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A high-resolution timescale for the Miocene Shanwang diatomaceous shale lagerstätte (China)

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1	A high-resolution timescale for the Miocene Shanwang diatomaceous shale lagerstätte (China):
2	development of Wavelet Scale Series Analysis for cyclostratigraphy
3	
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25 ABSTRACT

The Miocene aged Shanwang Formation from the Shanwang National Geopark in China 26 represents a succession of lacustrine diatomaceous shales containing an abundant and diverse biota 27 with lagerstätte fossilization of soft tissues. To date, the Shanwang Formation has not been 28 investigated for cyclostratigraphy nor has it been dated with high precision methods. Now we use 29 thorium data as a paleoenvironmental and paleoclimatic proxy to conduct a detailed 30 cyclostratigraphic analysis. A new and simple cyclostratigraphic method, Wavelet Scale Series 31 Analysis (WSSA), using the Wavelet Analysis toolbox in Matlab, is developed to recognize 32 33 Milankovitch cycles. A total of three short eccentricity and fifteen precession cycles are identified; obliquity cycles are not apparent. In the sedimentary succession, the corresponding precession and 34 short eccentricity cycles are 1.17 m and 4.98 m thick respectively, with this verified by Correlation 35 36 Coefficient (COCO) analysis and Multitaper-Method (MTM) spectral analysis. We estimate the studied interval was deposited over a duration of 0.3 Myr with a depositional rate of c. 5.7 cm/kyr. 37 Paleomagnetic and radio isotope dating data shows that the diatomaceous shale was deposited during 38 39 Chron C5En, which places it at approximately 18.5 Ma during the Burdigalian stage of the Early Miocene, rather than in the Middle Miocene as previously thought. The Shanwang lagerstätte biota 40 therefore predates the Middle Miocene Climate Optimum (MMCO) and did not form within it. The 41 42 geological time scale with a high resolution of 20 kyr was set accordingly. 43

Key words: Milankovitch cycles, Spectral analysis, Geochronology, Chron C5En, Burdigalian
45

46 1. INTRODUCTION

48	The Shanwang Formation in the Shanwang National Geopark (Shandong Province, E China)
49	comprises a succession of diatomaceous shales that formed in a small inland basin during the
50	Miocene (Liang et al., 2003). The Shanwang site is world famous because of the diversity of fossils
51	it contains, and because of their exceptional preservation, representing a rare occurrence of
52	lagerstätte grade fossilization of soft tissues (e.g., Seilacher et al., 1985) from the Miocene (Yang and
53	Yang, 1994). This can be compared favorably with Germany's famous Jurassic aged Solenhofen
54	Limestone site in terms of its scientific importance (Holden, 2001).
55	The majority of past research on the Shanwang Formation has focused on taxonomic and
56	systematic investigations of its fossils that have supported various palaeoecological and
57	palaeoclimate investigations (e.g., Yang and Yang, 1994; Sun et al., 2002; Liang et al., 2003). Li et al.
58	(1984) used the Shanwang fauna to define one of the Eastern Asian Land Mammal Ages of the
59	Neogene, designating from it the Shanwangian Stage that has been widely adopted by
60	paleontologists subsequently. He et al. (2011) undertook ${}^{40}Ar/{}^{39}Ar$ dating of the basalts in the
61	Shanwang Basin and determined those below the Shanwang Formation formed at 21.0 ± 2.5 Ma with
62	a total age range of 18.5–23.5 Ma, while those above the Shanwang Formation formed at 17.3 ± 1.4
63	Ma with a total range of 15.9–18.7 Ma. These radiometric age ranges are broad and lack precision
64	for determining the absolute age and rates of deposition for the Shanwang Formation. Research into
65	Milankovitch cyclicity has not been undertaken thus far on the Shanwang Formation, nor has a
66	high-resolution time scale for the succession been established. This restricts deep time climate
67	studies of this stratigraphic interval to some extent, although more recently new paleoclimate
68	classifications have been proposed to bridge the gap between modern and deep time climate studies

69 (e.g., Zhang et al., 2015).

70	As a newly developed non-biostratigraphic dating tool, cyclostratigraphy can provide a
71	high-resolution astronomical time scale (ATS) by tuning the cyclic stratigraphic records to
72	astronomical solutions (Hinnov and Ogg, 2007; Hilgen et al., 2010; Batenburg et al., 2012; Wu et al.,
73	2014). Here we present a high-resolution cyclostratigraphic analysis of the lagerstätte-bearing
74	diatomaceous shales in the Shanwang Basin for the first time, using thorium (Th) logging data. The
75	main objective of the present contribution is to provide a high-resolution geological time scale for
76	the diatomaceous shales in order to precisely date the Shanwang Formation, and to determine the
77	duration of its accumulation.

78

79 2. LOCATION AND GEOLOGICAL SETTING

The Shanwang Basin (36°N,118°E) is located 22 km northeast of Linqu County in the centre of Shandong Province, eastern China, adjacent to the Tan-Lu Fault Zone (Fig. 1a). It is a small maar lake basin formed in a volcanic crater that is oriented from northwest to southeast with an area less than 1 km² (Zhang and Shan, 1994).

The Miocene sediments in the basin from the bottom to the top comprise the Niushan, Shanwang and Yaoshan formations. The thickness of each of the Niushan and Yaoshan formations are over 100 m, while the total thickness of the Shanwang Formation is ~100m. The Shanwang Formation is divided into six units. These are a yellow sandstone and tuff breccia at the bottom (Unit1), which only occur at the edges of the basin and have an unconformable contact with Niushan Formation. The middle part of the formation (Unit 2) comprises gray and white diatomaceous shale, interspersed with multiple layers of tuff, phosphorus nodules and marl. The upper part of the

91	Formation (Units 3–6) comprises green mudstone, brown carbonaceous mudstone, interspersed with
92	two layers of basalt and apical sandstone (Fig. 1b). Our study deals with unit 2 from the Shanwang
93	Formation, which is the main diatomaceous succession containing abundant and well-preserved
94	fossils that comprises the principle unit of the fossil lagerstätten (Fig. 1c). The main lithology of the
95	studied section is diatomaceous shale, which is mainly composed of siliceous diatom and radiolarian
96	fossils, in addition to clay minerals and organic matter (Qin et al., 2004; Yu et al., 2017). The color of
97	the diatoms and radiolarians is typically white and brighter than that of the clay and organic matter.
98	Consequently, sediment color depends largely on the siliceous microfossil content; the more diatoms
99	and radiolarians are present, the brighter colored the sediment becomes (Fig. 2).
100	
101	Approximate position of Fig. 1
102	Approximate position of Fig. 2
103	
104	3. DATA AND METHODS
105	
106	3.1. Data Collection and Selection
107	Data most commonly used to study Milankovitch cycles in sediments are usually from
108	lithological outcrop or borehole cores. Methods typically use colour variation (e.g. gray values from
109	profile images), gamma ray logs, magnetic susceptibility, Total Organic Carbon (TOC) content, or
110	carbonate content of samples amongst other proxies (e.g., Prokoph and Barthelmes, 1996; Husson et
111	al., 2011; Batenburg et al., 2012; Pas et al., 2018). For this study, spectral gamma-ray (SGR) values
112	were measured in situ with a portable "GS-512" gamma spectrometer with evenly spaced sampling

intervals of 5 cm and vertically through the measured profile of Unit 2. This method is a quick and
simple, yet powerful technique to better correlate well data with surface geology (Aigner et al.,
1995).

SGR data relating to the amount of radioactive potassium (K), uranium (U) and thorium (Th) in 116 rocks have been widely used in paleoclimatic and paleoenvironmental research (Wu et al., 2009; 117 Zhang et al., 2010). Levels of K, U and Th vary within sedimentary rocks. K is common in 118 sediments containing feldspar, mica, clays or salts, while U and Th have a number of host minerals in 119 sedimentary rocks including clays, feldspars, heavy minerals, phosphates and organic matter. K is 120 121 leached from feldspars and muscovite during kaolinite formation under conditions of hot and humid climates, while Th is at least partially insoluble and concentrates during weathering (Parkinson, 1996; 122 Osmond and Ivanovich, 1992). U is more soluble than Th and thus prone to mobilisation during 123 124 leaching and clay mineral diagenesis.

Th logging data are considered to be more stable than K and U, and have been widely used as a 125 palaeoclimate indicator in previous studies. For example, Wu et al. (2013) used the Th logging data 126 from the Yaojia Formation to track lithological change, with high Th occurring in mudstones and low 127 Th in sandstones. In lacustrine sediments, higher Th values are related to higher content of clay 128 minerals and organic carbon, which may have resulted from wetter and warmer climate conditions. 129 Wet periods may have enhanced chemical weathering and clay mineral inputs, nutrient input and 130 higher productivity in the paleolakes, resulting in high values. Conversely, decreased chemical 131 weathering during dry periods may correspond to the negative peaks of Th values (Wu et al., 2009; 132 Wang et al., 2013). Wu et al. (2014) also used thorium (Th) logging data as a paleoenvironmental and 133 paleoclimatic proxy to conduct a detailed cyclostratigraphic study of the core from well SK-1n in 134

Songliao Basin northeastern China. For these reasons, the Th data series was selected in this study as
the most reliable paleoclimatic and paleoenvironmental proxy for cyclostratigraphic analysis (Fig.
3a).

138

139 **3.2. Data Analysis Method (WSSA)**

In the development of cyclostratigraphy, various different methods for spectral analysis have 140 been used to extract Milankovitch cyclicity within a time series of different geological signals, 141 including Fourier Transform (Park and Herbert, 1987; Wu et al., 2014), WALSH transform (Weedon, 142 143 1986, 1989), maximum entropy spectrum analysis (Hinnov and Goldhammer, 1991; Dimri and Prakash, 2001), and wavelet analysis (Prokoph and Barthelmes, 1996; Torrence and Compo, 1998). 144 Other methods including the neural estimator, PCA-Music method and the genetic algorithm (GA) 145 have also been introduced into this area (Tagliaferri et al., 2001), as have new methods or computer 146 packages such as the COCO (Correlation Coefficient) and MTM (Multitaper-Method spectral 147 analysis) (Thomson, 1982; Paillard et al., 1996; Ghil et al., 2002; Li et al., 2018). 148 149 Wavelet transform theory is a new signal processing technology developed in recent decades (Mallat, 1989; Chui, 1992). Because of its high resolution in both time and frequency domains, it is 150 informally termed the "mathematical microscope" and widely used in numerical signal processing 151 fields (James and Michael, 2006; Yu et al., 2010). As a method, it has been applied to the recognition 152 of Milankovitch cycles in different ways by previous researchers (e.g. Prokoph and Agterberg, 1999, 153 2000; Yu et al., 2008; Batenburg et al., 2012). There are two kinds of wavelet transform, namely, the 154 155 Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). CWT involves a transform from a one-dimensional time series (or frequency spectrum) to a diffuse two-dimensional 156

time-frequency image of the wavelet coefficient called scalogram, produced through the convolution 157 of a basic wavelet function $\Psi_{a,b}(x)$, with the analyzed signal f(x), a, b representing the scale factor 158 159 and shift factor of the basic wavelet function respectively (Fig. 3b; Eq. 1). Usually the Morlet wavelet is selected as the basic wavelet function in CWT, because the shape of this basic function is 160 similar to a sinusoid function, which allows interpretations of repeat time series and its sinusoidal 161 shape makes it particularly suitable for sedimentary cycles without well-defined shapes (Prokoph and 162 Agterberg, 2000). CWT was once regarded as an interesting diversion that produces colorful pictures 163 that were purely qualitative results because of the misconception of CWT itself. Here we propose a 164 165 new quantitative method, Wavelet Scale Series Analysis (WSSA), to extract periodic information within time series of paleoclimate proxies, and apply this to the recognize Milankovitch-cycle from 166 Thorium data. This method requires the following six steps. 167

168

169 (1) Do CWT to calculate the wavelet coefficient matrix of a signal $f(x) \in L^2(R)$:

$$CWT_{a,b} = \int_{R} f(x)\overline{\psi_{a,b}(x)}dx = |a|^{-\frac{1}{2}} \int_{R} f(x)\overline{\psi(\frac{x-b}{a})}dx,$$
(1)

171 to get the wavelet coefficient matrix $C_{a,b}$:

172

173
$$C_{a,b} = \begin{bmatrix} C_{a_1b_1} & C_{a_1b_2} & \dots & C_{a_1b_n} \\ C_{a_2b_1} & C_{a_2b_2} & \dots & C_{a_2b_n} \\ \vdots & \vdots & \ddots & \vdots \\ C_{a_mb_1} & C_{a_mb_2} & \dots & C_{a_mb_n} \end{bmatrix}.$$
(2)

174

175 (2) Calculate the absolute value of the wavelet coefficient matrix to form a new matrix:

177

$$C_{i,j} = |C_{a,b}| = \begin{bmatrix} |C_{a_ib_i}| & |C_{a_jb_2}| & \dots & |C_{a_jb_n}| \\ |C_{a_jb_i}| & |C_{a_jb_2}| & \dots & |C_{a_jb_n}| \\ \vdots & \vdots & \ddots & \vdots \\ |C_{a_mb_i}| & |C_{a_mb_2}| & \dots & |C_{a_mb_n}| \end{bmatrix}.$$
(3)

179 (3) Calculate the mean value of each row of the new matrix to get a vector, a scale series:

180

181
$$\overline{C}_{i} = \begin{bmatrix} \sum C_{1j}/n \\ \sum C_{2j}/n \\ \vdots \\ \sum C_{nj}/n \end{bmatrix} = \begin{bmatrix} \overline{C}_{1} \\ \overline{C}_{2} \\ \vdots \\ \overline{C}_{m} \end{bmatrix}.$$
(4)

182

183 (4) Locate the extreme points of the scale series to find the predominant scale needed.

184

(5) The scales corresponding to the extreme points represent the predominant scales (or cycles) and
the specific thickness values can be obtained according to the relationship between scale and
frequency in wavelet analysis (see Eq. 5).

188
$$F_a = \frac{F_c}{a \cdot \Delta}.$$
 (5)

189 where *a* is the scale factor, Δ is the sampling period, F_c is the center frequency of the wavelet, and F_a

is the quasi-frequency at a. F_a can be regarded as the real frequency of a within a tolerant error range.

191 F_a can be the number of cycles within a thickness unit if Δ is the sampling interval in thickness.

Morlet wavelet is used as the mother wavelet in our study, so $F_c = 0.8125$ Hz. The reciprocal of F_a is the predominant cycle we want to find.

194

(6) The number of the sinusoidal wave in the wavelet coefficient at the predominant scale can becounted.

198 **4. RESULTS**

199

200 4.1. WSSA Results

In this study, the WSSA method was undertaken in the Matlab platform and applied to the Th data series from the studied section. Five extreme points within the scale series have been recognized: $a_1 = 3, a_2 = 6, a_3 = 19, a_4 = 81, and a_5 = 114$ (Fig. 3c).

204

205 Approximate position of Fig. 3

206

Periods of the Milankovitch cycles (~20 kyr precession, 40 kyr obliquity, 100 kyr short 207 208 eccentricity, and 400 kyr long eccentricity) and their duration ratio (~1:2:5:20) are relatively stable in any particular geological interval. Matching the thickness of sedimentary cycles with Milankovitch 209 cycles is a widely accepted method to determine whether the sedimentary unit is affected by the 210 211 astronomical orbital forces (Hinnov, 2000; Weedon, 2003). According to the method for the 212 recognition of Milankovitch cycles, there are two equally possible matching schemes to fit the Milankovitch syndrome. The first is at the scale of a = 3 (a_1) and a = 6 (a_2), implying a 1:2 ratio, 213 corresponding to the ratio between precession and obliquity cycles. The second is at the scale of a =214 215 19 (a_3) and a = 81 (a_4), implying a 1:4.3 ratio, corresponding to the ratio between precession and short eccentricity cycles. When we enter a = 3 and a = 6 into Equation (5), periodic thicknesses for 216 217 the precession cycles of 0.18 m and obliquity cycles of 0.37 m are obtained. This would imply a duration for the entire 17 m thick studied section of about 2 Myr. A 2 Myr age range for the studied 218

219	section conflicts not only with the radio isotope dating results (He et al., 2011), but also with the
220	results of our own paleomagnetic analysis. In the studied section, our palaeomagnetic analysis
221	indicates that only a normal polarity intervals exist, but at no point during the Miocene does a normal
222	polarity interval last as long as 2 Myr (see below). However, when we enter values of a = 19 and a =
223	81 into Equation (5), periodic thicknesses for the precession cycles of 1.17 m and eccentricity of 4.98
224	m are obtained, and these values are much more reasonable. In this case, the deposition of the studied
225	section would have taken about 0.3 Myr, equivalent of 15 precession cycles. We therefore conclude
226	that the Th signal at the scale $a = 19$ and $a = 81$ reflects the precession and short eccentricity cycles
227	in the Shanwang Formation. The various cycles and their duration of accumulation in terms of
228	precession and eccentricity (a =19 and a = 81) are shown in Figure 4.
229	
230	Approximate position of Fig. 4
231	
232	4.2. Results with Parallel Methods
233	
234	In order to verify the validity of the WSSA method, the Correlation Coefficient (COCO) and
235	Multitaper-Method spectral analysis (MTM) methods were also applied to the detrended Th series to
236	test the robustness of the evidence in our cyclostratigraphic interpretation. These analyses were
237	performed with the computer routine ACycle 0.2.5 (Li et al., 2018). Long-term trend removal was
238	needed in order to avoid distortion of the low-frequency section of the spectrum using a "Lowess
239	smoother" (smoother = 50%). COCO analysis of the detrended Th series of the diatomaceous shale
240	indicates the mean sedimentation rate at 4.8 cm/kyr is the optimal result, the correlation coefficient

of which is the largest and exceed the critical significance level (Fig. 5a-c). The MTM power 241 spectrum of the detrended Th series from the diatomaceous shale shows an obvious peak of 5.06 m 242 (Fig. 5d), which is consistent well with the cycles recognized by our WSSA method (4.98 m). 243 Combined with the sedimentation rate (4.8 cm/kyr) determined from the COCO analysis, the cycle of 244 5.06 m is concluded as representing the short eccentricity cycle (105 kyr). Unfortunately, the peaks 245 of 0.83 m and 1.12 m (representing the precession cycle based on the sedimentation rate of 4.8 246 cm/kyr) are distinguishable but with a low value; confidence levels of these spectral peaks show 247 minor values below 90%. This is a common phenomenon for which possible reasons for the low 248 249 confidence levels include variations in accumulation rate, bioturbation, undetected hiatuses, or the possibility that a precession signal is not actually present in the Th series (Weedon, 2003). Overall, 250 this result is consistent with the cycles recognized by our WSSA method. Slight differences in the 251 252 average deposition rates (4.8 cm/kyr by COCO and 5.7 cm/kyr by WSSA) may be due to different mathematical algorithms. This is an uncommonly high sedimentation rate, but is not exceptional for 253 lacustrine settings. A high sedimentation rate for the Shanwang Formation has previously been 254 postulated by other researchers (e.g., Tian et al., 2015) on the basis of the extremely good 255 preservation of the fossils, enhancing their preservation potential through sedimentary obrution 256 (rapid burial or smothering event). 257

By comparison, it was found that the same results can be reached by both the WSSA and
parallel methods, and there are fewer redundant peaks in the WSSA results for final selection.
Furthermore, it is easier to implement WSSA method as no additional routine packages required to
undertake the analysis.

265 5. PALEOMAGNETIC ANALYSIS

In addition to the cyclostratigraphic analysis, we investigated whether the age data thus obtained 266 for the deposition of unit 2 of the Shanwang Formation fits with the established paleomagnetic 267 context of the Miocene. A detailed paleomagnetic survey was carried out on the basis of 93 oriented 268 samples with a size of 30 cm \times 23 cm \times 30 cm, which had a total weight of ~3 tons and spanned 269 almost the entire section under study. Samples were collected using an electric saw. As the tectonic 270 271 dip of the Shanwang Formation is less than 5°, implying a near-horizontal position, the orientation of the samples could be marked by indicating the direction of the magnetic North Pole on the bedding 272 surface of each sample. 273

274 From the 93 samples, 31 fairly evenly spaced specimens were selected; these were cut into 167 smaller oriented pieces with sizes of $2 \text{ cm} \times 2 \text{ cm} \times 2 \text{ cm}$ each for geomagnetic measurements. The 275 measurements were performed in the Paleomagnetism and Geochronology Laboratory (SKL-LE) of 276 277 the Institute of Geology and Geophysics, Chinese Academy of Sciences. Systematic demagnetization of all samples was done using a three-axes low-temperature superconducting magnetometer 2G760 278 and a stepwise progressive alternating demagnetization method. The twelve demagnetization 279 280 intensity steps were set at 0, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80 mT. The original demagnetization data were converted with data conversion tools, then processed with PMGSC4.2 281 software and finally presented in terms of the Zijderveld graphic method. The demagnetization 282 curves of most of these samples were found to yield a stable and reliable character remanence at the 283 fifth demagnetization step (20 mT). The declination and inclination curves of the effective samples 284

285	show that the entire profile of the diatomaceous shale part of the Shanwang Formation has a normal
286	polarity with stable declination and inclination (Fig. 6).
287	
288	Approximate position of Fig. 6
289	
290	6. CHRONOSTRATIGRAPHIC IMPLICATIONS
291	
292	We combined the above geomagnetic polarity result with the results from Fang et al. (1980) to
293	construct a geomagnetic polarity column (Fig. 7, middle). This presents, from bottom to top, the
294	lower part of the Niushan Formation with a normal polarity (N1), the upper part of the Niushan
295	Formation with a reversed polarity (R1), the main part of the Shanwang Formation with a normal
296	polarity (N2), the top part of the Shanwang Formation with a reversed polarity (R2), and the Yaoshan
297	Formation with a normal polarity (N3).
298	
299	Approximate position of Fig. 7
300	
301	Constrained by the ⁴⁰ Ar/ ³⁹ Ar dating results of He et al. (2011) (Fig. 7, left), who attributed an
302	age of 17.3±1.4 Ma to the lower part of the Yaoshan Formation, an age of 17–18 Ma to the lower part
303	of the Shanwang Formation, and an age of 21.0±2.5 Ma to the top of the Niushan Formation, the
304	Shanwang Formation can be correlated with the international GPTS (Ogg, 2012) (Fig. 7, right). It
305	was thus found that there are only two reasonable matching modes, that is, matching N2 with either
306	subchron 5Dn or subchron 5En of Chron 5 (Fig. 7). Considering that the duration of 0.298 Myr of

subchron 5Dn is shorter than the above WSSA results of the studied section, we consider it
appropriate to correlate N2 in the Shanwang Formation with subchron 5En. This implies that
deposition of the Shanwang Formation started about 18.5 Ma (Fig. 7).

According to Gradstein and Ogg (2004), the Early Miocene comprises the Aquitanian and 310 Burdigalian stages, whereas the Middle Miocene comprises the Langhian and Serravallian stages, 311 and the Late Miocene the Tortonian and Messinian stages. Using the current radiometric stage ages 312 (GTS 2018), the Early Miocene lasted from 23.03 to 15.97 Ma, the Middle Miocene from 15.97 to 313 11.63 Ma, and the Late Miocene from 11.63 to 5.33 Ma (Cohen et al., 2013: updated in 2018-08). 314 315 Consequently, the Shanwang Formation must have formed during the later part of the Early Miocene during the Burdigalian stage, and not during the Middle Miocene as previously suggested (Sun et al., 316 2002; Liang et al., 2003; Zbynek Rocek et al., year). In this stratigraphic context, the Shanwang 317 318 lagerstätte biota therefore predates the Middle Miocene Climate Optimum (MMCO), in which the initial warming began ca. 18 Ma (Harris et al., 2017) with a peak at ca. 17-14.75 Ma (Zachos et al., 319 2001). It was therefore not deposited during the onset or main period of the MMCO as previously 320 321 considered (e.g., He et al., 2011). However, we note that different age ranges for the MMCO have previously been published, including estimates of 16-14 Ma (Song et al., 2018), 16-14.8 Ma (Flower 322 and Kennett, 1994) and 17–15 Ma (Wan et al., 2009). With deposition of the studied section starting 323 at approx. 18.5 Ma and lasting 0.3 Myr, we conclude that the Shanwang Formation predates each of 324 325 these estimates for the MMCO.

According to recent research the age range of European Mammalian Zone MN4 is from 17.2–16.4 Ma and the age range of MN3 is ca. 19.5–17.2 Ma (Jovells and Casanovas, 2018). This is

not very different from the ages determined by Larrasoaña et al. (2006) who located the upper

329	boundary of MN3 at 16.8–17 Ma, and the lower boundary of MN3 at ca. 20.1 Ma. We conclude that
330	the biota in the Shanwang Formation should be correlated stratigrpahically to European Mammalian
331	Zone MN3, rather than to MN5 or MN4 as suggested by Deng et al. (2003).

333 7. CONCLUSIONS

Our detailed cyclostratigraphic study based on thorium data shows that the sedimentation of the 334 Miocene diatomaceous shale in the Shanwang Basin was driven by the precession and short 335 eccentricity astronomical cycles. A total of three short eccentricity and fifteen precession cycles have 336 337 been identified. The studied interval of the succession can be estimated to have lasted 0.3 Myr with a depositional rate of about 5.7 cm/kyr. Paleomagnetic analysis limited the formation time of the 338 Shanwang Formation to 18.5 Ma, giving a non-floating geologic time scale of the succession with a 339 resolution as high as 20 kyr. Based on these results, we think that the Shanwang lagerstätte biota was 340 not deposited during the onset or main period of the Middle Miocene Climate Optimum (MMCO), 341 but was deposited ahead of it. 342 The Wavelet Scale Series Analysis (WSSA) method derived from the so called 'mathematical 343 microscope' wavelet analysis can overcome the redundancy of CWT in recognizing the predominant 344 periodicity within one-dimensional signals and serve as a practical solution for identifying 345

- 346 Milankovitch cycles from geologic time series. .
- 347

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509 FIGURES



510

Fig. 1. (a) Location of the Shanwang Basin in Shandong Province (E. China). (b) Sedimentary

succession of the Shanwang Formation in Linqu (modified from the Fourth Geological Prospecting

- 513 Institute of Shandong 2002 and Liang et al., 2003). (c) Outcrops of the studied section. s1-s6:
- 514 positions of the samples from which the thin sections in Fig. 2 were prepared.

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Fig. 2. Thin section photomicrographs of the diatomaceous shales in plane polarized transmitted
light. (s1) Dark clay layer with small amount of bright diatoms. (s2) Bright diatom layer with small
amount of clay. (s3) Thick layer of dark organic matter with thin layer of bright diatom. (s4) Thick
layer of bright diatom with thin layer of dark clay. (s5) Dark clay layer with small amount of bright
diatoms. (s6) Bright diatom layer with small amount of clay. For sample locations, see Fig. 1.



Fig. 3. WSSA result. (a) Raw thorium (Th) (in ppm) data. (b) CWT scalogram of the Th series in the
studied section. The blue color represents low values and red high values for the wavelet coefficients
at different scale and depth. (c) Wavelet scale series curve of the Th series in the studied section.



Fig. 4. Sedimentary log of the studied section with concentration of thorium (Th) (in ppm) and

⁵³¹ corresponding Milankovitch cyclicity by WSSA.



Fig. 5. 2-slice COCO analysis and 2π MTM power spectra of the detrended Th series in the studied section. (a) COCO spectra shown with mean sedimentation rate at 4.8 cm/kyr. (b) H₀ significance level for the COCO results. (c) Number of contributing astronomical parameters. The target astronomical series using La04 solution at 18 Ma (Laskar et al., 2004). The number of Monte Carlo simulations is 2000. Sedimentation rates range from 1 to 30 cm/kyr with a step of 0.1 cm/kyr. (d) MTM spectra of the detrended Th series shows peaks of 5.06m, 1.12m and 0.83m, which are interpreted to represent short eccentricity (e) and precession (p).



Fig. 6. Result of paleomagnetic analysis of the section under study. dec = declination; inc =

544 inclination.



Fig. 7. Age of the Shanwang Formation constrained by radiometric dating and geomagnetic data.