A record of astronomically forced climate change in a late Ordovician (Sandbian) deep marine sequence, Ordos Basin, North China

Qiang Fang^{a,b}, Huaichun Wu^{a,b,*}, Linda A. Hinnov^c, Xunlian Wang^{a,d}, Tianshui Yang^{a,d},

Haiyan Li^a, Shihong Zhang^{a,d}

^a State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing 100083, China

^b School of Ocean Sciences, China University of Geosciences, Beijing 100083, China

^c Department of Atmospheric, Oceanic and Earth Sciences, George Mason University Fairfax, VA 22030, USA

^d School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China

* Corresponding author at: State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences, Beijing, 100083, China. Tel.: +86 10 82334699; fax: +86 10 82320065.

E-mail address: whcgeo@cugb.edu.cn

Abstract

The late Ordovician Pingliang Formation on the southwestern margin of the Ordos Basin, North China, consists of rhythmic alternations of shale, limestone, and siliceous beds. To explore the possible astronomical forcing preserved in this

lithological record, continuous lithological rank and magnetic susceptibility (MS) stratigraphic series were obtained from a ~34 m thick section of the Pingliang Formation at Guanzhuang. Power spectral analysis of the MS and rank series reveal 85.5 cm to 124 cm, 23 cm to 38 cm, and 15 cm to 27 cm thick sedimentary cycles that in ratio match that of late Ordovician short eccentricity, obliquity and precession astronomical cycles. The power spectrum of the MS time series, calibrated to interpreted short orbital eccentricity cycles, aligns with spectral peaks to astronomical parameters, including 95 kyr short orbital eccentricity, 35.3 kyr and 30.6 kyr obliquity, and 19.6 kyr and 16.3 kyr precession cycles. The 15 cm to 27 cm thick limestone–shale couplets mainly represent precession cycles, and siliceous bed deposition may be related to both precession and obliquity forcing. We propose that precession-forced sea-level fluctuations mainly controlled production of lime mud in a shallow marine environment, and transport to the basin. Precession and obliquity controlled biogenic silica productivity, and temperature-dependent preservation of silica may have been influenced by obliquity forcing.

Keywords: Astronomical forcing; Limestone–shale couplet; Silica input; Late Ordovician; North China

1. Introduction

Astronomically forced sedimentary records are being exploited to establish a

high-resolution astronomical time scale (ATS) (Hinnov and Hilgen, 2012). The construction of the ATS has now been almost completed for the Cenozoic Era, and for large stratigraphic segments of the Mesozoic Era, and even older geologic ages in both marine and non-marine strata (e.g., Hinnov, 2013; Wu et al., 2013a, 2013b, 2014). The ATS is based on accurate interpretation of paleoenvironmental or paleoclimatic proxies that are measured at high resolution along cyclic sedimentary sequences. Simple lithological ranking of alternations, such as limestone–shale (Schwarzacher and Fischer, 1982; Hinnov and Park, 1999), chert–mudstone (Yao et al., 2015), chert–shale (Ikeda et al., 2010; Ikeda and Tada, 2014), and limestone–marl (Bellanca et al., 1996; Dinarès-Turell et al., 2003) couplets, have been used to analyze high-resolution astronomical cycles in sedimentary sequences. However, ranks do not provide information on cycle amplitude compared with other proxies, e.g., magnetic susceptibility, and oxygen and carbon isotopes. Combined analyses of lithologic rank series together with independent (objective) proxy series can enhance confidence in the recognition of Milankovitch cycles in strata (e.g., Batenburg et al., 2012; Wagreich et al., 2012; Dinarès-Turell et al., 2014).

Earth's climate system during the Ordovician evolved from a mild greenhouse to extreme cold at the end of the period, with massive continental ice-sheets on the Gondwana continent (Herrmann et al., 2004a, b; Armstrong, 2007; Finnegan et al., 2011). A prolonged climatic transition with intermittent glaciation from the Middle to Late Ordovician lasted more than 20 Myr (Trotter et al., 2008; Turner et al., 2012).

The extent of changes in $\delta^{13}\text{C}$ records suggests that global climate during the Sandbian was warmer and more equable than in the Katian and Hirnantian (e.g., Kaljo et al., 2004; Saltzman and Young, 2005; Tobin et al., 2005; Bergström et al., 2009; Ainsaar et al., 2010). Although climate simulation (Berner and Kothavala, 2001) and geochemical and faunal evidences (Tobin and Bergström, 2002) indicate a relatively high pCO_2 , a steep latitudinal temperature gradient between the low- and high-latitudes during the Sandbian suggests the onset of icehouse conditions (Achab and Paris, 2007; Vandenbroucke et al., 2009, 2010a, 2010b).

Milankovitch forcing of sedimentary cycles in late Ordovician successions have been associated with astronomically driven changes in glacioeustasy (e.g., Williams, 1991; Sutcliffe et al., 2000; Long, 2007; Loi et al., 2010; Elrick et al., 2013; Hinnov and Diecchio, 2016). The Sandbian Pingliang Formation in northwestern China contains hundreds of limestone–shale alternations in the form of couplets and bundles ranging from centimeter- to decimeter-scale in thickness. The succession provides the opportunity to analyze the cycles for evidence of astronomical forcing, and for insights into climatic dynamics in the subtropics during a greenhouse to icehouse transition. Here we carry out a cyclostratigraphic analysis of the Pingliang Formation at the Guanzhuang section, North China. The main research objectives are: (1) to seek evidence for Milankovitch-forced climate change during the late Ordovician of north China, and (2) to interpret the climate-driven lithological alternations of the Pingliang Formation.

2. Geological background

Faunal (An et al., 1983; Zhou and Fortey, 1986), lithological (Zhou et al., 1989), and paleomagnetic (Cocks and Torsvik, 2002) evidence indicates that the North China Block (NCB) was located in the low- to mid- latitudes of the northern hemisphere during the Ordovician (Fig. 1a). The Ordos Basin is situated in the western NCB, and the southwest margin of the Ordos was in the North Qilian Orogen, Qinling–Dabie Orogen and NCB, where it formed typical deposits of trench–arc–basin systems of convergent plate margins (Song et al., 2013). During the early late Ordovician, the main part of the NCB was progressively uplifted and experienced a long-term regression with no Silurian–early Carboniferous marine deposits, except in the western and northern margins where deep marine sediments were deposited in a narrow "L"-shaped belt (Feng et al., 1990, 1999; Wu et al., 1994) (Fig. 1b).

The Pingliang Formation at the Guanzhuang section ($35^{\circ}29'29.48''\text{N}$, $106^{\circ}36'27.73''\text{E}$) is one of the best exposed late Ordovician outcrops in north China. It is located in Kongtong District, ~10 km southwest of the Pingliang City, Gansu Province. This section was a candidate for the Global Stratotype Section and Point (GSSP) for the Upper/Middle Ordovician boundary (Finney et al., 1999). The lithological sequence is mainly composed of yellow to black highly compacted shales with interbedded thin to medium–thick micritic limestone. Eleven turbidite beds and six K-bentonite layers have been found in this section (Wu et al., 1994; Wang et al.,

2015) (Fig. 2b). The shales contain diverse graptolite faunas, while the limestone beds are rich in conodonts and radiolarian fossils (Wang, 1991, 1993; Fu et al., 1993; Finney et al., 1999; Wang et al., 2013a, b). The chronostratigraphic framework of the section is well constrained by the graptolite and conodont sequences (Finney et al., 1999; Wang et al., 2013a, b) (Fig. 2).

3. Methods

3.1. Lithological ranks

Three bed-by-bed stratigraphic logs were measured at the centimeter scale at the outcrop covering 33.4 m of the middle Pingliang Formation (Fig. 2b). We constructed three rank series to reflect the lithologies, and carbonate and silicate content variations. In the first series, we ranked the yellow argillaceous shale, black–brown siliceous shale, gray micritic limestone, and dark gray siliceous limestone as "1", "2", "3", and "4", respectively according to observed CaCO_3 content and biogenic content of siliceous organisms along section (Lithological Rank in Fig. 2b). For further explanation of the orbital forcing of limestone–shale couplet and siliceous beds, two other rank series were established. In the carbonate rank, we focused on the limestone–shale couplets, and nominated shale as "0" and limestone "1" to reflect the changes of CaCO_3 content (Fig. 2b). This means that "1" and "2" in the lithological rank were converted into "0" in the carbonate rank, and "3" and "4" into "1". In the silica rank, we ranked non-siliceous beds as "0" and siliceous beds as "1",

respectively (Fig. 2b). Thus, "1" and "3" in the lithological rank were converted into "0", and "2" and "4" into "1" to make it more clear. Eleven sandy limestone beds in this section are interpreted as gravitational flows deposits (Wu et al., 1994) (red rectangles in Fig. 2b). The turbidites and K-bentonites were excluded due to their allochthonous and instantaneous origin (Fig. 2b).

3.2. Sampling and rock magnetism measurements

An uneven sampling strategy was followed to ensure that every limestone–shale couplet was adequately measured. A 1–2 cm sampling interval was adopted for shale beds, and 2–3 cm for (thicker) limestone intervals. We collected at least three approximately equal-interval samples from each limestone–shale couplet in order to capture the precession cycle information (Kodama and Hinnov, 2015) assuming that one limestone–shale couplet represents a precession cycle (Hinnov and Park, 1998). A total of 1986 unoriented samples was collected from 34.4 m of the middle Pingliang Formation (Fig. 2b).

All rock samples were crushed and put into 8 cm³ plastic boxes. Magnetic susceptibility (MS) was measured using the KLY-4s Kappabridge. In order to identify the composition of magnetic minerals, rock magnetic experiments were carried out on representative samples from different lithologies. Temperature dependence of low-field magnetic susceptibilities (χ -T) was measured in an argon atmosphere to avoid oxidation of the magnetic minerals, using a KLY-4S Kappabridge magnetic susceptibility meter with a temperature apparatus (CS-3). The MS and χ -T data were

normalized by mass. Both MS and χ -T measurements were performed in the Paleomagnetism and Environmental Magnetism Laboratory at the China University of Geosciences. Isothermal remanent magnetization (IRM) experiments were conducted on representative samples at room temperature using a MicroMag Model 3900 Vibrating Sample Magnetometer (VSM) at the Institute of Geophysics, China Earthquake Administration.

3.3. Time-series analysis

The MS and rank series were interpolated to a uniform spacing of 1 cm with linear and staircase methods, respectively. Spectral analysis was performed using the multitaper method (MTM) spectral estimator (Thomson, 1982) with a classical red noise null model (Mudelsee, 2015). A fast Fourier transform (FFT) based evolutionary spectrogram was used to identify potential sediment accumulation rate (SAR) changes. The spectral analysis and astronomical calibration were conducted with Matlab functions (Husson, 2013), and Gaussian filtering and amplitude spectrum analysis were carried out in AnalySeries 2.0.8 (Paillard et al., 1996). Amplitude modulation is a useful way to determine whether Milankovitch forcing affected the sequence (e.g., Hinnov, 2000; Wu et al., 2013a; Fang et al., 2015). Amplitude modulation analysis was applied as follows: (1) the time-calibrated series was band-pass filtered to isolate the interpreted astronomical frequency; (2) the amplitude curves were extracted using the Hilbert transform (e.g., Hinnov, 2000); and (3) the extracted amplitude curves were conducted by amplitude spectrum analysis.

3.4. Astronomical time calibration

Astronomical calibration ("tuning") was performed on interpreted short eccentricity cycles in the MS series by assigning 95 kyr to each of the interpreted short eccentricity cycles. The limestone–shale couplets are interpreted as precession cycles (e.g., Hinnov and Park, 1998). We also separately calibrated a long precession cycle period of 19.2 kyr corrected to Ordovician value (see Section 3.5) to each limestone–shale couplet, although theoretically long precession is composed of two main frequencies. We undertook this calibration in two ways (Fig. 3): (1) the duration of each limestone (or shale) represents a half precession cycle (e.g., Hinnov and Park, 1998) (Fig. 3a); and (2) adjacent halves of one limestone and one shale represent a half precession cycle (Fig. 3b). The lithological, carbonate, and silica rank series were assigned to the reconstructed time scale to search for evidence of astronomical forcing.

3.5. Late Ordovician astronomical parameters

There is no full astronomical solution for the early Paleozoic, but the consistency of the 405 kyr long orbital eccentricity cycle is expected to have persisted throughout much of the geological time due mainly to the stable orbit of Jupiter (Laskar et al., 2004). Berger and Loutre (1994) estimated the astronomical parameter periodicities at 440 Ma, as 405 kyr for long eccentricity, 128 kyr and 95 kyr for short eccentricity (i.e., unchanged from present-day values), and due to faster length-of-day, 31.1 kyr for obliquity, and 19.5 kyr and 16.6 kyr for precession. The ratio of these periods is 24.4:

7.71: 5.72: 1.87: 1.17: 1, which is different with that at 500 Ma (Table 1). Recently, Svensen et al. (2015) interpreted an obliquity cycle with a period of 30.3 kyr, and precession cycles with periods of 19.2 kyr and 16.3 kyr, from equivalent Sandbian cyclostratigraphy of the Arnstad Formation (southern Norway) with time calibration from high-precision U-Pb zircon geochronology. The ratio of these periods is 24.85: 7.85: 5.83: 1.86: 1.18: 1 (Table 1). We will test these periodicity estimates in the analysis that follows.

4. Results

4.1. Bed thickness

The most obvious lithological characteristics of the Pingliang Formation are the shale and limestone couplets. The thicknesses of 176 beds of shales range from 1–41 cm, with an average of 7.96 cm, whereas the thicknesses of 177 beds of limestone range from 1 to 36 cm, with an average of 11.17 cm (Fig. 2b).

4.2. Rock magnetism results

The thermomagnetic curves display a gradual drop of magnetic susceptibility up to 300 °C (Fig. 4a–d), indicating the presence of paramagnetic minerals. A gradual drop from 600 °C to 700 °C reveals hematite (Fig. 4a–d). The cooling curves are higher than the heating curves (Fig. 4a–d), suggesting that some new ferromagnetic (magnetite or Ti-magnetite) minerals are produced from the transformation of paramagnetic clay minerals during 580 °C–700 °C heating.

The IRMs increase quickly with the pulse field strengthening before 300 mT (Fig. 4e–h), indicating that magnetic mineral is mainly magnetite. The IRMs also gradually increased after 300 mT, which is evidence for high coercivity minerals (e.g., hematite). The back-field demagnetization curves reveal that the remanence coercivities are between 10 mT and 30 mT (Fig. 4e–h). This means that the main remanence-carrier of the samples is low coercivity magnetite. The rock magnetic experiments indicate a similar source of the susceptibility signal in the different lithologies, and therefore variations in the MS series mainly reflects fluctuations in the input of detrital magnetite.

The MS series is related closely to the lithology (Fig. 5). Argillaceous shale corresponds to higher MS values ranging from 4.45×10^{-7} to $9.27 \times 10^{-6} \text{ m}^3 \cdot \text{kg}^{-1}$ with an average of $5.23 \times 10^{-6} \text{ m}^3 \cdot \text{kg}^{-1}$, whereas micritic limestone corresponds to lower values from 3.01×10^{-8} to $6.61 \times 10^{-6} \text{ m}^3 \cdot \text{kg}^{-1}$ with an average of $2.18 \times 10^{-6} \text{ m}^3 \cdot \text{kg}^{-1}$.

4.3. Cyclostratigraphy

4.3.1. Spectral analysis

The evolutionary spectrograms of the MS and lithological rank stratigraphic series indicate abrupt changes at three levels (~8.4 m, ~14.06 m, and ~24.04 m) (Fig. 6a, c). Therefore, spectral analysis was conducted on four stratigraphic subsets above and below these horizons, respectively (Fig. 6b, d).

The 33.4 m thick middle Pingliang Formation mostly covers the *Baltoniodus variabilis* and *B. gerdae* conodont subzones (Fig. 2b), with a combined duration of

~3.2 Myr (GTS2012; Gradstein et al., 2012). If the sediment accumulation rate remained generally stable throughout this interval, the long eccentricity, short eccentricity, obliquity and precession cycles would be estimated as ~420 cm, ~105 cm, ~32 cm, and ~20 cm, respectively. The power spectrum of Subset 1 of the MS stratigraphic series (Fig. 6b) shows wavelengths of 85.5 cm above 95% CL, 23.8 cm above 85% CL, and 15.7–16.3 cm above 90% CL. In Subset 2, wavelengths are concentrated at 93 cm, 30.1 cm and 18.9 cm, in Subset 3 at 128 cm, 42.7 cm and 25.6 cm, and in Subset 4 at 114 cm, 33 cm and 18.3 cm. These wavelengths have a similar ratio of 5:1.5:1 with that of the late Ordovician astronomical periods (Table 1). We provisionally interpret these sedimentary cycles as short eccentricity, obliquity and precession cycles, respectively (Fig. 6a, b).

The power spectra of Subset 1 of lithological rank (Fig. 6c, d) show main spectral peaks at wavelengths of 23.8 cm and 15.5 cm with a ratio of 1.53:1, which could correspond to the Sandbian ratio of obliquity to precession (Berger and Loutre, 1994; Svensen et al., 2015) (Table 1). Prominent sedimentary cycles at wavelengths of 30.1 cm and 19.3 cm in Subset 2, 38 cm and 27 cm in Subset 3, and 34.1 cm and 18.3 cm in Subset 4 have similar ratios and could be interpreted as obliquity and precession cycles, respectively (Fig. 6d). Sedimentary cycles at wavelengths of 85.5 cm in Subset 1, 97 cm in Subset 2, 124 cm in Subset 3, and 114 cm in Subset 4 might be related to short eccentricity (128 kyr and 95 kyr). These low frequency peaks are below the 80% CL in the power spectra (Fig. 6d), because the rank series only picks

up frequency modulations in the precession band, and does not pick up the precession amplitude modulations as does the MS proxy. These wavelengths can be detected in the evolutionary fast Fourier transform spectrum (Fig. 6c). No spectral peaks occur at wavelengths near 420 cm, indicating poor preservation of long eccentricity in both MS and rank series.

4.3.2. Astronomical calibrations

The prominent short eccentricity cycles were identified in the MS series in the stratigraphic domain (Fig. 6b) and the bandpass filtering outputs show a total of 33 short eccentricity cycles in the MS stratigraphic series (Fig. 5). The multitaper method power spectrum of this 95 kyr-calibrated MS time series has spectral peaks at 95 kyr, 30.6 kyr, 19.6 kyr, and 16.3 kyr above 95% CL (Fig. 7).

Multitaper method power spectrum of the half-precession-calibrated lithological rank shows spectral peaks at 105 kyr, 38.4 kyr, 30.6 kyr, 19.2 kyr, and 17.2 kyr that correspond reasonably well to the predicted Sandbian short eccentricity, obliquity and precession periodicities (Fig. 8a; Table 1). Time-calibrated carbonate rank series shows little influence of the obliquity forcing, especially in the result using the second tuned approach (Figs. 3b, 8e). It is interesting to find that the power spectrum of time-calibrated silica rank reveals prominent obliquity signals at 30.6 kyr (Fig. 8c, f). We interpret that the formation of siliceous beds was controlled more by the obliquity cycles than precession cycles in the studied interval (see Section 5.3). The multitaper method power spectra of the second tuned approach (Figs. 3b, 8d–f) show similar

patterns as those of the first approach (Figs. 3a, 8a–c). Thus, both calibration approaches seem plausible.

4.3.3. Modulation of short eccentricity and precession

It is well known that long-period orbital cycles modulate short-period orbital eccentricity, obliquity and precession cycles (Laskar et al., 2004). A straightforward stratigraphic representation of these modulations involves analyzing the lithological couplets and bundles. The Guanzhuang section shows three orders of sedimentary cyclicity, which are shown as the repetition of different lithologies and the distribution pattern of lithologic bed thickness (Fig. 5). The hierarchical structure of five to six limestone–shale couplets bundle into one large cycle, which correlates well with precession and short eccentricity cycles. The MS stratigraphic series also shows this bundling pattern (Fig. 5).

The amplitude modulation of the filtered 95 kyr eccentricity signal of the 95 kyr-calibrated MS time series (Fig. 9a) shows significant peaks in long eccentricity cycles of 400 kyr, 760 kyr and 2040 kyr (Fig. 9d). The power spectra of the amplitude modulation envelope of the precession band from the precession-calibrated lithological rank time series (Fig. 9b, c) show spectral peaks at ~100 kyr short eccentricity and a 390 kyr cycle close to the long eccentricity cycle (Fig. 9e, f). These results provide further evidence that our astronomically forced sedimentary cycle interpretation of this stratigraphic sequence is reasonable.

5. Discussion

5.1. Durations and sediment accumulation rates of the middle Pingliang Formation

The spectrum analysis indicates that if one limestone–shale couplet approximately equals a 19.2 kyr precession cycle, then 176 lithologic couplets indicate an estimated duration of 3.38 Myr for the middle Pingliang Formation. The 95 kyr calibrated MS time series has an estimated duration of 3.22 Myr, a little shorter than 3.38 Myr from precession-calibrated lithological rank series. Short eccentricity cycles vary from 95 kyr to 128 kyr (Hinnov, 2000), and it is hard to determine whether 95 kyr or 128 kyr eccentricity cycles dominated the late Ordovician. Some interpreted short eccentricity cycles modulate more than 5 precession cycles in the Pingliang Formation (e.g., No. 33 short eccentricity cycle in Fig. 5), which likely indicates 128 kyr short eccentricity cycles. If a short eccentricity cycle modulating 6 limestone–shale couplets was assigned as a duration of 95 kyr, the resulted short eccentricity calibrated duration would be a little shorter than the precession-calibrated one. Our estimated duration of middle Pingliang Formation is in good agreement with ~3.2 Myr of the duration of *Baltoniodus variabilis* and *B. gerdae* conodont subzones in GTS2012 (Gradstein et al., 2012).

The lithological record of middle Pingliang Formation generates a time series of ~3.38 Myr, indicating a ~1 cm/kyr sediment accumulation rate. This calculated sediment accumulation rate is similar to 0.85 cm/kyr of a Jurassic limestone–shale

sequence from Lombardy Pre-Alps, northern Italy (Hinnov and Park, 1998).

5.2. Astronomical forcing of limestone-shale couplets

The late Ordovician climate belts are thought to have been similar to the present day (Herrmann et al., 2004b; Trotter et al., 2008) with key oceanographic boundaries identified as the Subtropical–Subpolar Transition at $\sim 35^{\circ}\text{S}$ and the Polar Front at $\sim 55^{\circ}\text{--}70^{\circ}\text{S}$ (Vandenbroucke et al., 2010a). Lower gradient climatic boundaries in the northern hemisphere were due to the much-reduced continental area compared to the southern hemisphere (Herrmann et al., 2004a; Vandenbroucke et al., 2009). Our analysis shows that limestone–shale couplets mainly represent precession cycles in the Pingliang Formation, which is consistent with the paleogeography of the NCB during the late Ordovician (Fig. 1), since precession forcing is expected to be most prominent at low- and mid-latitudes (Herbert and Fischer, 1986).

The precession cycles have little influence on changes in total amount of insolation received on Earth. Precession-forced changes in insolation during one season or a certain time interval in the northern hemisphere should be responsible for the formation of limestone–shale couplets in the Pingliang area. The Paleozoic micritic limestone in basin settings was derived mostly from the abrasion and transportation of coarser grained shallow-water carbonates with sea-level changes (Elrick and Hinnov, 2007). The possible controlling factor of sea-level fluctuations would be small-scale glaciations/deglaciations occurring in one hemisphere, although no direct evidence for mid-latitude glaciations has been reported.

Precession was a primary controlling factor of sea-level oscillations of the Pingliang area. A minimum in precession-forced insolation corresponds maximum glaciation, and hence lower sea level and lower shallow marine productivity. This situation corresponds with shale deposition (Fig. 10). A more exposed continent leads to higher erosion rates and increased magnetite input from the Ordos continent to the Pingliang area, which is reflected in higher MS values of shales. When a maximum of insolation occurs with minimum glaciation, sea level is at a maximum, with higher shallow marine carbonate productivity and more carbonate transported to the basin. It corresponds with limestone deposition (Fig. 10).

Obliquity forcing had comparatively little influence on the limestone–shale couplets (Fig. 8b, e). High southern latitude continental ice sheet growth may have initiated during the Sandbian (Buggisch et al., 2010), inducing obliquity-scale sea-level oscillations that in turn influenced the depositional system of the Pingliang area.

5.3. Astronomical forcing of siliceous beds

The siliceous deposits in the Pingliang Formation are characterized by a high biogenic silica (BSi) content principally from radiolarians (Wang, 1991, 1993). The radiolarians in the siliceous limestone include mainly the Inaniguttidae family (Wang, 1991, 1993), which is an indicator of a pelagic setting (Cui et al., 2000; Zong et al., 2015). Sufficient dissolved silica (DSi) and nutrients are required for radiolarian growth and productivity. In the modern ocean, approximately 56% of BSi is dissolved

in the euphotic zone before it reaches the seabed; BSi dissolution continues during sedimentation, resulting in ~3% preservation (Tréguer and De La Rocha, 2013). The highest sea level of the Paleozoic (Haq and Schutter, 2008) is associated with extensive anoxia of the sea floor during the Sandbian (Leggett et al., 1981). Generation of siliceous sediments in Sandbian marine environments may have favored higher silica preservational conditions than those driven by high productivity (Kidder and Tomescu, 2016). Analysis of the silica rank series reveals that a prominent obliquity signal (compared with precession) in silica deposition in the Pingliang Formation (Fig. 8c, f). This finding is important for understanding the controlling mechanism of productivity and preservation of BSi during a greenhouse to icehouse transition.

Continental weathering and river run-off are the major sources of DSi input for radiolaria (Baumgartner, 2013; Tréguer and De La Rocha, 2013). A maximum of precession-forced insolation induced stronger monsoon activity and lower sea level when more DSi was transported into the marine settings, favoring radiolarian productivity (Fig. 10). Today, volcanic silica input is an order of magnitude smaller than continental weathering (Tréguer and De La Rocha, 2013), but increased Sandbian submarine volcanism may have contributed more DSi to the oceans. The onset of ophiolite emplacement supports the possibility of a late Ordovician superplume (Vaughan and Scarrow, 2003). Volcanism-derived silica may have enhanced radiolarian productivity and the formation of deep-water radiolarian chert

near Pingliang (Li et al., 1997). Obliquity-forced Pleistocene Pacific volcanic eruptions were associated with changes in surface mass loading and the isostatic adjustment of the Earth due to the redistribution of massive continental ice sheets (Kutterolf et al., 2012). We do not reject the possibility that the Ordovician silica cycle may have been similarly controlled by obliquity-forced volcanic activity.

Contourites in the study area and adjacent regions (Li, 1994; Gao et al., 1995; Qu et al., 2010) have been explained as deposits resulting from thermohaline circulation (Heezen et al., 1966). Thermohaline circulation (THC) could transfer high-latitude climate forcing to the subtropical deep marine environment. An obliquity-induced THC signal could be explained by changes in meridional temperature or density gradient. During the Sandbian, steep latitudinal temperature gradients (Achab and Paris, 2007; Vandenbroucke et al., 2009, 2010b) likely favored strong THC and vertical overturning, which may have ensured sufficient DSi and nutrient fluxes for increased radiolarian productivity (Fig. 10). During minimum obliquity, weaker insolation at high latitudes cools the surface ocean and increases density (e.g., Brickman et al., 1999; Tuenter et al., 2005) resulting in an intensified THC and increased radiolarian productivity in the mid-latitudes ocean.

Even though the precession-controlled continental weathering and river run-off pattern was the main source of the DSi input, the silica rank series reveals a more prominent obliquity signal (Fig. 8c, f). Obliquity-forced variations of mid water mass temperature may have facilitated silica preservation. The basinal sedimentary setting

of the Pingliang area remained stable in the studied interval (Fu et al., 1993; Yuan et al., 2014). Anoxic bottom waters may preserve silica by suppressing bioturbation that would otherwise induce dissolved silica to recycle into the water column (Kidder and Tomescu, 2016). Silica dissolution in anoxic deep-marine settings is mainly temperature dependent, because lower temperatures decrease silica solubility, silica concentration in pore fluids, and rates of diagenetic reactions (Kamatani, 1982). High silica concentrations are found in low temperature environment (e.g., Williams and Crerar, 1985). As discussed above, an obliquity-induced THC could affect meridional temperature gradients and generate a teleconnection between the mid- and high-latitude ocean. Subtropical mid-water masses may have formed in high latitude areas and their temperature is sensitive to obliquity forcing. Therefore, the obliquity signal in siliceous beds would be enhanced through temperature-dependent silica preservation conditions (Fig. 10). Preservation model was more likely than productivity-based model for BSi accumulation during Sandbian. It could be a reasonable explanation for a more prominent obliquity signal in the siliceous beds of the Pingliang Formation.

5.4. Differential diagenesis

The sedimentary rhythms of the Pingliang Formation must have been enhanced by diagenesis. Silica (carbonate) may have migrated from clay-rich zones to the radiolarian- (carbonate-) rich zones (Hallam, 1986; Decker, 1991; Tada, 1991), and hence radiolarian- (carbonate-) rich layers would lose less thickness than the

non-radiolarian (carbonate) ones. The result of differential compactions in the spectrum resembles that of high-frequency changes in accumulation rate along the sedimentary sequence (Westphal et al., 2004). Restoring of differential compactions indicates little distortion (Westphal et al., 2010), but no significant destruction (Yao et al., 2015) of astronomical cycles.

6. Conclusions

A cyclostratigraphic analysis was conducted on the Pingliang Formation, Ordos Basin, North China. Time series analysis reveals the presence of astronomical signals with period consistent with long orbital eccentricity (~405 kyr), short orbital eccentricity (~100 kyr), obliquity (~30.6 kyr), and precession cycles (19.2 kyr and 16.2 kyr) in lithological rank and MS series. The shorter obliquity and precession cycles were well preserved in both series. The 19.2 kyr precession- and 95 kyr short eccentricity-calibrated results gave the middle Pingliang Formation durations as 3.38 Myr and 3.22 Myr, respectively. The 95 kyr-calibrated MS series is shorter than the precession-calibrated lithological rank series, because it is difficult to determine whether 95 kyr or 128 kyr short eccentricity cycle dominated late Ordovician.

The spectra of time-calibrated lithological, carbonate, and silica rank series reflect different amplitude of orbital frequencies. Orbital forcing of the latitudinal and annual distribution of insolation may have been responsible for the observed lithological variations in the Pingliang Formation:

a) Precession was a primary controlling factor of the limestone–shale couplets. Precession forced climate changes in the late Ordovician northern hemisphere periodically varied between maximum and minimum northern hemisphere insolation. High (low) insolation resulted in high (low) sea level that increased (decreased) lime mud production in the shallow marine platform environment and transportation into the basin setting of the Pingliang area. This can mainly explain the formation of the limestone–shale couplets.

b) Both precession and obliquity may have controlled biogenic silica productivity. Sandbian basinal silica accumulation may have associated with temperature-dependent preservational conditions controlled by obliquity forcing. Minimum obliquity was associated with steep ocean temperature gradients from low to high latitudes and intensification of thermohaline circulation. An obliquity-induced thermohaline circulation could generate a teleconnection between the mid- and high-latitude ocean. Subtropical mid-water masses may have formed in high latitude areas and hence, their temperature is sensitive to obliquity forcing.

Acknowledgments

Qiang Fang is grateful for the discussions with Dr. Xiuchun Jing. The authors greatly appreciated assistance from Junjie Xu, Meinan Shi, and Jichuang Fang in the field and lab. We thank editor in chief (Prof. Jasper Knight), and two reviewers (Prof. Ken Kodama and an anonymous reviewer) for their careful review and constructive

suggestions that significantly improved the paper. This study was supported by the National Science Foundation of China (41422202, 41576062), the fundamental research funds for the Central Universities (2652015297, 2652015162) and National Key Basic Research Development Program of China (2012CB822002).

References

- Achab, A., Paris, F., 2007. The Ordovician chitinozoan biodiversification and its leading factors. *Palaeogeography, Palaeoclimatology, Palaeoecology* 245, 5–19.
- Ainsaar, L., Kaljo, D., Martma, T., 2010. Middle and Upper Ordovician carbon isotope chemostratigraphy in Baltoscandia: A correlation standard and clues to environmental history. *Palaeogeography, Palaeoclimatology, Palaeoecology* 294, 189–201.
- An, T.X., Zhang, F., Xiang, W.D., Zhang, Y.Q., Xu, W.H., Zhang, H.J., Jiang, D.B., Yang, C.S., Cui, Z.T., Lin, L.D., Yang, X.C., 1983. The conodonts of North China and the adjacent regions. Science Press, Beijing, 223 pp. (in Chinese with English abstract)
- Armstrong, H.A., 2007. On the cause of the Ordovician glaciation. In: Williams, M., Haywood, A.M., Gregory, F.J., Schmidt, D.N. (Eds.), *Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies*. Special Publications of the Micropalaeontological Society, The Geological Society, London, pp. 101–121.
- Batenburg, S.J., Sprovieri, M., Gale, A.S., Hilgen, F.J., Hüsing, S., Laskar, J., Liebrand, D., Lirer, F., Orue-Etxebarria, X., Pelosi, N., 2012. Cyclostratigraphy and astronomical tuning of the Late Maastrichtian at Zumaia (Basque country, Northern Spain). *Earth and Planetary Science Letters* 359, 264–278.
- Baumgartner, P.O., 2013. Mesozoic radiolarites—accumulation as a function of sea

- surface fertility on Tethyan margins and in ocean basins. *Sedimentology* 60, 292–318.
- Bellanca, A., Claps, M., Erba, E., Masetti, D., Neri, R., Premoli Silva, I., Venezia, F., 1996. Orbitally induced limestone/marlstone rhythms in the Albian–Cenomanian Cismon section (Venetian region, northern Italy): Sedimentology, calcareous and siliceous plankton distribution, elemental and isotope geochemistry. *Palaeogeography, Palaeoclimatology, Palaeoecology* 126, 227–260.
- Berger, A., Loutre, M.F., 1994. Astronomical forcing through geological time. In: De Boer, P.L., Smith, D.G. (Eds.), *Orbital forcing and cyclic sequences*. Blackwell Scientific Publications, Oxford, pp. 15–24.
- Bergström, S.M., Chen X., Schmitz, B., Young, S., Rong J.Y., Saltzman, M.R., 2009. First documentation of the Ordovician Guttenberg $\delta^{13}\text{C}$ excursion (GICE) in Asia: Chemostratigraphy of the Pagoda and Yanwashan formations in southeastern China. *Geological Magazine* 146, 1–11.
- Berner, R.A., Kothavala, Z., 2001. GEOCARB III: a revised model of atmospheric CO_2 over Phanerozoic time. *American Journal of Science* 301, 182–204.
- Brickman, D., Wright, D.G., Hyde, W., 1999. Filtering of Milankovitch cycles by the thermohaline circulation. *Journal of Climate* 12, 1644–1658.
- Buggisch, W., Joachimski, M.M., Lehnert, O., Bergström, S.M., Repetski, J.E., Webers, G.F., 2010. Did intense volcanism trigger the first Late Ordovician icehouse? *Geology* 38, 327–330.

- Cocks, L.R.M., Torsvik, T.H., 2002. Earth Geography from 500 to 400 Million Years Ago: A Faunal and Palaeomagnetic Review. *Journal of the Geological Society* 159, 631–644.
- Cooper, R.A., Sadler, P.M., 2012. The Ordovician period. In: Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G. (Eds.), *The Geologic Time Scale 2012*. Elsevier, Boston, pp. 489–523.
- Cui, Z.L., Hua, H., Song, Q.Y., 2000. The Late Ordovician Radiolarian Assemblage of the North Qingling Back-arc Basin, China. *Acta Geologica Sinica* 74, 254–268. (in Chinese with English abstract)
- Dinarès-Turell, J., Baceta, J.I., Pujalte, V., Orue-Etxebarria, X., Bernaola, G., Lorito, S., 2003. Untangling the Palaeocene climatic rhythm: An astronomically calibrated Early Palaeocene magnetostratigraphy and biostratigraphy at Zumaia (Basque basin, northern Spain). *Earth and Planetary Science Letters* 216, 483–500.
- Dinarès-Turell, J., Westerhold, T., Pujalte, V., Röhl, U., Kroon, D., 2014. Astronomical calibration of the Danian stage (Early Paleocene) revisited: Settling chronologies of sedimentary records across the Atlantic and Pacific Oceans. *Earth and Planetary Science Letters* 405, 119–131.
- Elrick, M., Hinnov, L.A., 2007. Millennial-scale paleoclimate cycles recorded in widespread Palaeozoic deeper water rhythmites of North America. *Palaeogeography, Palaeoclimatology, Palaeoecology* 243, 348–372.

Elrick, M., Reardon, D., Labor, W., Martin, J., Desrochers, A., Pope, M., 2013.

Orbital-scale climate change and glacioeustasy during the early Late Ordovician (pre-Hirnantian) determined from $\delta^{18}\text{O}$ values in marine apatite. *Geology* 41, 775–778.

Fang, Q., Wu, H.C., Hinnov, L.A., Jing, X.C., Wang, X.L., Jiang, Q.C., 2015.

Geologic evidence for chaotic behavior of the planets and its constraints on the third-order eustatic sequences at the end of the Late Paleozoic Ice Age. *Palaeogeography, Palaeoclimatology, Palaeoecology* 440, 848–859.

Feng, Z.Z., Wang, Y.H., Zhang, J.S., Zhuo, W.Q., Zhang, X.L., Hong, G.L., Chen,

J.X., Wu, S.H., Chen, Y.T., Chi, Y.L., Yang, C., 1990. Lithofacies Paleogeography of Early Paleozoic of North China Platform. Geological Publishing House, Beijing, 270 pp.

Feng, Z.Z., Bao, Z.D., Kang, Q.F., Zhang, Y.S., Tan, J., Li, Z.Y., Pang, F.M., Zhao,

X.R., 1999. Palaeotectonics of Ordovician in Ordos. *Journal of Palaeogeography* 1, 83–94. (in Chinese with English abstract)

Finnegan, S., Bergmann, K., Eiler, J.M., Jones, D.S., Fike, D.A., Eisenman, I.,

Hughes, N.C., Tripathi, A.K., Fischer, W.W., 2011. The magnitude and duration of Late Ordovician–Early Silurian glaciation. *Science* 331, 903–906.

Finney, S.C., Bergström, S.M., Chen, X., Wang, Z.H., 1999. The Pingliang section,

Gansu Province, China: Potential as global stratotype for the base of the *Nemagraptus gracilis* Biozone and the base of the global Upper Ordovician

- Series. *Acta Universitatis Carolinae–Geologica* 43, 73–75.
- Fu, L.P., Hu, Y.X., Zhang, Z.F., Wang, S.X., 1993. The Mark on the Ecology of Sedimentarial environment in middle and upper Ordovician at Ordos Basin. *Northwest Geoscience* 14, 1–88. (in Chinese with English abstract)
- Gao, Z.Z., Luo, S.S., He, Y.B., Zhang, J.S., Tang, Z.J., 1995. The Middle Ordovician Contourite on the West Margin of Ordos. *Acta Sedimentologica Sinica* 13, 16–26. (in Chinese with English abstract)
- Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G. (Eds.), 2012. *The Geologic Time Scale 2012*. Elsevier, Amsterdam, 1127 pp.
- Guo, F., Guo, L., Zhao, W.W., 2010. Ordovician paleogeography in Helan aulacogen. *Marine Geology & Quaternary Geology* 15, 14–20. (in Chinese with English abstract)
- Haq, B.U., Schutter, S.R., 2008. A chronology of Paleozoic sea-level changes. *Science* 322, 64–68.
- Heezen, B.C., Hollister, C.D., Ruddiman, W.F., 1966. Shaping of the continental rise by deep geostrophic contour currents. *Science* 152, 502–508.
- Herbert, T.D., Fischer, A.G., 1986. Milankovitch climatic origin of mid-Cretaceous black shale rhythms, central Italy. *Nature* 321, 739–743.
- Herrmann, A.D., Haupt, B.J., Patzkowsky, M.E., Dan, S., Slingerland, R.L., 2004a. Response of Late Ordovician paleoceanography to changes in sea level, continental drift, and atmospheric $p\text{CO}_2$: Potential causes for long-term cooling

- and glaciation. *Palaeogeography, Palaeoclimatology, Palaeoecology* 210, 385–401.
- Herrmann, A.D., Patzkowsky, M.E., Pollard, D., 2004b. The impact of paleogeography, pCO_2 , poleward ocean heat transport and sea level change on global cooling during the Late Ordovician. *Palaeogeography, Palaeoclimatology, Palaeoecology* 206, 59–74.
- Hinnov, L.A., 2000. New Perspectives on Orbitally Forced Stratigraphy. *Annual Review of Earth and Planetary Sciences* 28, 419–475.
- Hinnov, L.A., 2013. Cyclostratigraphy and its revolutionizing applications in the earth and planetary sciences. *Geological Society of America Bulletin* 125, 1703–1734.
- Hinnov, L.A., Diecchio, R.J., 2016. Milankovitch cycles in the Juniata Formation, Late Ordovician, Central Appalachian Basin, USA. *Stratigraphy* 12, 287–296.
- Hinnov, L.A., Hilgen, F.J., 2012. Cyclostratigraphy and astrochronology. In: Gradstein, F.M., Ogg, J.G., Schmitz, M.D., Ogg, G.M. (Eds.), *Geological Time Scale 2012*. Elsevier, Amsterdam, pp. 63–83.
- Hinnov, L.A., Park, J.J., 1998. Detection of astronomical cycles in the sedimentary record using frequency modulation analysis. *Journal of Sedimentary Research* 68, 325–338.
- Hinnov, L.A., Park, J.J., 1999. Strategies for assessing Early–Middle (Pliensbachian–Aalenian) Jurassic cyclochronologies. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*

357, 1831–1859.

Husson, D., 2013. RedNoise_ConfidenceLevels, <http://www.mathworks.com/matlabcentral/fileexchange/45539-rednoise-confidencelevels>.

Ikeda, M., Tada, R., 2014. A 70 million year astronomical time scale for the deep-sea bedded chert sequence (Inuyama, Japan): Implications for Triassic–Jurassic geochronology. *Earth and Planetary Science Letters* 399, 30–43.

Ikeda, M., Tada, R., Sakuma, H., 2010. Astronomical cycle origin of bedded chert: A middle Triassic bedded chert sequence, Inuyama, Japan. *Earth and Planetary Science Letters* 297, 369–378.

Kaljo, D., Hints, L., Martma, T., Nõlvak, J., Oraspõld, A., 2004. Late Ordovician carbon isotope trend in Estonia, its significance in stratigraphy and environmental analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology* 210, 165–185.

Kamatani, A., 1982. Dissolution rates of silica from diatoms decomposing at various temperatures. *Marine Biology* 68, 91–96.

Kidder, D.L., Tomescu, I., 2016. Biogenic chert and the Ordovician silica cycle. *Palaeogeography, Palaeoclimatology, Palaeoecology* doi: 10.1016/j.palaeo.2015.10.013.

Kodama, K.P., Hinnov, L.A., 2015. *Rock Magnetic Cyclostratigraphy*. Wiley-Blackwell Fast-Track Monograph, New Analytical Methods in Earth and Environmental Science Series, 176 pp.

- Kutterolf, S., Jegen, M., Mitrovica, J.X., Kwasnitschka, T., Freundt, A., Huybers, P.J., 2012. A detection of Milankovitch frequencies in global volcanic activity. *Geology* 41, 227–230.
- Laskar, J., Robutel, P., Joutel, F., Gastineau, M., Correia, A.C.M., Levrard, B., 2004. A long-term numerical solution for the insolation quantities of the Earth. *Astronomy & Astrophysics* 428, 261–285.
- Leggett, J.K., McKerrow, W.S., Cocks, L.R.M., Rickards, R.B., 1981. Periodicity in the early Paleozoic marine realm. *Journal of the Geological Society* 138, 167–176.
- Li, R., 1994. Identification of contourites in Middle Ordovician Gongwushu Formation, Zhuozishan, and depositional environment. *Oil & Gas Geology* 15, 235–240. (in Chinese with English abstract)
- Li, W.H., Mei, Z.C., Chen, J.W., Lu, H.R., 1997. Genetic environment of Ordovician radiolarian cherts and volcanic tuffs in Weibei, Shaanxi Province. *Regional Geology of China* 16, 422–427. (in Chinese with English abstract)
- Loi, A., Ghienne, J.F., Dabard, M.P., Paris, F., Botquelen, A., Christ, N., Elaouad-Debbaj, Z., Gorini, A., Vidal, M., Videt, B., 2010. The Late Ordovician glacio-eustatic record from a high-latitude storm-dominated shelf succession: The Bou Ingarf section (Anti-Atlas, Southern Morocco). *Palaeogeography, Palaeoclimatology, Palaeoecology* 296, 332–358.
- Long, D.G., 2007. Tempestite frequency curves: A key to Late Ordovician and Early

- Silurian subsidence, sea-level change, and orbital forcing in the Anticosti foreland basin, Quebec, Canada. *Canadian Journal of Earth Sciences* 44, 413–431.
- Mudelsee, M., 2014. *Climate Time Series Analysis: Classical Statistical and Bootstrap Methods*. Second edition. Springer, Heidelberg, New York, Dordrecht London, 454 pp.
- Paillard, D., Labeyrie, L., Yiou, P., 1996. Macintosh Program performs time-series analysis. *Eos, Transactions American Geophysical Union* 77, 379.
- Pope, M.C., Steffen, J.B., 2003. Widespread, prolonged late Middle to Late Ordovician upwelling in North America: A proxy record of glaciation? *Geology* 31, 63–66.
- Qu, H.J., Mei, Z.C., Li, W.H., Guan, L.Q., Feng, Y.W., Fan, Y.H., 2010. The characteristics of Middle Ordovician contour current deposits and geological implication in Fuping region, Shaanxi Province, China. *Geological Bulletin of China* 29, 1304–1309. (in Chinese with English abstract)
- Reijmer, J.J.G., Sprenger, A., Ten Kate, W.G.H.Z., Schlager, W., Krystyn, L., 1994. Periodicities in the composition of Late Triassic calciturbidites (Eastern Alps, Austria). In: De Boer, P.L., Smith, D.G. (Eds.), *Orbital Forcing and Cyclic Sequences*. IAS Special Publication 19, pp. 323–343.
- Saltzman, M.R., Young, S.A., 2005. Long-lived glaciation in the Late Ordovician? Isotopic and sequence–stratigraphic evidence from western Laurentia. *Geology*

33, 109–112.

Schwarzacher, W., Fischer, A.G., 1982. Limestone–shale bedding and perturbations of the Earth's orbit. In: Einsele, G., Seilacher, A. (Eds.), *Cyclic and event stratification*. Springer-Verlag, Berlin, pp. 72–95.

Song, S.G., Niu, Y.L., Su, L., Xia, X.H., 2013. Tectonics of the North Qilian orogen, NW China. *Gondwana Research* 23, 1378–1401.

Sutcliffe, O.E., Dowdeswell, J.A., Whittington, R.J., Theron, J.N., Craig, J., 2000. Calibrating the Late Ordovician glaciation and mass extinction by the eccentricity cycles of Earth's orbit. *Geology* 28, 967–970.

Svensen, H.H., Hammer, Ø., Corfu, F., 2015. Astronomically forced cyclicity in the Upper Ordovician and U-Pb ages of interlayered tephra, Oslo Region, Norway. *Palaeogeography, Palaeoclimatology, Palaeoecology* 418, 150–159.

Thomson, D.J., 1982. Spectrum estimation and harmonic analysis. *Proceedings of the IEEE* 70, 1055–1096.

Tobin, K.J., Bergström, S.M., 2002. Implications of Ordovician (≈ 460 Myr) marine cement for constraining seawater temperature and atmospheric $p\text{CO}_2$. *Palaeogeography, Palaeoclimatology, Palaeoecology* 181, 399–417.

Tobin, K.J., Bergström, S.M., Garza, P.D.L., 2005. A mid-Caradocian (453 Ma) drawdown in atmospheric $p\text{CO}_2$ without ice sheet development? *Palaeogeography, Palaeoclimatology, Palaeoecology* 226, 187–204.

Tréguer, P.J., Rocha, C.L.D.L., 2013. The world ocean silica cycle. *Annual Review of*

Marine Science 5, 477–501.

Trotter, J.A., Williams, I.S., Barnes, C.R., Christophe, L., Nicoll, R.S., 2008. Did cooling oceans trigger Ordovician biodiversification? Evidence from conodont thermometry. *Science* 321, 550–554.

Tuenter, E., Weber, S.L., Hilgen, F.J., Lourens, L.J., Ganopolski, A., 2005. Simulation of climate phase lags in response to precession and obliquity forcing and the role of vegetation. *Climate Dynamics* 24, 279–295.

Turner, B.R., Armstrong, H.A., Wilson, C.R., Makhoul, I.M., 2012. High frequency eustatic sea-level changes during the Middle to early Late Ordovician of southern Jordan: Indirect evidence for a Darriwilian Ice Age in Gondwana. *Sedimentary Geology* 251, 34–48.

Vail, P.R., Audemard, F., Bowman, S.A., Eisner, P.N., Perez-Cruz, C., 1991. The stratigraphic signatures of tectonics, eustasy and sedimentology—an overview. In: Einsele, G., Ricken, W., Seilacher, A. (Eds.), *Cycles and Events in Stratigraphy*. Springer-Verlag, Berlin, pp. 617–659.

Vandenbroucke, T.R.A., Armstrong, H.A., Williams, M., Zalasiewicz, J.A., Sabbe, K., 2009. Ground-truthing Late Ordovician climate models using the paleobiogeography of graptolites. *Paleoceanography* 24, PA4202, doi: 10.1029/2008PA001720

Vandenbroucke, T.R.A., Armstrong, H.A., Williams, M., Paris, F., Sabbe, K., Zalasiewicz, J.A., Nölvak, J., Verniers, J., 2010a. Epipelagic chitinozoan

- biotopes map a steep latitudinal temperature gradient for earliest Late Ordovician seas: Implications for a cooling Late Ordovician climate. *Palaeogeography, Palaeoclimatology, Palaeoecology* 294, 202–219.
- Vandenbroucke, T.R.A., Armstrong, H.A., Williams, M., Paris, F., Zalasiewicz, J.A., Sabbe, K., Nölvak, J., Challands, T.J., Verniers, J., Servais, T., 2010b. Polar front shift and atmospheric CO₂ during the glacial maximum of the Early Paleozoic Icehouse. *Proceedings of the National Academy of Sciences* 107, 14983–14986.
- Vaughan, A.P.M., Scarrow, J.H., 2003. Ophiolite obduction pulses as a proxy indicator of superplume events? *Earth and Planetary Science Letters* 213, 407–416.
- Wagreich, M., Hohenegger, J., Neuhuber, S., 2012. Nannofossil biostratigraphy, strontium and carbon isotope stratigraphy, cyclostratigraphy and an astronomically calibrated duration of the Late Campanian *Radotruncana calcarata* Zone. *Cretaceous Research* 38, 80–96.
- Wagreich, M., Lein, R., Sames, B., 2014. Eustasy, its controlling factors and the limno-eustatic hypothesis—concepts inspired by Eduard Suess. *Austrian Journal of Earth Sciences* 107, 115–131.
- Wang, Y.J., 1991. On Progress In the Study of Paleozoic Radiolarians in China. *Acta Micropalaeontologica Sinica* 8, 237–251. (in Chinese with English abstract)
- Wang, Y.J., 1993. Middle Ordovician radiolarians from the Pingliang Formation of Gansu Province, China. In: Blueford J. (Ed), *Radiolaria of Giant and Subgiant Fields in Asia*. Micropaleontology Press, New York, pp. 98–114.

- Wang, Z.H., Bergström, S.M., Zhen, Y.Y., Zhang, Y.D., 2013a. New Discovery of Conodonts from the upper Ordovician Pingliang Formation of Pingliang, Gansu, China and its significance. *Acta Micropalaeontologica Sinica* 30, 123–131. (in Chinese with English abstract)
- Wang, Z.H., Bergström, S.M., Zhen, Y.Y., Chen, X., Zhang, Y.D., 2013b. On the integration of Ordovician conodont and graptolite biostratigraphy: New examples from Gansu and Inner Mongolia in China. *Alcheringa: An Australasian Journal of Palaeontology* 37, 510–528.
- Wang, Z.T., Zhou, H.R., Wang, X.L., Jing, X.C., Zhang, Y.S., 2015. Volcanic event records at the southwestern Ordos Basin: The message from geochemical and zircon U-Pb geochronology of K-bentonites from Pingliang Formation, Shaanxi and Guansu region. *Acta Petrologica Sinica* 31, 2633–2654. (in Chinese with English abstract)
- Westphal, H., Böhm, F., Bornholdt, S., 2004. Orbital frequencies in the sedimentary record: distorted by diagenesis? *Facies* 50, 3–11.
- Westphal, H., Hilgen, F., Munnecke, A., 2010. An assessment of the suitability of individual rhythmic carbonate successions for astrochronological application. *Earth-Science Reviews* 99, 19–30.
- Williams, G.E., 1991. Milankovitch-band cyclicity in bedded halite deposits contemporaneous with Late Ordovician–Early Silurian glaciation, Canning Basin, Western Australia. *Earth and Planetary Science Letters* 103, 143–155.

- Williams, L.A., Crerar, D.A., 1985. Silica diagenesis, II. General mechanisms. *Journal of Sedimentary Research* 55, 0312–0321.
- Wu, H.C., Zhang, S.H., Feng, Q.L., Jiang, G.Q., Li, H.Y., Yang, T.S., 2012. Milankovitch and sub-Milankovitch cycles of the early Triassic Daye Formation, South China and their geochronological and paleoclimatic implications. *Gondwana Research* 22, 748–759.
- Wu, H.C., Zhang, S.H., Hinnov, L.A., Jiang, G.Q., Feng, Q.L., Li, H.Y., Yang, T.S., 2013a. Time-calibrated Milankovitch cycles for the late Permian. *Nature Communication* 4, 2452. doi: 10.1038/ncomms3452.
- Wu, H.C., Zhang, S.H., Jiang, G.Q., Hinnov, L.A., Yang, T.S., Li, H.Y., Wan, X.Q., Wang, C.S., 2013b. 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* 385, 55–70.
- Wu, H.C., Zhang, S.H., Hinnov, L.A., Jiang, G.Q., Yang, T.S., Li, H.Y., Wan, X.Q., Wang, C.S., 2014. Cyclostratigraphy and orbital tuning of the terrestrial upper Santonian–Lower Danian in Songliao Basin, northeastern China. *Earth and Planetary Science Letters*, 407, 82–95.
- Wu, S.H., Feng, Z.Z., Xu, X.Y., 1994. Sedimentology of gravity flow deposits of Middle Ordovician Pingliang Formation in west and south margins of Ordos. *Oil & Gas Geology* 15, 226–235. (in Chinese with English abstract)

- Yao, X., Zhou, Y.Q., Hinnov, L.A., 2015. Astronomical forcing of a Middle Permian chert sequence in Chaohu, South China. *Earth and Planetary Science Letters* 422, 206–221.
- Yuan, L.P., Zhou, H.R., Jing, X.C., Wang, Z.T., Chuan, T.T., Fang, Q., 2014. Microfacies and Facies Analysis of the Ordovician Carbonates in the South Margin of the Ordos Basin. *Acta Geologica Sinica* 88, 421–432. (in Chinese with English abstract)
- Zhou, Z.Y., Fortey, R.A., 1986. Ordovician trilobites from north and northeast China. *Palaeontographica Abteilung A*, 157–210.
- Zhou, Z.Y., Zhou, Z.Q., Zhang, J.L., 1989. Ordovician Trilobite biofacies of North China Platform and its western marginal area. *Acta Palaeontologica Sinica* 28, 298–313. (in Chinese with English abstract)
- Zong, R.W., Wang, Z.Z., Gong, Y.M., Wang, G.C., Xiao, L., Wang, Z.H., Fan, R.Y., 2015. Ordovician radiolarians from the Yinisala ophiolitic mélange and their significance in western Junggar, Xinjiang, NW China. *Science China Earth Sciences* 58, 776–783.

Figure captions

Fig. 1. (a) Late Ordovician global paleogeography. Geographic base map is modified from Pope and Steffen (2003). (b) Late Ordovician paleogeography of southwest Ordos Basin (modified from Guo et al., 2010).

Fig. 2. Stratigraphy of Pingliang Formation of the Guanzhuang section. (a) The geological time scale, graptolite and conodont biozones of the Sandbian Stage are based on GTS2012 (Cooper and Sadler, 2012). (b) Graptolite and conodont biozones of the studied interval are integrated from Finney et al. (1999) and Wang et al. (2013b). Red rectangles in (b) infer the horizons of turbidites. The numbers "2" and "4" in the lithological ranks are compared with "1" and "3" to reflect variations of silica content, but do not indicate that siliceous shales contain less biogenic silica than micritic or siliceous limestone.

Fig. 3. Two precession-scale tuning approaches, assuming that (a) the duration of each limestone (or shale) represents a half precession cycle, and (b) adjacent halves of one limestone and one shale bed represent a half precession cycle. P infers different precession cycle boundaries, with a period of 19.2 kyr.

Fig. 4. Temperature dependence of low-field magnetic susceptibility (χ -T) (a-d) and normalized acquisition curves and opposite field demagnetizations of isothermal

remanent magnetization (IRM) (e–h) of representative samples. (a and e) micritic limestone (sample PL305), (b and h) siliceous limestone (sample PL887), (c and g) argillaceous shale (sample PL892), (d and h) siliceous shale (sample PL897). The red and blue lines in (a–d) represent the heating and cooling curves, respectively.

Fig. 5. Bundling pattern, interpreted Milankovitch cycles, and correlation of carbonate rank and magnetic susceptibility (MS) series in the stratigraphic domain. The figures in (a) and (c) indicate the number of the limestone–shale couplet. The red curves are the interpreted short eccentricity cycles extracted from the MS series using Gaussian band-pass filters with a passband of 0.012 ± 0.002 cycles/cm (b) and 0.0085 ± 0.002 cycles/cm (d), respectively.

Fig. 6. Spectrum of the Pingliang Formation MS and lithological rank series in the stratigraphic domain. Evolutionary fast Fourier transform spectrum of the MS (a) and rank series (c) with 5 m sliding window. 2π multitaper method power spectra of the lithological MS (b) and rank (d) series subsets of 0–8.4 m (Subset 1), 8.4–14.06 m (Subset 2), 14.06–24.04 m (Subset 3) and 24.04–33.4 m (Subset 4), respectively. Significant peaks are labeled in centimeters. e, O and P represent the short eccentricity, obliquity and precession cycles, respectively. White horizontal lines in (a) and (c) indicate the stratigraphic horizons of turbidites. The red, green, purple and blue dashed curves represent the median smoothed, fitted red noise spectrum, with 85%,

90% and 95% confidence levels.

Fig. 7. 2π multitaper method power spectrum of the 95 kyr-calibrated MS time series with significant peaks labeled in kyr. The red, green, purple and blue dashed curves represent the median smoothed, fitted red noise spectrum, with 85%, 90% and 95% confidence levels.

Fig. 8. 2π multitaper method power spectrum of the long precession calibrated lithological, carbonate and silica rank series for two different tuning approaches. (a), (b) and (c) are spectra of precession-tuned lithological, carbonate, and silica rank series, respectively using approach in Fig. 3a; (d), (e) and (f) are spectra of precession-tuned lithological, carbonate, and silica rank series, respectively using approach in Fig. 3b.

Fig. 9. Amplitude modulation analysis of the astronomically calibrated series and 2π multitaper method amplitude spectra. The red solid lines define the amplitude modulation envelopes. The numbers in the multitaper method spectra are labeled in kyr. (a) Amplitude modulation envelopes of short eccentricity signal from 95 kyr-calibrated MS series. The short eccentricity signal is extracted with a Gaussian passband filter of 0.0094 ± 0.002 cycles/kyr. (b) Amplitude modulation envelopes of precession signal from astronomically calibrated lithological rank series based on the

first P-tuning approach (Fig. 3a). Gaussian filter of the lithological rank time series using a passband of 0.052 ± 0.015 cycles/kyr. (c) Amplitude modulation envelope of the precession signal from astronomically calibrated lithological rank series based on the second precession-tuning approach (Fig. 3b). Gaussian filter of the lithological rank series using a passband of 0.052 ± 0.01 cycles/kyr. (d), (e), (f) are amplitude spectra of the amplitude modulation envelopes shown in (a), (b) and (c).

Fig. 10. Summary scheme and proposed model of the periodic changes in climatic, oceanographic and environmental conditions in the boreal summer for the Pingliang Formation. The numbers 1–4 represent the lithological ranks of the yellow argillaceous shale, black–brown siliceous shale, gray micritic limestone, and dark gray siliceous limestone. Curves in (b) represent precession (blue) and obliquity (red) cycles.

Table caption

Table 1. Frequency ratios of 440 Ma, 454 Ma, and 500 Ma orbital periods. E, e, O, and P represent the long eccentricity, short eccentricity, obliquity, and precession cycles, respectively. The P1, P2, and O1 periods for 440 Ma and 500 Ma are from Berger and Loutre (1994), and that for 454 Ma are from Svensen et al. (2015). e1, e2, and E periods are from Hinnov (2000).

(a)

(b)

(a)

• magnetite ★ dissolved silica ⊙ lime mud ★ radiolaria
↻ thermohaline circulation ▲ Pingliang area

(b)

Age	Period of orbital parameters (kyr)						Ratio
	E	e2	e1	O1	P1	P2	
440 Ma	405	128	95	31.1	19.5	16.6	24.40: 7.71: 5.72: 1.87: 1.17: 1
454 Ma	405	128	95	30.3	19.2	16.3	24.85: 7.85: 5.83: 1.86: 1.18: 1
500 Ma	405	128	95	29.9	19	16.2	25.00: 7.90: 5.86: 1.85: 1.17: 1