new ATS (Fig. 8), the age of the polarity boundary of C33r/C34n is estimated at 83.63 Ma. Three short polarity reversal events identified at the upper part of chron C4n in the K2y have not been observed globally (He et al., 2012). Further studies are needed to confirm their global significance. If their presence is corroborated, the ATS ages for these three events are estimated at 84.819 Ma (upper boundary) to 84.862 Ma (lower boundary) to 84.862 Ma (lower boundary) to 84.862 Ma (lower boundary) to 84.862 Ma (lower boundary).
boundary), 84.982 Ma (upper boundary) to 85.092 Ma (lower boundary), and 85.240 Ma (upper boundary) to 85.629 Ma (lower boundary), with durations of 43 kyr, 110 kyr and 389 kyr, respectively (Figs. 2 and 8). Our estimates of the ages and durations of these short polarity reversals provide constraints for future identification and global correlation of such events within the upper Cretaceous Normal Superchron (CNS) in other successions.

5.3. Sediment accumulation rates (SAR)

Our ATS for the SK-1s core provides a strong basis for the estimation of sediment accumulation rate (SAR) in the SLB. SAR is determined using the e cycles but assuming 405-kyr (E) tuned ages at their boundaries. The SAR variation through the core shows significant 405 kyr cycles with SAR maxima corresponding to long eccentricity maxima (Fig. 2). It indicates that changes in SAR are directly related to astronomically driven enhanced siliciclastic input during wet and warm periods.

The SAR variations in SK-1s core can be divided into four stages, which coincide with major environmental changes related to SLB tectonic evolution (Feng et al., 2010) (Fig. 2):

1. The SARs of the K3n1+2 decrease from 22.1 cm/kyr in the lower part to 15.9 cm/kyr in the upper part, with an average of 18.8 cm/kyr. SARs in the K3n1+2 are related to the depositional environments, which are mainly fluvial channel sandstones in the lower part, and mudstone, siltstone and sandstone in the upper part.

2. K2qn consists of mainly mudstone, with the lower part deposited in deep lake environments and the upper part in moderately deep to shallow lake environments. The SARs of the K2qn vary from 5.6 cm/kyr to 14.4 cm/kyr, with an average of 9.27 cm/kyr.

3. The average SAR of the K2y is 11.8 cm/kyr and varies from 8.3 cm/kyr to 13.9 cm/kyr.

4. The SAR increases abruptly in the K2y1+2, with values from 10.7 cm/kyr to 17.5 cm/kyr and an average of 13.2 cm/kyr. The average SAR in the deep lacustrine K2y1+2 is higher than that of the underlying shallow lacustrine K2y. This phenomenon seems to conflict with the common depositional model and may have resulted from tectonic uplift during K2y1+2 deposition, in response to an episode of accelerating uplift from Pacific Plate subduction.

5.4. Sangliao Lake anoxic events

Two lacustrine anoxic events (LAEs) in the SLB have been documented in K2qn1 and K2n2 (Fig. 2) (Gao et al., 1994; Li and Pang, 2004; Wu et al., 2009). The cause of the LAEs remains uncertain, although some researchers believe that they are related to great marine incursions that occurred in the SLB (Wang et al., 2001; Li and Pang, 2004; Xi et al., 2011). Based on our new ATS for the SK-1s core, the ages of LAE1 and LAE2 are estimated as 91.3 Ma and 83.8 Ma (Fig. 8). This points to global coastal onlap events T4 and Cam1, at 89.54 Ma and 83.1 Ma, respectively, based on the Ogg et al. (2008) timescale (Snedden and Liu, 2010), as possible origins of the incursions. It is also possible that the LAEs are terrestrial expressions of Oceanic Anoxic Event 3 (OAE3), during which a series of carbon cycle events have been found throughout late Turonian–early Campanian time, although they are restricted to the Atlantic Provinces (Wagreich, 2012).

5.5. Implications for Solar System behavior during the Late Cretaceous

The secular frequencies of planetary motion reflect longitude of perihelia (g4) and inclination (s5) of the orbits for each planet in the Solar System, e.g., g1, g2, g3, g4 and g5 are for Mercury, Venus, Earth, Mars and Jupiter, respectively. Earth’s orbital eccentricity variation has four long-term cycles with modeled periods of ~2.34 Myr, 960 kyr, 680 kyr and 405 kyr (Fig. 4). These long-period cycles correspond to the interactions between the orbital perihelia of the planets, g4–g5, g1–g5, g2–g5 and g3–g5, respectively. The major terms are the 2.34 Myr (g2–g5) and 405 kyr (g2–g5) cycles, both of which strongly modulate the short eccentricity variation, e.g., (g4–g5) and (g3–g5) (Fig. 5 in Laskar et al., 2011). Earth’s obliquity variation has a long-period modulation cycle of ~1.2 Myr related to inclination variations of the Earth’s orbital plane and its interaction with that of Mars, s4–s5, appearing as a beat frequency in the obliquity variation, i.e., (k + s4) − (k + s5), where k is Earth’s precession constant (e.g., Hunnow, 2000).

The two orbital motions of Earth and Mars described by s4–s5 and s5–s5 are presently in 2:1 secular resonance (i.e., 2.4 Myr:1.2 Myr), which has persisted as far back as the Oligocene, and documented in cyclostratigraphy (Pålile et al., 2004; van Dam et al., 2006; Abels et al., 2010).

It is hypothesized that the Solar System experienced chaotic behavior between 60 Ma and 100 Ma (Laskar et al., 2004, 2011). Because it is impossible to numerically compute the exact motion of the planets for times prior to ~50 Ma, Cretaceous cyclostratigraphy uniquely provides an opportunity to detect possible chaotic signals in the astronomical parameters to pinpoint chaotic intervals.

Thus far in Cretaceous stratigraphy, putative g4–g5 cycles have been reported in multi-million year long cyclostratigraphic sequences: 2.5 Myr cycles in South Atlantic DSDP cores of the Late Cretaceous (Herbert, 1999), and 1.6 Myr cycles in Tethyan Aptian strata of central Italy (Huang et al., 2010a). Further back in time, ~2 Myr cycles are present in the Kimmeridgian–Tithonian Kimmridge Clay of Dorset, UK (Huang et al., 2010b), 2.0 Myr cycles in the Oxfordian Terres Noires Formation, Vooncant Basin, France (Boullia et al., 2010), 1.7 Myr cycles in the Late Triassic Newark Basin, USA (Olsen and Kent, 1999), and 1.8 Myr cycles in the Triassic bedded chert sequence of Inuyama, Japan (Ikeda et al., 2010). These variable periodicities all point to (although have not yet confirmed) instability in the Earth–Mars orbits throughout the Mesozoic Era. There is also increasing evidence that many so-called “third order eustatic sequences” are related to s4–s5 forcing during the Cenozoic icehouse, and to g4–g5 forcing in the Mesozoic greenhouse (Boullia et al., 2011).
Table 1
The depth and ages of the top boundaries of the ostracode biozones identified in the SK-4 core (Wan et al., 2013—this issue) and their durations.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Ostracode biozones</th>
<th>Depth (m)</th>
<th>Age (Ma)</th>
<th>Duration (Myr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nenjiang</td>
<td>C. liaukhenensis—lyocypridocra</td>
<td>959.55</td>
<td>89.21</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>M. magna—M. heliozaienensis</td>
<td>1015.76</td>
<td>85.47</td>
<td>2.23</td>
</tr>
<tr>
<td></td>
<td>C. gracilis—C. gansuensis</td>
<td>1029.33</td>
<td>83.92</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>C. anonyma—C. fabiforma</td>
<td>1063.05</td>
<td>84.15</td>
<td>0.55</td>
</tr>
<tr>
<td>Yajiao</td>
<td>C. formosa—C. sunghuangianensis</td>
<td>1130.38</td>
<td>84.70</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>C. favosa—M. tabulate</td>
<td>1221.26</td>
<td>85.47</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>C. exornata—C. dongjiangensis</td>
<td>1252.25</td>
<td>85.74</td>
<td>0.22</td>
</tr>
<tr>
<td>Qingshankou</td>
<td>C. panda—M. obscura</td>
<td>1279.41</td>
<td>85.96</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>T. vestita—T. faviiformis—T. pumilis</td>
<td>1310.05</td>
<td>86.21</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>C. fuyanensis—T. symmetrica</td>
<td>1417.73</td>
<td>87.46</td>
<td>0.43</td>
</tr>
<tr>
<td></td>
<td>C. elenitula—Lycopteroepgus grandis</td>
<td>1465.18</td>
<td>87.89</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>C. nota—S. tumida</td>
<td>1511.09</td>
<td>88.28</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>C. gibbosa—C. dakehoiensis</td>
<td>1611.99</td>
<td>89.38</td>
<td>0.83</td>
</tr>
<tr>
<td>Quantou</td>
<td>M. longicudata—C. subtraberculipes</td>
<td>1781.20</td>
<td>91.35</td>
<td>1.14</td>
</tr>
</tbody>
</table>

Empirical estimates of the $g_4$ and $s_3$ terms may be recovered from the amplitude modulation (AM) series of the interpreted long eccentricity and obliquity variations in the GR-Th records, and compared with those of the theoretical astronomical solutions. The GR-Th series is longer and more highly resolved than the MS series (Figs. 2 and 3), and so GR-Th was selected for the amplitude modulation analysis. The results (Figs. 8 and 9) indicate some similarities between data and theory, but also many notable differences.

Amplitude modulations of the interpreted 405 kyr and 95 kyr bands of the GR-Th time series show long period cycling that are partially in phase in the younger part of the series, and are decoupled in the older part (Fig. 8f, j). There is an extended interval of low amplitude associated with the deep and moderately deep lake facies, where carbonate contribution to the sediment may dilute contributions from radioactive carriers (organic carbon, clay, igneous grains). In theory the AM series of the 405-kyr and 95-kyr bands should be anti-phas, as in Fig. 8i, p for La2010a eccentricity and Fig. 8r, v for La2004 eccentricity. There are numerous possible reasons for the mismatching, ranging from amplitude disruptions caused by facies changes, to the possibility that an eccentricity signal is not actually present in the GR-Th series. On the other hand, the short eccentricity-filtered GR-Th series (Fig. 8g) shows bundling patterns that match closely with the direct 405-kyr filtered series, as does the same filtering in the Laskar solutions (Fig. 8n, s, and t). Together with the power spectrum of the GR-Th time series (Fig. 7a), constitutes strong evidence for a robust orbital eccentricity signal in the GR-Th time series.

The obliquity AM series of the GR-Th time series (Fig. 9g) is characterized by ~1 Myr cycles, along with a long term trend that could be related to facies changes (as with the AM eccentricity series). Both La2004 and La2010a AM obliquity series (Fig. 9h, j) have strong 1.2 Myr cycles; La2004 has more minima that coincide with GR-Th AM obliquity minima.

Fig. 9. Amplitude modulations of the interpreted obliquity variation in the SLB, compared with those of the La2010a and La2004 solutions. (a) to (e) are as in Fig. 8; (f) amplitude modulations of the 37.4-kyr band of the GR-Th time series; (g) filtered 37.4-kyr band of the GR-Th time series; (h) amplitude modulations of the La2010a obliquity variation (37.4-kyr band); (i) filtered 37.4-kyr band of the La2010a obliquity variation; (j) amplitude modulations of the La2004 obliquity variation (37.4-kyr band); (k) filtered 37.4-kyr band of the La2004 obliquity variation. Bandpass filter definitions are given in Figs. 4 and 7a. La2010a obliquity was obtained using the procedure given in the Appendix.
Closer comparison of the AM time series for the GR-Th series, La2010a and La2004 eccentricity and obliquity and their spectra (Fig. 10) is, however, non-conclusive: in the time domain, the GR-Th AM series resembles that of the La2004 solution. The two GR-Th AM spectra (Fig. 10g) are very noisy: the bracketed 8 Myr peak, which appears in both spectra, reflects the extended suppression of GR amplitudes through the middle of the series related to facies changes. Discounting this frequency from the GR-Th spectrum leaves the following modulation periodicities for consideration: for the AM eccentricity band, 2.6 Myr and 1.05 Myr; for the AM obliquity band, 2.9 Myr, 1.95 Myr, 1.44 Myr, and 0.99 Myr (Fig. 10g). From this perspective, the GR-Th series is more comparable to La2010a. In particular, the AM obliquity of La2010a has large 2.25 Myr and 1.17 Myr components (Fig. 10g), compared with GR-Th components at 1.95 Myr and 1.44 Myr (Fig. 10h). AM eccentricity-AM obliquity cross-phase studies (not shown) indicate that none of the frequencies are phase-locked for either the data or the models. Thus it is impossible to conclude confidently whether the 1 Myr to 2 Myr scale modulations in the SLB are of astronomical origin.

A final surprise in this work is the spectrum of the SAR time series (Fig. 11). The 405 kyr-tuned SAR time series was evaluated at a 100-kyr sampling rate. Its amplitude spectrum shows a strong 400-kyr cycle, influenced in part by the 405-kyr tuning. In addition, there are longer, million-year scale variations with periodicities of 2.8 Myr, 1.97 Myr, 1.42 Myr, 0.99 Myr and 0.75 Myr. This is remarkably similar to the AM obliquity amplitude spectrum (from Fig. 10g). These results imply that SLB sedimentation rates were influenced by obliquity forcing. Direct evidence for obliquity variation in SLB is relatively weak in the GR-Th series, but relatively strong in the MS series (compare Fig. 7a and c). The MS series tracks the concentration of magnetic minerals in the sediment, all of which are detrital materials eroded from surrounding areas. The MS spectrum thus suggests a significant component of obliquity forcing in climate processes leading to erosion, transport and deposition of SLB sediment.

6. Conclusions

Spectrum and wavelet analysis of the GR (Th for K2y) and MS time series measured in the SK-Is borehole and core from the Late Cretaceous Songliao Basin, China, show strong astronomical signals with frequency components indicative of 405 kyr long orbital eccentricity, the multiple ~100 kyr terms of short orbital eccentricity, 37.4 kyr obliquity and 20 kyr precession index cycles. An astronomical time scale [ATS] was established by calibrating extracted 405-kyr cycles to the La2010a astronomical solution. This ATS provides high-resolution estimates of the ages and durations of Late Cretaceous geological and geophysical events in the SLB, as follows:

- The SK-Is borehole covers 8.68 Ma from 83.40 Ma–92.08 Ma (Early Turonian to Early Campanian).

![Fig. 11. 2n multitapered amplitude spectra of the SAR time series (black solid line) and the AM obliquity (37.4) of the GR-Th time series (red dashed line). Underlined labels indicate GR-Th AM obliquity periods in Myr.](image-url)
Inner Solar System dynamics can be represented in part by the interactions of the orbits of Earth and Mars. This information is embedded in the amplitude modulations of Earth’s orbital eccentricity and obliquity variations. In the SLB GR-Th series, million-year scale cyclicity is present in amplitude modulations filtered out from the eccentricity and obliquity bands. The extracted modulations do not maintain a 2:1 period ratio between obliquity bands. The extracted modulations do not maintain a 2:1 secular resonance, and experienced chaotic interactions.

Two lacustrine anoxic events in the SLB occur at 91.341 Ma (LAE1) and at 83.834 Ma (LAE3), which correspond to times of major global sea level transgressions (Tu4 and Cam1).

Acknowledgments

We express our sincere appreciation to the editor (Prof. Dave Bottjer) and two anonymous reviewers for their careful review and constructive suggestions that significantly improved the paper. The magnetic susceptibility data from the SK-Is core was kindly provided by Professor Chenglong Deng from the Institute of Geology and Geophysics, Chinese Academy of Sciences. This work was jointly supported by the National Key Basic Research Development Program of China (2012CB822002, 2006CB701400), the National Science Foundation of China (Grants 40802012, 91128102) and Fundamental Research Funds for the Central Universities. LH was partially supported by US National Science Foundation Grant EAR-0718905.

Appendix A

Computation of obliquity and precession index for the La2010a solution was accomplished on a Linux platform as follows.

1. The Laskar et al. (1993) astronomical solution FORTRAN code and input files were downloaded from the online VizieR Catalogue Service:

   http://vizier.cfa.harvard.edu/ftp/cats/V/63/prepa.f
   http://vizier.cfa.harvard.edu/ftp/cats/V/63/prepa.par
   http://vizier.cfa.harvard.edu/ftp/cats/V/63/integ.f
   http://vizier.cfa.harvard.edu/ftp/cats/V/63/integsub.f
   http://vizier.cfa.harvard.edu/ftp/cats/V/63/climavar.f
   http://vizier.cfa.harvard.edu/ftp/cats/V/63/climavar.par

2. Concatenate integ.f and integsub.f into a single file integall.f.

3. Compile prepaf, integall.f and climavar.f with gfortran.

4. Edit prepaf, integall.f and climavar.f as follows:

   &NAMSTD
   nomfich = ’ELLBIN’,
   nomfichder = ’DERBIN’,
   nomascpos = ’ORBELP.ASC’,
   nomascneg = ’ORBELN.ASC’,
   datedeb = = 100.00,
   datefin = 0.00,
   statut = ’unknown’

   &END

5. Edit integ.par as follows:

   &NAMSTD
   nomfich = ’ELLBIN’,
   nomfichder = ’DERBIN’,
   pas = 200,
   nechant = 5,
   datefin = 0.00,
   datedeb = = 100.00,
   statut = ’unknown’,
   e = ecc = 0.00,
   eprecc = 0.00,
   ficherpos = ’PRECP.ASC’,
   ficherneg = ’PRECN.ASC’,
   &END

6. Edit climavar.par as follows:

   &NAMSTD
   nomascpos = ’ORBELP.ASC’,
   nomascneg = ’ORBELN.ASC’,
   nomprecpos = ’PRECP.ASC’,
   nomprecneg = ’PRECN.ASC’,
   nomsolpos = ’CLIVARP.ASC’,
   nomsolneg = ’CLIVARN.ASC’,
   datedeb = = 100.00,
   datefin = = 0.00,
   statut = ’unknown’

   &END

7. Download La2010a orbital solution file La2010a_alhakk31.dat from:

   http://www.imcce.fr/Equipes/ASD/insola/earth/La2010/index.html

   Edit this file to delete columns 2 and 3 (”a” and ”I”); save as ORBELN.ASC.

   (Mac users will have to run the output file through mac2unix.)

8. Run prepa, then run integall, choosing FGAM = 1 and CMAR = 1.3 (to match output of La2004); finally, run climavar. The output file CLIVARN.ASC has 4 columns for t, e, eps, and CP, where t = time in kiloyears before present (negative), e = eccentricity, eps = obliquity (in radians), and CP = sin(longitude of perihelion from moving equinox) = precession index.

References


