Milankovitch paleoclimatic, tectonic, and sedimentary signals in late Permian-Early Triassic fluvial-lacustrine records, Bogda Mountains, NW China

Wentao Zhang and Wan Yang, Missouri University of Science and Technology*

Summary

Non-marine cyclostratigraphic records are a manifestation of repetitive changes of ancient continental environmental, paleoclimatic, tectonic, and ecosystem conditions. Stratigraphic sections in Bogda Mountains, NW China, provide detailed records of the late Permian-Early Triassic terrestrial paleoenvironmental and paleoclimatic evolution at the paleo-mid-latitude of NE Pangea.

Cycles of fluvial-lacustrine environmental shifts are related to variable forcing mechanisms and may have been influenced by various Milankovitch climatic forcings. This study is to identify the Milankovitch signals in our records and characterize the controlling factors of cyclic sedimentation in the terrestrial rift basin and temporal evolution. Methods include gamma and spectral analyses of lithological and depositional environment variations.

Introduction

Astronomically-induced variations in Earth's eccentricity, precession and obliquity drive climate changes in the Earth system. The long-term orbitally-induced Milankovitch climate cycles are manifested as changes in different geographic and sedimentary processes. In turn, the sediment influx into all depositional environments carries different components. Consequently, the cyclic climatic changes attributable to orbital forcing are readily encoded in stratigraphic successions. However, the signals of Milankovitch cycles in the sedimentary record are mixed with those of many other processes. In addition, sedimentary systems are prone to shifts in accumulation rates and sediment composition induced by non-Milankovitch factors, such as regional tectonics and temporally irregular shifting of fluvial-delta depocenters. The sedimentary records in the greater Turpan-Junggar rift basin of the mid-latitude NE Pangea have not been tested for Milankovitch signals. Those records could contain various Milankovitch climatic, tectonic, and sedimentary signals over time.

Many previous studies used astronomical tuning methods to estimate and reduce the distorting effects of long-term variable sedimentation rates of sedimentary records. However, the short-term sedimentation rate variation of different lithofacies should also be considered. The gamma analysis of Kominz and Bond (1990) estimates the faciesdependent thickness-time conversion factors (gammas) to convert and tune the thickness series into time series before spectral analysis.

In this study, the lithology and interpreted depositional environment curves of the South Taodonggou section are analyzed to test whether Milankovitch climatic, tectonic, and sedimentary signals were recorded by terrestrial fluviallacustrine sedimentation, using the method of gamma and spectral analyses.

Geological Background

Late Permian - Early Triassic fluvial, and lacustrine deposits were accumulated in grabens and half grabens and are exposed along the foothills of the Bogda Mountains, Xinjiang Uygur Autonomous Region, NW China (Yang et al., 2007, 2010, 2021; Obrist-Farner and Yang., 2015, 2017). Recent plate tectonic reconstruction places the study area at the easternmost Kazakhstan Plate at approximately 45ºN in NE Pangea during the Permian-Triassic time (Sengör and Natal'in, 1996; Scotese and Wright, 2018; Şengör et al., 2018). Lake expansion and contraction and fluvial peneplanation and deposition had occurred in the basin (Yang et al., 2007, 2010, 2021). Fluvial and lacustrine sediments include conglomerate, sandstone, mudrock, paleosol, and rare carbonate and volcanic deposits (Yang et al., 2007, 2010, 2021; Obrist-Farner and Yang, 2015).

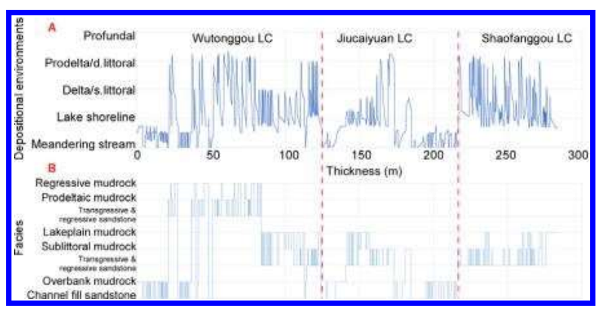

Figure 1: A) Depositional environment curve of South Taodonggou section. B) Environmental-litho-facies curve of South Taodonggou section.

In this study, lithology and interpreted depositional environments are used in quantitative analysis because the environmental shifts occurred probably mainly in response to climatic changes. The section was measured at a cm-dm scale to document the lithology, sedimentary texture and structure, fossils, and stratal geometry. The stratigraphic thickness of the South Taodonggou section is 283 m. Eight facies ranks were defined based on the depositional environment and lithology (Fig. 1).

Methodology

Gamma Analysis

Gamma analysis of Kominz and Bond (1990), Bond et al. (1991), and Kominz et al. (1991) is a test of cycle periodicity and an estimate of relative effective accumulation rates of the lithofacies that constitute the cycles.

$$TT_{cccc,jj} = \sum_{ii=1}^{nn} \gamma\gamma_{ii} \times cc_{ii,jj} \qquad (1)$$

$$TT = \sum_{jj=1}^{mm} \sum_{ii=1}^{nn} \gamma\gamma_{ii} \times cc_{ii\,jj} \qquad (2)$$

where nn = number of facies in a cycle, mm = number of cycle ($mm > nn$), ii = facies number, jj = cycle number, cc = facies thickness, $TT_{cccc,jj}$ = period of the jjth cycle, TT = duration of the entire cyclic section.

Gamma analysis assumes that the cycles used in the analysis have approximately the same duration. Positive leastsquares regression was used by Kominz et al. (1991) to solve the over-constrained linear problem in Eq. 1. The best-fit $\gamma\gamma$s minimize the variations in TT_{cccc} among all mm cycles. The cycles with large differences from predicted (TT_{cccc}) are removed successively until the best-fit $\gamma\gamma$s stabilize. The $\gamma\gamma$tuned time series which was converted from a facies curve using Eq. 2, is used for spectral analysis. The gamma correction has nonuniformly stretched the facies curve using facies-dependent $\gamma\gamma$s, reducing variation in cycle period.

Spectral Analysis

Spectral analysis provides a means of detecting the strength of periodic (sinusoidal) components in a time or spatial series at different frequencies. Multi-taper method (MTM) power spectral analysis and evolutive MTM are used to characterize the frequency content of the $\gamma\gamma$-untuned and tuned series.

Preliminary Results and Discussion

Results of Gamma Analysis

The best-fit $\gamma\gamma$s of the two facies in meandering stream cycles becomes stable after the removal of two cycles (Fig. 2A). The stable $\gamma\gamma$s indicate that the overbank mudrock facies has a larger $\gamma\gamma$ value (i.e., smaller sedimentation rate) than the channel-fill sandstone facies.

The best-fit $\gamma\gamma$s of the three facies in lacustrine deltaic cycles become stable after the removal of two cycles (Fig. 2B). The transgressive and regressive sandstone facies has a larger $\gamma\gamma$ value than the prodeltaic mudrock facies. The regressive mudrock facies has a smaller $\gamma\gamma$ value than the prodeltaic mudrock facies.

Since only a few lakeplain-littoral cycles contain all three facies, and most cycles contain two major facies, these cycles are divided into two subgroups. The best-fit $\gamma\gamma$s of the two facies in Subgroup 1 are stable without removal of any cycles (Fig. 2C). The lakeplain mudrock facies has a smaller $\gamma\gamma$ value than the transgressive and regressive sandstone facies. The best-fit $\gamma\gamma$s of the two facies in Subgroup 2 become stable after the removal of three cycles (Fig.2D). The sublittoral mudrock facies has a larger $\gamma\gamma$ value than the transgressive and regressive sandstone facies.

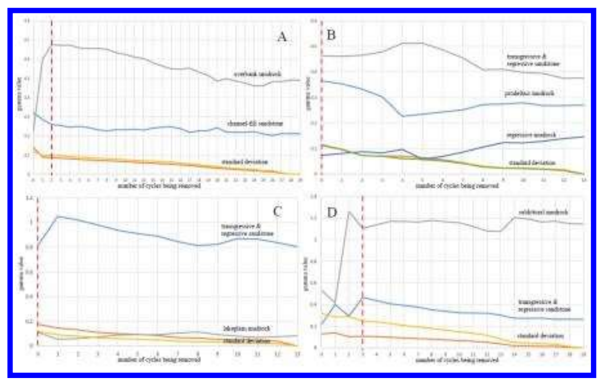

Figure 2: Gamma results of the South Taodonggou section for meandering stream cycles (A), lacustrine deltaic cycles (B), and lakeplain-littoral cycles (C, D). The red vertical dashed lines show the $\gamma\gamma$ values used for $\gamma\gamma$ normalization and tuning.

The gamma results suggest that environmental lithofacies in the South Taodonggou section have approximately constant time-thickness relations. However, the four sets of $\gamma\gamma$s for the four types of high-order cycles (HC) were calculated separately and need to be normalized. Six normalization schemes are experimented (Fig. 3).

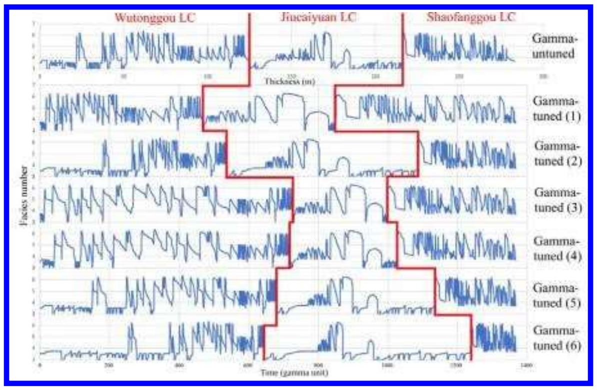

Figure 3: Gamma-untuned and six normalized gamma-tuned depositional environment curves of the South Taodonggou section. Base of the stratigraphic section is at the left.

Results of Spectral Analysis

The spectra of the gamma-untuned and six gamma-tuned series of the South Taodonggou section have several statistically significant peaks at the frequency smaller than 0.2 cycles/meter or 0.03 cycles/gamma unit (Fig. 4). The significant peaks were compared with the line spectrum of Milankovitch climatic cycles at 244-249 Ma (Berger et al., 1992; Hinnov, 2000). The spectra of gamma-tuned series 3 and 4 match with line spectrum better than those of all the other series. Five peaks above or close to the 99% confident limit in the spectra of gamma-tuned series 3 all match with the line spectrum. Thus, the spectra of gamma-tuned series 3 was chosen for calibration with Milankovitch climatic cycles. The peak at frequency 0.0127 was assigned to the long-obliquity of a period of 40.5 kyr. The short-eccentricity peaks are at periods of 117.4 and 86 kyr, the long-obliquity at 40.5 kyr, the long-precession index at 20.7 and 19.9 kyr. Two low-amplitude peaks may also match with the Milankovitch peaks. They are the long (29.6 kyr) and shortobliquity (24.3 kyr) cycles. The good match of the spectrum of the third gamma-tuned series with that of Milankovitch cycles, suggesting that the cyclic sedimentation of the South Taodonggou section was significantly influenced by Milankovitch climatic forcing.

The spectral character of the South Taodonggou section was further investigated through the evolutive MTM spectral analysis. The spectra of the gamma-tuned series 1, 3, and 4 show more high amplitude peaks at the high frequency than those of the gamma-untuned and -tuned series 2, 5, and 6, which only contain high-amplitude peaks at the low frequency (Fig. 5). In the evolutive MTM spectra of gammatuned series 1, 3, and 4, the significant peaks of obliquity and precession index occur mostly in the Wutonggou and Shaofanggou LCs. The obliquity peaks are not well defined in the Jiucaiyuan LC in comparison to those of the Wutonggou and Shaofanggou LCs (Fig. 5). The results demonstrate that the evolutive MTM spectral analysis can effectively identify the shift of Milankovitch climatic forcing through time.

The duration represented by the total thickness of the South Taodonggou section was calculated as 0.7 Myr, using the sedimentation rates of respective lithofacies. The duration is the time represented by complete and partially eroded cycles (Sadler, 1994), excluding the hiatal time represented by completely missing cycles, which were not used in gamma analysis (Yang and Kominz, 1999). Thus, the duration can be regarded approximately as the duration of deposition of a section. On the other hand, the total duration of the South Taodonggou section, including time represented by both rocks and hiatal surfaces is 2.59 Myr (Yang et al., 2021). The stratigraphic completeness of the South Taodonggou section is estimated to be 27% as the ratio between depositional duration and total duration. The great incompleteness of the

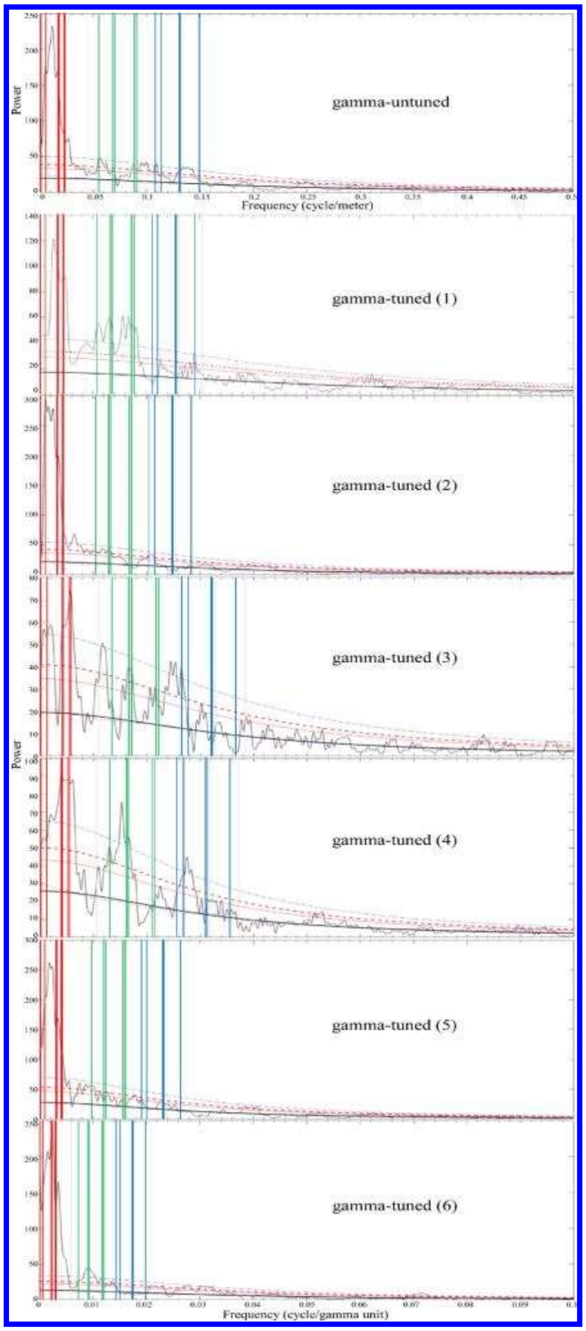

Figure 4: 2.5π-MTM spectral results of gamma-untuned and -tuned depositional series of the South Taodonggou section. The line spectrum of Milankovitch climatic cycles in each spectrum shows the best match to the spectral peaks.

section probably results from gaps due to the erosion at the HC scale, especially the HCs subjacent to the erosional facies, as well as the long nondepositional or erosional diastems at the LC boundaries, resulted from tectonic uplift and fluvial peneplanation (Yang et al., 2021).

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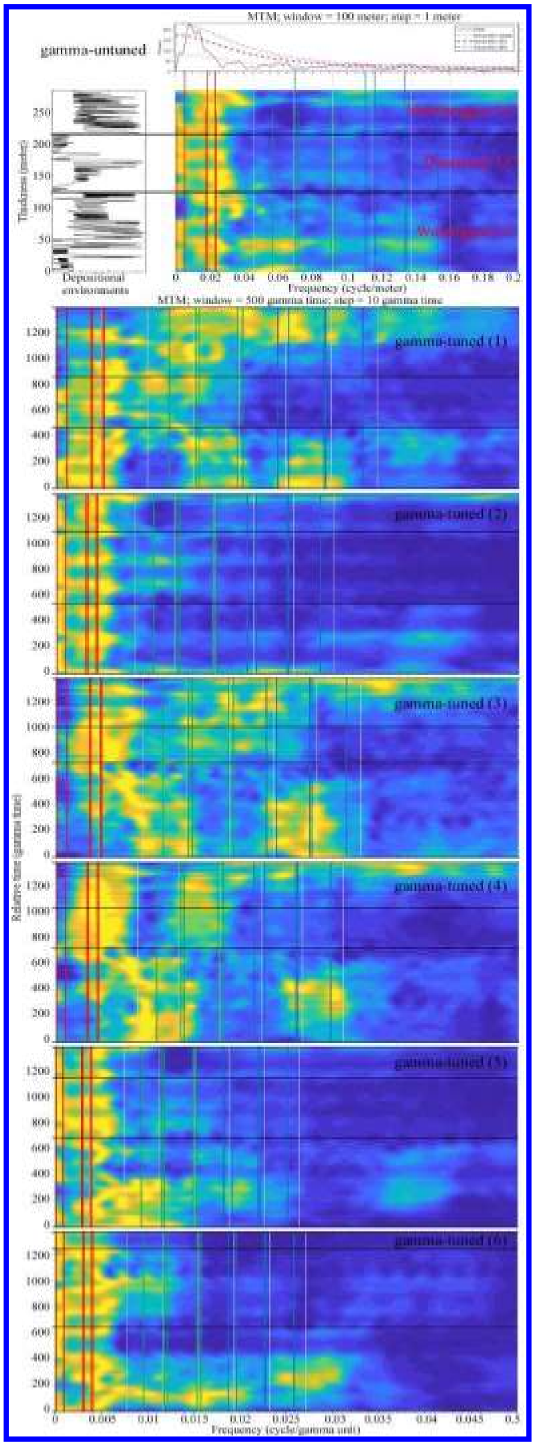

Figure 5: Evolutive MTM spectral results of gamma-untuned and -tuned series of the South Taodonggou section. The best-fit Milankovitch line spectrum is the same as those on the MTM spectra in Figure 4.

Preliminary gamma results show that the time-thickness relations of the same facies are stable, indicating relatively constant effective sedimentation rate of similar lithologies. The calibration between spectral results of gamma-tunned series 3 and line spectrum of Milankovitch cycles indicates that the Milankovitch climatic forcing likely influenced the cyclic sedimentation in the South Taodonggou section. The channel-fill sandstone has the highest sedimentation rate, while the lacustrine deltaic transgressive and regressive sandstone has the lowest sedimentation rate.

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