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1. METHODS AND RESULTS

1.1. Lithostratigraphy

The detailed stratigraphy of the Yan'an Formation in the Dongsheng coalfield of the northeast Ordos Basin (Figs. S1 and S2) was laid out based on measured sections at five open-pit coal mines, namely the Nangai, Gaoxigou, Chaonaolinag, Lijialiang and Nayuan mine sites (Fig. 1). Stratigraphic sections were measured at each site by using a tape measure and by recording lithology and sedimentary facies across the subparallel beds exposed by mining (Fig. S3). Stratigraphic correlation across the measured mine sections was aided by a network of exploration drill core logs of the Dongsheng Coalfield, made available by the National Geological Archives of the China Geological Survey (Yin et al., 1990). A composite stratigraphic section of the Yan'an Formation was constructed based on the measured Gaoxigou and Nayuan sections (Fig. S4), which collectively intercept all its major coal seams. The cyclostratigraphic work of this study (see 1.4.) was based on the latter two sites and all other stratigraphic information were projected onto the composite section.

1.2. U-Pb geochronology

1.2.1 Analytical procedures

Five samples of tonstein directly associated with known Yan'an Formation coal seams (Table S1 and Fig. S1) were collected from the Chaonaolinag, Lijialiang, Nayuan and Nangai open mine sections and one tuffaceous mudstone was collected from the Gaoxigou mine site of the Dongsheng coalfield (see Table S2 and Fig. S3) for U-Pb zircon geochronology by the CA-ID-TIMS method. Analytical techniques followed the general procedures described in Ramezani et al. (2011). The average sample size was 5 kg. After crushing and removal of fine particles, the samples underwent heavy-mineral separation by magnetic and high-density liquid methods. Zircons were hand-selected under a binocular microscope with preference given to sharply-faceted, prismatic zircons with axial glass (melt) inclusions (Fig. S3). All analyzed zircons were pre-treated by a chemical abrasion technique modified after Mattinson (2005), in order to mitigate the effects of radiation-induced Pb loss. This involved thermal annealing in a furnace at 900 °C for 60 h, followed by partial dissolution in 29M HF at 210 °C inside high-pressure vessels for 12 h. The chemically abraded grains were fluxed in several hundred microliters of dilute HNO₃ and 6M HCl, successively on a hot plate and in an ultrasonic bath (1 h each), and rinsed with several volumes of Millipore water in between to remove the leachates. The thoroughly rinsed grains were spiked with the EARTHTIME ET535 mixed ²⁰⁵Pb-²³³U-²³⁵U isotopic tracer solution (Condon et al., 2015; McLean et al., 2015) prior to complete dissolution at 210 °C for 48 h. Lead and U were separated by a miniaturized HCl-based ion-exchange column chemistry procedure using AG1X-8 anion resin modified from Krogh (1973). Purified U and Pb were then loaded onto outgassed Re filaments together with a silica gel emitter solution and their isotopic ratios were measured on an Isotopx X62 multi-collector thermal ionization mass spectrometer equipped with a Daly photomultiplier ion-counting systems at MIT. Pb isotopes were measured as mono-atomic ions in a peak-hopping mode on the ion-counter and were corrected for a mass-dependent isotope fractionation of 0.18% ± 0.05% per atomic mass unit (2σ). U isotopes were measured as dioxide ions simultaneously using three Faraday collectors, while subjected to a within-run mass fractionation correction using the ²³³U/²³⁵U ratio

of the tracer and a predicted sample $^{238}\text{U}/^{235}\text{U}$ ratio of 137.818 ± 0.045 (Hiess et al., 2012), as well as an oxide correction based on an independently determined $^{18}\text{O}/^{16}\text{O}$ ratio of 0.00205 ± 0.00005 .

For data reduction including U-Pb date calculation and propagation of uncertainties, the Tripoli and ET_Redux algorithms and computer applications were used (Bowring et al., 2011; McLean et al., 2011). All common Pb was assumed to be laboratory blank and corrected using isotopic compositions determined by repeat analyses of spiked total procedural blanks. $^{206}\text{Pb}/^{238}\text{U}$ dates were corrected for the initial ^{230}Th disequilibrium in magma based on an estimated Th/U ratio of 2.81 ± 1 (2σ) for the felsic parent magma of tonsteins. Complete U and Pb isotopic data for 38 single zircon analyses from six dated samples are listed in Table S3.

Sample dates are calculated based on the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of the youngest cluster of zircon analyses that overlap within 2σ analytical uncertainty from each sample, provided that there are at least 3 analyses in the cluster. This is done after excluding distinctly older analyses interpreted as xenocrystic or detrital. In two cases (CNL072718-1, z1 and CNL072718-2, z5) a distinctly young outlier analysis was excluded on the basis of persistent Pb loss resulting in an out of sequence date. The calculated weighted mean date is interpreted as the maximum age of deposition for the corresponding bed. A set of high-resolution U-Pb dates from closely spaced ash beds that obey the stratigraphic order provide reliable estimates of the true depositional age. The relationship of the dated samples to the coal seams are shown in Table S2. The weighted mean uncertainties are reported at 95% confidence level and given in the $\pm X/Y/Z$ Ma format, where X is the 2σ analytical error (only), Y incorporates X as well as the tracer calibration errors, and Z includes Y in addition to the U decay constant errors of Jaffey et al. (1971). Complete uncertainties (Z) must be taken into account when age data from different isotopic chronometers (e.g., U-Pb versus $^{40}\text{Ar}/^{39}\text{Ar}$) are compared. Calculated dates and their detailed uncertainties are listed in Table 1 and illustrated in date distribution plots of Figure 3.

1.2.2. Results and age interpretation

Sample NG072818-3 was collected from a thin (1.3 cm) white tonstein in the middle of an auxiliary, 60 cm-thick coal bed, 4 m above the main coal seam #3-1 at the Nangai mine site. Five single zircons analyzed from this sample form without any outliers (Table 1 and Fig. 3) a statistically coherent cluster with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $171.975 \pm 0.047/0.088/0.20$ Ma (MSWD = 1.5). This date places a lower age limit on the #3-1 coal.

Samples GXG072718-2 was collected from a greyish-brown (tuffaceous) mudstone layer 9 m below the #3-1 coal seam at the Gaoxigou mine site. Zircon grains were relatively small with low radiogenic to common Pb ratios (Table S3), resulting in higher analytical uncertainties. All five analyzed zircons form a coherent cluster with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $172.65 \pm 0.25/0.31/0.36$ Ma (MSWD = 1.6) (Table 1 and Fig. 3), representing a maximum depositional age for the #3-1 coal.

Sample CNL072718-2 was a 1 cm-thick, white tonstein from within the #6-1 coal at the Chaonaoliang mine site. The youngest 3 out of a set of 6 zircon analyses from this sample overlap within uncertainty and yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $173.328 \pm 0.059/0.096/0.21$ Ma (MSWD = 0.61) (Table 1 and Fig. 3). A seventh analysis (z5, Table S3) was significantly younger with a $^{206}\text{Pb}/^{238}\text{U}$ date of 172.82 ± 0.17 Ma, which is inconsistent with the stratigraphic position of the tonstein and probably resulted from persistent Pb loss. This outlier was thus excluded from age calculation. The above calculated date constrains the age of the #6-1 coal.

Sample Ordos3-1 was collected from a 3 cm-thick tonstein inside the #6-2s coal bed at the Lijialiang mine site. With the exception of one older (detrital) outlier, all other 7 zircon analyses from this sample yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $173.558 \pm 0.044/0.088/0.21$ Ma (MSWD = 1.1) (Table 1 and Fig. 3). This date constrains the depositional age of the #6-2s coal.

Sample Ordos6-2 was from a 2 cm-thick tonstein inside the #6-2z coal bed at the Nayuan mine site. All 6 analyses from this sample define a single age population with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $173.727 \pm 0.085/0.12/0.22$ Ma (MSWD = 0.97) (Table 1 and Fig. 3). This is interpreted as the age of deposition of the #6-2z coal.

Sample CNL072718-1 was collected from a 7 cm-thick, white tonstein in the middle of the #7 coal seam. All but one of the analyzed zircons from this sample form a coherent cluster with a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of $173.992 \pm 0.053/0.094/0.21$ Ma (MSWD = 0.28) (Table 1 and Fig. 3). The distinctly younger outlier (z1) produced a $^{206}\text{Pb}/^{238}\text{U}$ date of 173.75 ± 0.12 Ma, which we interpret as persistent Pb loss.

1.3 Bayesian Age Modeling

Our new U-Pb geochronology places direct age constraints on four coal seams of the Yan'an Formation at the Dongsheng Coalfield (Fig. 3 and S3). The ages of the remaining coal beds, as well as those of the formation boundaries, will have to be extrapolated based on the dated tonsteins and their relative stratigraphic positions. To construct an age–stratigraphic framework for the entire Yan'an Formation we have employed a Bayesian model using the Bchron package (version 4.3.0) in the R (version 3.5.1) platform (Haslett and Parnell, 2008; Parnell et al., 2008). The underlying Markov Chain Monte Carlo statistical algorithm of Bchron takes into account possible variation in sediment accumulation rate in between the dated horizon and provides objective uncertainties for the age model. Bayesian algorithms have been increasingly used in cases of chronostratigraphies derived from radioisotopic age data (De Vleeschouwer and Parnell, 2014; Keller et al., 2018; Trayler et al., 2019). The technical details for Bchron are given in Haslett and Parnell (2008). It requires the weighted mean $^{206}\text{Pb}/^{238}\text{U}$ dates and uncertainties as well as the associated stratigraphic positions of the dated ash beds as input parameters, and produces a non–parametric chronological model based on its compound Poisson–gamma model. The results predict a depositional age and an associated 95% confidence interval uncertainty for each stratigraphic horizon (Fig. 5 and Table 2).

1.4 Cyclostratigraphy

1.4.1. Magnetic measurements

High–resolution measurements of magnetic susceptibility (MS) were carried out on sedimentary successions of the Gaoxigou and Nayuan mine sections to explore Milankovitch cyclicity. MS is a measure of the degree of magnetization of a material in response to an applied magnetic field and reflects the abundance of paramagnetic minerals (e.g., Fe-oxides) in the sediment as a function of composition and a potential proxy for climate change. MS has proven a powerful tool in studies of astronomical cyclicity and terrestrial paleoclimate (Wu et al., 2013; Zhang et al., 2019). Magnetic measurements were made at the outcrop with a ca. 13 cm sampling resolution using a ZH instruments® SM-30 portable magnetic susceptibility meter with a sensitivity of $1\text{E}-7$ SI units, containing an oscillator with a 50 mm diameter pickup coil. At the

Gaoxigou section, 798 MS measurements were carried out on 103.61 m of strata, ranging from the top of the Yan'an Formation down to the #5-1 coal (Table S5). The Nayuan section, 561 MS measurements were carried out, covering 72.80 m of strata from the top of coal the #5-1 coal down to the bottom of #7 coal (Table S5). Therefore, a total of 1359 MS data points were generated that range in value from -0.030×10^{-7} SI to 0.768×10^{-7} SI with an average value of 0.114×10^{-7} SI (Fig. S4). The observed variations in the MS signal appear to correlate to the first order with lithology (detrital input), such that sandstones, mudstones and coal corresponds to the high, low and the lowest MS values, respectively.

1.4.2. Time series analysis

The MS data selected for cyclostratigraphic analysis were linearly interpolated every 13 cm using MATLAB®, and de-trended in the KaleidaGraph by subtracting weighted averages before spectral analysis (Cleveland, 1979). Subsequently, Multitaper method (MTM) power spectral analysis and evolutionary fast Fourier transform spectrograms were employed using the Astrochron package (Meyers, 2014) in the RStudio® for astrochronology to evaluate the cycles, with robust red noise models (Confidence limits at 90, 95 and 99%) and F-test (confidence limits above 80%) to test estimated spectra (Fig. S4). Initially, the direct cycle counting method was used to establish the cyclostratigraphic framework of the Yan'an Formation following the method of Westerhold et al. (2007). The interpreted long (405 k.y.) and short (~100 k.y.) eccentricity cycles were extracted using Gaussian band-pass filters in Analyseries 2.0.8, respectively.

2. CYCLOSTRATIGRAPHY OF AALENIAN $\delta^{13}\text{C}_{\text{belemnite}}$ SERIES

2.1. Data Compilation and Preparation

Our compiled data set includes 314 previously published $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ measurements on well-preserved calcareous macrofossils (belemnite rostra), from the Aalenian of the western Tethyan (European) marine sections (Table S4), which are sensitive to astroclimatic changes (Martinez and Dera, 2015). Each data point is tied to an ammonite subzone (GROUPE FRANÇAIS D'ÉTUDE DU JURASSIQUE, 1997), whose age is modeled based on the latest calibration of the Jurassic time scale (Ogg et al., 2012) and the astronomically constrained duration of the Aalenian Stage (Hinnov and Park, 1999, Huret et al., 2008), by assuming an equal ammonite subzone chron duration. The age calibrated $\delta^{13}\text{C}$ series was then created using the Timescale Creator software version 7.3. (Table S4).

2.2. Spectral Analysis

The $\delta^{13}\text{C}$ data selected for cyclostratigraphic analysis were linearly interpolated every 0.027 Myr using Matlab, and detrended in the software KaleidaGraph before spectral analysis by subtracting weighted averages (Cleveland, 1979). Subsequently, Multitaper method (MTM) power spectral analysis and evolutionary Fast Fourier transform spectrograms were applied to evaluate the cycles using the R Package for astrochronology, with robust red noise models (confidence limits at 90, 95 and 99%) and F-test (confidence limits above 80%) to test estimated spectra. Finally, Gaussian band-pass filters were performed in the Analyseries 2.0.8.

2.3. Result

As the sampling resolution of $\delta^{13}\text{C}$ data is below the Nyquist limit for obliquity and precession, the power spectra show only 405-kyr eccentricity cycles (Fig. S5). However, the confidence of the 405-kyr peak in $\delta^{13}\text{C}$ data is at 80% level in AR(1), and at 95% level in F-test (Fig. S2). Low resolution and age uncertainty, linked to both inaccuracy of the GTS 2012 (Ogg et al., 2012) and temporal positions of data points within ammonite chrons in $\delta^{13}\text{C}$ data, could explain the low confidence of 405-kyr peak in AR(1). The Gaussian band-pass filter (frequency: 0.0024 cycles/m; bandwidth: 0.0006) of $\delta^{13}\text{C}$ data indicate that negative $\delta^{13}\text{C}$ excursions are associate with 405-kyr eccentricity maxima, and conversely, minima in 405-kyr eccentricity correspond with peaks in $\delta^{13}\text{C}$ (Fig. 7).

3. AGE-DEPTH MODELING – BCHRON CODE

```
> library(Bchron)
> setwd("~/Documents/W-Work documents/U-U-Pb/O-Ordos/B chron for Ordos")
> CUGBOD11 = read.table(file = 'CUGBOD11.txt', header = TRUE)
> print (CUGBOD11)
> CUGBOD11Out = Bchronology(ages = CUGBOD11$ages, ageSds = CUGBOD11$ageSds,
calCurves = CUGBOD11$calCurves, positions = CUGBOD11$position, positionThicknesses =
CUGBOD11$thickness, ids = CUGBOD11$id, predictPositions = seq(0, 174, by = 0.01))
> write.csv(CUGBOD11Out$thetaPredict, "CUGBOD11Out.csv")
> CUGBOD11OutPredict = matrix(nrow = 17401, ncol = 3)
> for (i in 1: 17401) {CUGBOD11OutPredict[i,] = quantile(CUGBOD11Out$thetaPredict[,i],
probs = c(0.025, 0.5, 0.975))}
> write.csv(CUGBOD11OutPredict, "CUGBOD11OutPredictquantiles.csv")
>
```

REFERENCES CITED

- Bowring, J.F., McLean, N.M., and Bowring, S.A., 2011, Engineering cyber infrastructure for U-Pb geochronology: Tripoli and U-Pb_Redux: *Geochemistry Geophysics Geosystems*, v. 12, <https://doi.org/10.1029/2010GC003479>.
- Cleveland, W.S., 1979, Robust Locally Weighted Regression and Smoothing Scatterplots: *Journal of the American Statistical Association*, v. 74, p. 829–836, <https://doi.org/10.1080/01621459.1979.10481038>.
- Condon, D.J., Schoene, B., McLean, N.M., Bowring, S.A., and Parrish, R.R., 2015, Metrology and traceability of U-Pb isotope dilution geochronology (EARTHTIME Tracer Calibration Part I): *Geochimica et Cosmochimica Acta*, v. 164, p. 464–480, <https://doi.org/10.1016/j.gca.2015.05.026>.
- De Vleeschouwer, D., and Parnell, A.C., 2014, Reducing time-scale uncertainty for the Devonian by integrating astrochronology and Bayesian statistics: *Geology*, v. 42, no. 6, p. 491–494, <https://doi.org/10.1130/G35618.1>. **[[Not cited?]]**
- [[Journal name?]]** Dera, G., Brigaud, B., Monna, F., Laffont, R., Pucat, E., Deconinck, J.F., Pellenard, P., Joachimski, M.M., and Durlet, C., 2011, Climatic ups and downs in a disturbed Jurassic world: *Journal*, v. 39, p. 215–218, <https://doi.org/10.1130/G31579.1>.

- Gomez, J.J., Canales, M.L., Ureta, S., and Goy, A., 2009, Palaeoclimatic and biotic changes during the Aalenian (Middle Jurassic) at the southern Lurasian Seaway (Basque–Cantabrian Basin, northern Spain): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 275, p. 14–27, <https://doi.org/10.1016/j.palaeo.2009.01.009>.
- Gomez, J.J., Goy, A., and Canales, M.L., 2008, Seawater temperature and carbon isotope variations in belemnites linked to mass extinction during the Toarcian (Early Jurassic) in Central and Northern Spain. Comparison with other European sections: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 258, p. 28–58, <https://doi.org/10.1016/j.palaeo.2007.11.005>.
- GROUPE FRANÇAIS D'ÉTUDE DU JURASSIQUE, 1997, Biostratigraphie du Jurassique ouest-européen et méditerranéen: zonations parallèles et distribution des invertébrés et microfossiles, in Cariou, E., Hantzpergue, P. (coordinators), Bull. Centre Rech. Elf Explor. Prod., Mém. 17, p. 440.
- Haslett, J., and Parnell, A., 2008, A simple monotone process with application to radiocarbon-dated depth chronologies: Journal of the Royal Statistical Society, Series C (Applied), v. 57, p. 399–418, <https://doi.org/10.1111/j.1467-9876.2008.00623.x>.
- Hiess, J., Condon, D.J., McLean, N., and Noble, S.R., 2012, 238U/235U Systematics in Terrestrial Uranium-Bearing Minerals: Science, v. 335, p. 1610–1614, <https://doi.org/10.1126/science.1215507>.
- Hinnov, L.A., and Park, J.J., 1989, 1999, Strategies for assessing early-middle (Pliensbachian–Aalenian) Jurassic cyclochronologies: Philosophical Transactions of the Royal Society of London, v. 357, p. 1831, <https://doi.org/10.1098/rsta.1999.0403>.
- Huret, E., Hinnov, L.A., Galbrun, B., Collin, P.-Y., Gardin, S., and Rouget, I., 2008, Astronomical calibration and correlation of the Lower Jurassic, Paris and Lombard basins (Tethys), in 33rd International Geological Congress: Oslo, Norway.
- Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., and Essling, A.M., 1971, Precision Measurement of Half-Lives and Specific Activities of ²³⁵U and ²³⁸U: Physical Review. C, v. 4, p. 1889–1906, <https://doi.org/10.1103/PhysRevC.4.1889>.
- Keller, C.B., Schoene, B., and Samperton, K.M., 2018, A stochastic sampling approach to zircon eruption age interpretation: Geochemical Perspectives Letters, v. 8, p. 31–35, <https://doi.org/10.7185/geochemlet.1826>.
- Krogh, T.E., 1973, Low-Contamination Method for Hydrothermal Decomposition of Zircon and Extraction of U and Pb for Isotopic Age Determinations: Geochimica et Cosmochimica Acta, v. 37, p. 485–494, [https://doi.org/10.1016/0016-7037\(73\)90213-5](https://doi.org/10.1016/0016-7037(73)90213-5).
- Li, S., Yang, S., and Jerzykiewicz, T., 1995, Upper Triassic–Jurassic foreland sequences of the Ordos Basin in China, in Dorobek, S.L., and Ross, G.M., eds., Stratigraphic Evolution of Foreland Basins. SEPM (Society for Sedimentary Geology), pp. 233–241.
- Martinez, M., and Dera, G., 2015, Orbital pacing of carbon fluxes by a~ 9-My eccentricity cycle during the Mesozoic: Proceedings of the National Academy of Sciences of the United States of America, v. 112, p. 12604–12609, <https://doi.org/10.1073/pnas.1419946112>.
- Mattinson, J.M., 2005, Zircon U/Pb chemical abrasion (CA-TIMS) method; combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages: Chemical Geology, v. 220, p. 47–66, <https://doi.org/10.1016/j.chemgeo.2005.03.011>.
- McLean, N.M., Bowring, J.F., and Bowring, S.A., 2011, An algorithm for U–Pb isotope dilution data reduction and uncertainty propagation: Geochemistry Geophysics Geosystems, v. 12, <https://doi.org/10.1029/2010GC003478>.

- McLean, N.M., Condon, D.J., Schoene, B., and Bowring, S.A., 2015, Evaluating uncertainties in the calibration of isotopic reference materials and multi-element isotopic tracers (EARTHTIME Tracer Calibration Part II): *Geochimica et Cosmochimica Acta*, v. 164, p. 481–501, <https://doi.org/10.1016/j.gca.2015.02.040>.
- Meyers, S.R., 2014, Astrochron: An R Package for Astrochronology: <https://cran.r-project.org/package=astrochron>.
- Ogg, J.G., Hinnov, L.A., and Huang, C., 2012, Jurassic, in Gradstein, F.M., Ogg, J.G., Schmitz, M.D., and Ogg, G.M., eds., *The Geologic Time Scale 2012*, 1 ed: Oxford, Elsevier, p. 731–791, <https://doi.org/10.1016/B978-0-444-59425-9.00026-3>.
- Parnell, A.C., Haslett, J., Allen, J.R.M., Buck, C.E., and Huntley, B., 2008, A flexible approach to assessing synchronicity of past events using Bayesian reconstructions of sedimentation history: *Quaternary Science Reviews*, v. 27, p. 1872–1885, <https://doi.org/10.1016/j.quascirev.2008.07.009>.
- Ramezani, J., Hoke, G.D., Fastovsky, D.E., Bowring, S.A., Therrien, F., Dworkin, S.I., Atchley, S.C., and Nordt, L.C., 2011, High-precision U-Pb zircon geochronology of the Late Triassic Chinle Formation, Petrified Forest National Park (Arizona, USA): Temporal constraints on the early evolution of dinosaurs: *Geological Society of America Bulletin*, v. 123, p. 2142–2159, <https://doi.org/10.1130/B30433.1>.
- Trayler, R.B., Schmitz, M.D., Cuitiño, J.I., Kohn, M.J., Bargo, M.S., Kay, R.F., Strömberg, C.A.E., and Vizcaíno, S.F., 2019, An improved approach to age-modeling in deep time: Implications for the Santa Cruz Formation, Argentina: *Geological Society of America Bulletin*, v. 132, p. 233–244, <https://doi.org/10.1130/B35203.1>.
- Wang, S., 1996, Coal accumulation and coal resources evaluation of Ordos Basin [in Chinese with English abstract]: Beijing, China Coal Industry Publishing House.
- Wang, S., and Zhang, Y., 1999, Study on the formation, evolution and coal-accumulating regularity of the Jurassic Ordos Basin [in Chinese with English abstract]: *Earth Science Frontiers*, v. 6, no. 5, p. 147–155.
- Westerhold, T., Röhl, U., Laskar, J., Raffi, I., Bowles, J., Lourens, L.J., and Zachos, J.C., 2007, On the duration of magnetochrons C24r and C25n and the timing of early Eocene global warming events: Implications from the Ocean Drilling Program Leg 208 Walvis Ridge depth transect: *Paleoceanography*, p. 22, <https://doi.org/10.1029/2006PA001322>.
- Wu, H., Zhang, S., Jiang, G., Hinnov, L., Yang, T., Li, H., Wan, X., and Wang, C., 2013, 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: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 385, p. 55–70, <https://doi.org/10.1016/j.palaeo.2012.09.004>.
- Yin, L., Zhang, G., and Zhang, G., 1990, Dongsheng Coalfield Geological Data Compilation (No. 6802): National Geological Archives of the China Geological Survey (<http://www.ngac.cn>) (in Chinese).
- Zhang, R., Jin, Z., Liu, Q., Li, P., Huang, Z., Shi, J., Ge, Y., and Du, K., 2019, Astronomical constraints on deposition of the Middle Triassic Chang 7 lacustrine shales in the Ordos Basin, Central China: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 528, p. 87–98, <https://doi.org/10.1016/j.palaeo.2019.04.030>.

Figure S1. (A) Mesozoic lithofacies and sequence stratigraphy of the Ordos Basin. (B) Distribution of the Yan'an Formation depositional facies throughout the Ordos Basin. (C) Sedimentary architecture of the Yan'an Formation in cross-section. Modified after Li et al. (1995).

Figure S2. (A) Sedimentary isopach map of the Yan'an Formation. (B) Cumulative thickness of Yan'an Formation coal seams. Modified after Wang and Zhang (1999).

Figure S3. Characteristics of sampled tonstein layers from the Dongsheng Coalfield. (A) White tonstein layer (CNL072718-1) seen as a distinct bed inside #7 coal at the bottom of the outcrop at the Chaonaoliang mine site. #6 coal seams are exposed on the slope in the background. (B) Thin tonstein (NG072818-3) inside a minor coal bed above the #3 coal at the Nangai mine site. (C) Variegated fluvial deposits of the Zhiluo Formation disconformably overlying the #2 coal (Yan'an Formation) at the Nangai mine site. (D) Photomicrograph of separated zircons from sample CNL072718-1.

Figure S4. Magnetic susceptibility (MS) cyclostratigraphy of the Yan'an Formation (black) based on the Gaoxigou (GXG) and Nayuan (NY) composite section. The interpreted 100-kyr (blue) and 405-kyr (red) sedimentary cycles were extracted using Gaussian filters with passbands of 0.035 ± 0.01 cycles/m and 0.14 ± 0.04 cycles/m, respectively. These cycles are used to calculate sediment accumulation rates (SAR, green). 2π MTM power spectrum and FFT spectrogram of the untuned MS series of Yan'an Formation are shown to the right. The sliding window is 35 m and the step rate is 0.13 m.

Figure S5. (A) $\delta^{13}\text{C}_{\text{lemnite}}$ series from European sections. (B) 2π MTM power spectra of the $\delta^{13}\text{C}_{\text{lemnite}}$ series from European sections.