Vol. 81 No. 6 pp. 996–1001 ACTA GEOLOGICA SINICA Dec. 2007

# Recognition of Milankovitch Cycles in the Natural Gamma—Ray Logging of Upper Cretaceous Terrestrial Strata in the Songliao Basin

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**Abstract: Spectrogram analysis of seven natural gamma-ray logging of Member 1 of the Qingshankou Formation ($K_2qn^1$) and Member 1 and 2 of the Nenjiang Formation ($K_2n^{1\text{-}2}$) of Late Cretaceous age in the Songliao Basin reveals sedimentary cyclicities controlled by Milankovitch climate periodicities. The recognition of Milankovitch cycles allows estimation of an average accumulation rate of ~7.55–8.62 cm/ka for the $K_2qn^1$ sections, and ~6.69–10.16 cm/ka for the $K_2n^{1\text{-}2}$ sections. Two marine transgression events occurred during the deposition of $K_2qn^1$ and $K_2n^{1\text{-}2}$ and their ages are at ~0.74–1.10 Ma and ~2.38–4.84 Ma, respectively. Identification of Milankovitch cycles from fine-grained deep lake sedimentary rocks in the Songliao Basin may provide great potential for high-resolution stratigraphic subdivisions and correlations.**

**Key words: Songliao Basin, gamma-ray logging, Milankovitch cycles, marine transgression events**

## 1 Introduction

The Cretaceous climate was an extreme greenhouse climate (Huber et al., 2002; Wilson et al., 2002). Understanding the controlling factors of Cretaceous climate change has important implications not only for rebuilding the Cretaceous climate history but also for predicting the future greenhouse climate change (Wang, 2006). As a global climate change model, Milankovitch theory provides a reasonable interpretation for the driving mechanisms of Quaternary glacial-interglacial cycles (Milankovitch, 1941; Berger, 1988). Many studies indicated that Milankovitch climate forcing was significant in Cretaceous (Stage, 1999, 2003; Prokoph et al., 2001; D'Argenio et al., 2004; Niebuhr, 2005; Latta et al., 2006). With the strong greenhouse climate dominated in Cretaceous, even the third order sea-level changes in the Cenomanian stage might be driven by the long eccentricity cycle (400 ka) (Gale et al., 2002). Van der Zwan (2002) suggested that the impact of Milankovitch-scale sediment supply is expected to be more significant in the absence of significant sea-level fluctuations in a greenhouse world. However, few studies so far have recognized Milankovitch climate changes from terrestrial sedimentary basins, preventing a better understanding of the Cretaceous global climate change (Kump and Arthur, 1999).

The periods of astronomical orbital parameters (Milankovitch climate forcing) cause climate change periodically on earth, which results in sedimentary cycles expressed by periodicities in sedimentary structure, lithology, lithofaces, and geophysical and geochemical properties of sedimentary strata (Berger and Loutre, 1994; Schwarzacher, 2000). High-resolution and continuous geophysical logs are commonly applied to analyze Milankovitch cycles in lithologically homogeneous deep water strata and to identify the duration of geological events (Rampino et al., 2000; Prokoph et al., 2001; Stage, 2003).

As one of the largest Cretaceous terrestrial basins in the world, the Songliao Basin preserves perhaps the most complete Cretaceous sedimentary record to study the Cretaceous geological events (Wang, 2006). In order to understand whether Milankovitch climate forcing had influences on the Cretaceous lacustrine deposits in the Songliao Basin, we have conducted a detailed spectral analysis on seven natural gamma-ray logging of Member 1 of the Qingshankou Formation ($K_2qn^1$) and Member 1 and

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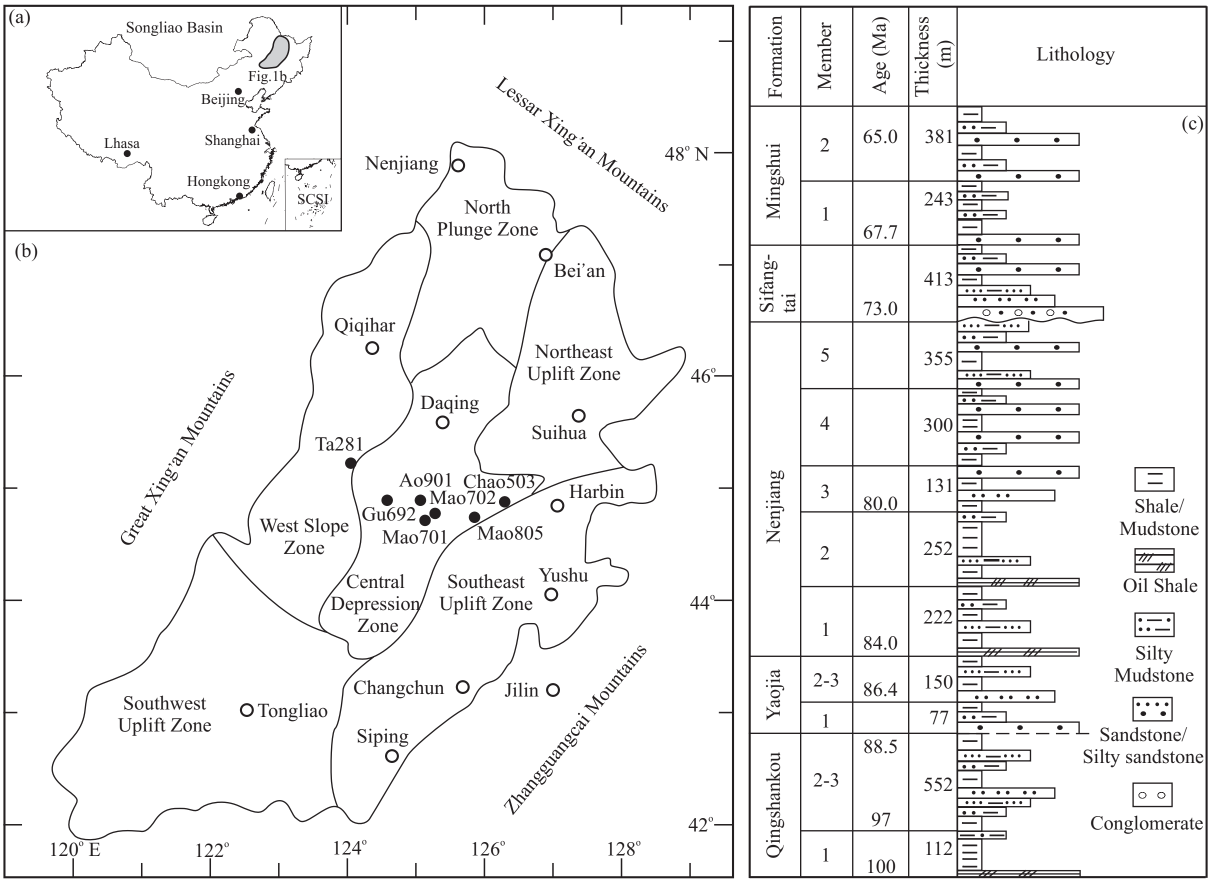

Fig. 1. (a) Location of the Songliao Basin in northeastern China; (b) Sketch map of structural zones in the Songliao Basin and locations of the study wells; (c) Generalized stratigraphy of upper Cretaceous in the Songliao Basin (age data according to Wang et al., 1995).

2 of the Nenjiang Formation ($K_2n^{1-2}$) of Late Cretaceous age in the central depression and west slope of the Songliao Basin. The study reveals clear Milankovitch cycles in these strata, which can be used to calculate the average sedimentary rate and duration of two major marine transgression events.

## 2 Geological Setting

The Songliao basin in northeastern China is one of the largest Mesozoic continental basins formed during rifting (Fig. 1a). The tectonic evolution of Songliao Basin can be divided into four phases: (1) Late-Jurassic thermal rise and rift phase, (2) Early Cretaceous stretching fault phase, (3) middle Early-Cretaceous thermal subsidence depression phases, and (4) Late Cretaceous structural inversion phase (Liu, 1996; Chen et al., 1996; Hu et al., 1998). According to the characteristics of rises and depressions, the Songliao Basin can be divided into six first-order tectonic units: central depression zone, north plunge zone, west slope zone, northeast uplift zone, southeast uplift zone, and southwest uplift zone (Gao et al., 1994; Li and Guo, 1998) (Fig. 1b). The basement of the Songliao basin consists of pre-Paleozoic and Paleozoic metamorphic and igneous rocks. Unconformably overlying the basement, ~4000 m thick Mesozoic and Cenozoic terrestrial strata are unevenly distributed across the basin (Gao et al., 1994).

Early to middle Late Cretaceous was the time of the largest extension for the Songliao Basin and thus the strata of this age are ideal for studying the sedimentary responses to paleoclimate change in a terrestrial basin. Strata of this age in the Songliao Basin are dominated by fluvial and lacustrine clastic rocks with volcanic and volcanoclastic layers. The Upper Cretaceous strata, in an ascending order, includes the Qingshankou, Yaojia, Nenjiang, Sifangtai, and Mingshui formations (Fig.1c). Two large scale marine transgression events occurred during the deposition of Member 1 of the Qingshankou Formation ($K_2qn^1$) and Member 1 and 2 of the Nenjiang Formation ($K_2n^{1-2}$). These marine transgressions caused extensive anoxic events in the basin (Gao et al., 1994; Huang et al., 1998). The $K_2qn^1$ and $K_2n^{1-2}$ sections, which are composed of thick black mudstone, shale and silty mudstone, are also the most prolific petroleum source rock units in the basin (Gao et al., 1994; Huang et al., 1998).

## 3 Data and Methods

Natural gamma-ray logging consists of measuring in boreholes the intensity of the gamma ray emitted during the decay of the atomic nuclei of radioactive elements contained in a stratigraphic sequence (Liu et al., 2001). The intensity of gamma-ray is related to the amount of $^{40}K$, $^{232}Th$ and $^{238}U$ in rocks. Clay and organic particles have strong capacity for absorbing the radioactive elements. Small grain size and slow deposition rate of clay-size particles allow that the radioactive element have enough time to separate from fluid. The gamma-ray logging curves can therefore reflect the change of the amount of muddy and organic materials in sediments, both of which are sensitive to the controlling factors such as climate changes. Thus Gamma-ray logging has been widely used to reconstruct the paleoenvironment and paleoclimate (Liu et al., 1999; Liu et al., 2001; Chen et al., 2004) and to study the Milankovitch cycles (Li, 1996; Rampino et al., 2000; Prokoph et al., 2001; Stage, 2003; Li et al., 2005).

Deep water sedimentary successions can often preserve a more complete record of orbital cycles than shallow-water successions (Gale et al., 2002). To ensure a continuous stratigraphic record, we conducted gamma-ray logging of the $K_2qn^1$ and $K_2n^{1\text{-}2}$ sections from six wells in the central depression zone and 1 well in west slope zone (Fig.1b). The seven wells extend from east to west for about 300 km (Fig.1b).

Spectrogram analysis, which can estimate the frequency for the signal of periods, was used to analyze the Milankovitch cyclicity signals in sedimentary strata (Rampino et al., 2000; Prokoph et al., 2001; Stage, 2003; Niebuhr, 2005; Latta et al., 2006). In this study, spectrogram analysis was performed with REDFIT software package (Schulz and Mudelsee, 2001).

## 4 Results and Discussion

### 4.1 Results of Milankovitch cycle analysis

According to the Milankovitch theory, earth orbital parameters include eccentricity, obliquity and precession (Milankovitch, 1941). Eccentricity frequencies are thought to have remained constant through geologic time, whereas obliquity and precession frequencies are dynamic and variable through time (Berger and Loutre, 1994). In the late Cretaceous, these orbital frequencies were ~10% shorter than the present. Major Milankovitch periodicities include long ($E_3$=405 ka) and short ($E_2$=123 ka and $E_1$=95 ka) eccentricity, obliquity ($O_2$=51.2 ka and $O_1$=39.4 ka) and precession ($P_2$=22.5 ka and $P_1$=18.6 ka) (Berger and Loutre, 1994).

One of the best ways to identify whether the observed cycles in sedimentary strata are controlled by astronomical forcing is to compare the relative ratio of the observed cycles with the relative ratio of the Milankovitch cycles. If they are similar, it would likely indicate that the periods of astronomical forcing controls the periodicities in the strata.

The spectral analysis is performed on the data while it is still on a depth scale, so that the peaks in spatial frequency can be determined. Cycle thickness can then be calculated because it is the inverse of the spatial frequency. The power spectra of gamma-ray data from the seven wells is shown in Fig. 2, which indicate that all the natural gamma-ray profiles show significant periodicities. For example, spectral analysis on the well Gu692 gamma-ray logging of $K_2qn^1$ indicates that 19 frequency peaks are present (Fig. 2c), and the ratios of cycle thickness for the six main peaks are 10.60 : 8.25 : 4.39 : 3.39 : 1.81 : 1.57 (m). These ratios are similar to the ratios of the long periods of Milankovitch forcing during Late Cretaceous (123 : 95 : 51.2 : 39.4 : 22.5 : 18.6). Therefore, the six major spectral peaks are considered to be caused by eccentricity (123 ka and 96 ka), obliquity (51 and 39.4 ka), and precession (21.2ka and 18.2 ka), respectively. The strata thickness of $K_2qn^1$ from well Gu692 is 74.0 m, which record 8.97 short eccentricity ($E_1$) cycles. Based on the duration of individual Milankovitch cycles, the average sediment accumulation rate can be estimated as 8.62 cm/ka and the duration of $K_2qn^1$ as 0.86 Ma (Table 1, Fig. 2c). Assuming a stable tectonic setting and constant accumulation rates during this time period, average sedimentation rate of 7.55–8.62 cm/ka and 6.69–10.16 cm/ka can be estimated for the Upper Cretaceous $K_2qn^1$ and $K_2n^{1\text{-}2}$ sections in the Songliao Basin, respectively (Table 1). The dominance of long-period eccentricity signals in gamma-ray logging of the $K_2n^{1\text{-}2}$ section indicates that it may provide a new tool for high-resolution stratigraphic correlation for the Cretaceous terrestrial strata across the Songliao Basin (Fig. 2 h-l, Table 1).

### 4.2 Estimation for the duration of marine transgression events

Many studies indicated that marine transgressions occurred in the Songliao Basin during late Cretaceous. Fossil remains of euryhaline organisms such as bivalves (Gu et al., 1976), fishes (Zhang and Zhou, 1978), dinoflagellates (Gao et al., 1992), and nannofossils (Ye and Wei, 1996) were found in the $K_2n^{1\text{-}2}$ sections. Liu and Wang (1997) found brackish to fresh-water argillaceous dolomite concretions in the $K_2n^{1\text{-}2}$ sections. Paleontological and organic geochemical studies (e.g., Hou et al., 2000) provided additional evidence for marine transgression events during the deposition of the $K_2qn^1$

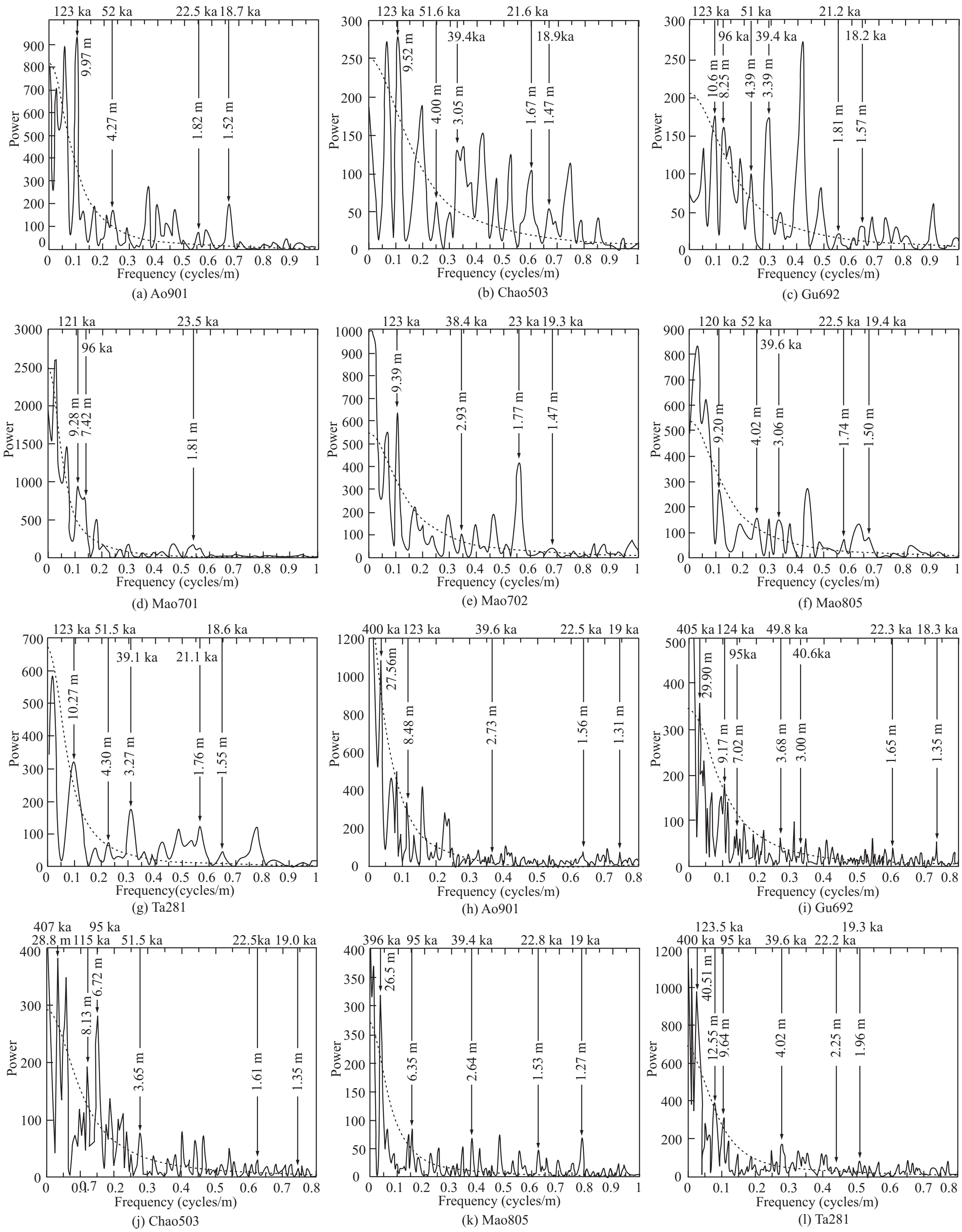


Fig. 2. Spectrogram analysis of gamma-ray loggings of the $K_2qn^1$ (a-g) and $K_2n^{1\text{-}2}$ (h-l) sections in the Songliao Basin. Also shown is calculated red-noise (dashed line) variance of power spectrum.

and $K_2n^{1\text{-}2}$. It has also been suggested that marine transgression events played an important role in the formation of prolific petroleum source rocks (Hou et al., 2000; Li and Pang, 2004).

It is difficult, however, to precisely estimate the duration for the two massive marine transgression events

**Table 1 Milankovitch cycles and thicknesses from gamma-ray loggings of the $K_2qn^1$ and $K_2n^{1\text{-}2}$ sections in the Songliao Basin**

| Well | Thickness (m) | Cycle thicknesses (m) | | | | | | | Duration (Ma) | Accumulation rate (cm/ka) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Eccentricity | | | Obliquity | | Precession | | | |
| | | $E_3$ (ka) | $E_2$ (ka) | $E_1$ (a) | $O_2$ (ka) | $O_1$(ka) | $P_2$ (ka) | $P_1$ (ka) | | |
| Orbital Cycles (ka/cycle) | | 400 | 123 | 95 | 51.2 | 39.4 | 22.5 | 18.6 | - | - |
| Member 1 of Qingshankou Formation ($K_2qn^1$) | | | | | | | | | | |
| Ao901 | 89.5 | - | 9.97 | - | 4.27 | - | 1.82 | 1.52 | 1.10 | 8.11 |
| | Cycle ratio | - | 123 | - | 52 | - | 22.5 | 18.7 | | |
| Chao503 | 76.0 | - | 9.52 | - | 4.00 | 3.05 | 1.67 | 1.47 | 0.98 | 7.74 |
| | Cycle ratio | - | 123 | - | 51.6 | 39.4 | 21.6 | 18.9 | | |
| Gu692 | 74.0 | - | 10.60 | 8.25 | 4.39 | 3.39 | 1.81 | 1.57 | 0.86 | 8.62 |
| | Cycle ratio | - | 123 | 96 | 51 | 39.4 | 21.2 | 18.2 | | |
| Mao701 | 74.0 | - | 9.28 | 7.42 | - | - | 1.81 | - | 0.98 | 7.55 |
| | Cycle ratio | - | 121 | 96 | - | - | 23.5 | - | | |
| Mao702 | 75.0 | - | 9.39 | - | - | 2.93 | 1.77 | 1.47 | 0.98 | 7.63 |
| | Cycle ratio | - | 123 | - | - | 38.4 | 23 | 19.3 | | |
| Mao805 | 64.0 | - | 9.20 | - | 4.02 | 3.06 | 1.74 | 1.50 | 0.83 | 7.67 |
| | Cycle ratio | - | 120 | - | 52 | 39.6 | 22.5 | 19.4 | | |
| Ta281 | 61.5 | - | 10.27 | - | 4.30 | 3.27 | 1.76 | 1.55 | 0.74 | 8.34 |
| | Cycle ratio | - | 123 | - | 51.5 | 39.1 | 21.1 | 18.6 | | |
| Member 1 and 2 of Nenjiang Formation ($K_2n^{1\text{-}2}$) | | | | | | | | | | |
| Ao901 | 330.5 | 27.56 | 8.48 | - | - | 2.73 | 1.56 | 1.31 | 4.80 | 6.89 |
| | Cycle ratio | 400 | 123 | - | - | 39.6 | 22.5 | 19 | | |
| Gu692 | 357.5 | 29.90 | 9.17 | 7.02 | 3.68 | 3.00 | 1.65 | 1.35 | 4.84 | 7.38 |
| | Cycle ratio | 405 | 124 | 95 | 49.8 | 40.6 | 22.3 | 18.3 | | |
| Chao503 | 260.0 | 28.8 | 8.13 | 6.72 | 3.65 | - | 1.61 | 1.35 | 3.67 | 7.08 |
| | Cycle ratio | 407 | 115 | 95 | 51.5 | - | 22.5 | 19.0 | | |
| Mao805 | 303.0 | 26.5 | - | 6.35 | - | 2.64 | 1.53 | 1.27 | 4.53 | 6.69 |
| | Cycle ratio | 396 | - | 95 | - | 39.4 | 22.8 | 19 | | |
| Ta281 | 241.5 | 40.51 | 12.55 | 9.64 | - | 4.02 | 2.25 | 1.96 | 2.38 | 10.16 |
| | Cycle ratio | 400 | 123.5 | 95 | - | 39.6 | 22.2 | 19.3 | | |

due to (1) the lack of materials appropriate for precise age dating in the black shale and mudstones of the Qingshankou and Nenjiang Formations and (2) the difficulty for age determination and correlation between terrestrial and marine fossils. Gao et al.(1994) suggested that the age of the two marine transgressions are Cenomanian and late Turonian–early Coniacian. Based on the K-Ar ages from mudstones, Wang et al.(1995) proposed that the Qingshankou Formation is Cenomanian –Turonian in age and estimated the duration of the $K_2qn^1$ section to be ~3 Ma. Rb-Sr ages from carbonate rocks indicated that the Nenjiang Formation is most likely Campanian and the duration of the $K_2n^{1\text{-}2}$ section is ~4 Ma, while carbon isotope data from the Qingshankou Formation preferred a Cenomanian age (Wan et al., 2005). Taking the later suggestion, the age for the first member of the Qingshankou Formation is early Cenomanian.

Based on the spectral analysis and duration of Milankovitch cycles, we estimate that the marine transgression recorded in the $K_2n^{1\text{-}2}$ section lasted ~2.38–4.84 Ma, which is consistent with the estimation of Wang et al. (1995) and Wan et al.(2005). However, the duration of the marine transgression recorded by $K_2qn^1$ section is ~0.74–1.10 Ma, which is nearly half of the estimation of Wang et al.(1995).

## 5 Conclusions

(1) Spectral analysis of the gamma-ray logging of the $K_2qn^1$ and $K_2n^{1\text{-}2}$ sections indicate that Milankovitch climate forcing controlled the sedimentary cycles during Late Cretaceous in the Songliao Basin. The clear signal for Milankovitch cycles in gamma-ray logs may provide a new tool for high-resolution stratigraphic subdivisions and correlations of the Cretaceous terrestrial strata in the Songliao Basin.

(2) The duration of marine transgression events recorded in Member 1 of the Qingshankou Formation ($K_2qn^1$) and Member 1 and 2 of the Nenjiang Formation ($K_2n^{1\text{-}2}$) are ~0.74–1.10 Ma and ~2.38–4.84 Ma, respectively.

## Acknowledgements

This study was jointly supported by the National Key Basic Research Development Program of China (Grant 2006CB701406), Program for New Century Excellent Talents University (Grant NCET-04-0727), and Research Found of State Key Laboratory of Geological Processes and Mineral Resources (Grant GPMR200651). The authors are grateful to the help of Wang Chengshan, Wan Xiaoqiao, Wang Pujun, Jiang Ganqing, Ren Yanguang and Dang Yimin.

Manuscript received Aug. 25, 2007
accepted Sept. 25, 2007
edited by Fei Hongcai

## References


Berger, A., 1988. Milankovitch theory and climate. *Reviews of Geophysics,* 26: 624–657.

Berger, A., and Loutre, M.F., 1994. Astronomical forcing through geologic time. In: de Boer, P.L., Smith, D.G., (eds.), *Orbital forcing and cyclic sequences.* International Association of Sedimentologists Special Publication, 19: 15–24.

Chen Fajing, Zhao Hailing, Chen Zhaonian and Wang Xin, 1996. Features of Mesozoic–Cenozoic extensional basin tectonics & geodynamic settings. *Ear. Sci.,*21(4):357–365 (in Chinese).

Chen Zhonghong, Cha Ming and Jin Qiang, 2004. Application of natural gamma ray logging and natural gamma spectrometry logging to recovering paleoenvironment of sedimentary basin. *Chinese J. Geophys.,* 47(6): 1145–1150 (in Chinese).

D'Argenio, B., Fischer, A.G., Premoli-Silva, I., Weissert, H., and Ferreri, V., 2004. *Cyclostratigraphy: Approaches and case histories*. Society for Sedimentary Geology (SEPM) Special Publication, 81: 1–311.

Gale, A.S., Hardenbol, J., Hathway, B., Kennedy, W.J., Young, J.R., and Phansalkar, V., 2002. Global correlation of Cenomanian (Upper Cretaceous) sequences: Evidence for Milankovitch control on sea level. *Geology*, 30(4): 291–294.

Gao Ruiqi, Zhang Ying and Cui Tongcui, 1994. *Cretaceous Petroleum Bearing Strata in the Songliao Basin*. Petroleum Industry Press, Beijing, 1–333 (in Chinese).

Gao Ruiqi, He Chengquan and Qiao Xiuyun, 1992. A new genus and species of Cretaceous dinoflagellates from two transgressive beds in Songliao Basin, NE China. *Acta Micropalaeontologica Sinica,* 31(1):17–29 (in Chinese).

Gu Zhiwei, Huang Baoyu, Chen Chuhuo and Wen Shixuan, 1976. *Lamellibranch fossils in China*. Beijng: Science Press. (in Chinese).

Hou Dujie, Li Maowen and Huang Qinghua., 2000. Marine transgressional events in the gigantic freshwater lake Songliao: paleontological and geochemical evidence. *Organic Geochemistry*, 31: 763–768.

Hu Wangshui, Cai Chunfang, Wu Zhiyong and Li Jianmin, 1998. Structural style and its relation to hydrocarbon exploration in the Songliao basin, northeast China. *Marine and Petroleum Geology*, 15 (1): 41–55.

Huang Qinghua, Chen Chunrui, Wang Pingzai, Han Minxin, Li Xingjun and Wu Daqing, 1998. The late cretaceous bio-evolution and anoxic events in the ancient lake in the songliao basin. *Acta Micropalaeontologica Sinica*, 15(4): 417–425.

Huber, B.T, Norris, R.D and MacLeod, K.G., 2002. Deep-sea paleotemperature record of extreme warmth during the Cretaceous. *Geology,* 30(2): 123–126.

Kump, L.R., and Arthur, M.A., 1999. Interpreting carbon-isotope excursions, carbonates and organic matter. *Chem. Geol.,* 161: 181–198.

Latta, D.K., Anastasio, D.J., Hinnov, L.A., Elrick, M., and Kodama, K.P., 2006. Magnetic record of Milankovitch rhythms in lithologically noncyclic marine carbonates. *Geology,* 34(1): 29–32.

Li Anfen and Guo Zhanqian, 1998. Crustal structure of Songliao basin and its tectonic environment. *Earth Science*, 23 (Sup.): 1–11(in Chinese).

Li Bin, Meng Zifang, Li Xiangbo, Lu Hongxuan and Zheng Min, 2005. Analysis of Milankovitch cycles of Yanchang Formation in Jing'an Oilfield. *Geological Science and Technology Information,* 24(2): 64–70 (in Chinese).

Li Maowen and Pang Xiongqi, 2004. Contentious Petroleum Geochemical Issues in China's Sedimentary Basins. *Petroleum Science*, 1(3): 4–22.

Li Qingmou, 1996. The analysis and application of Milankovitch cycles by logging data. *Acta Geophysica Sinica*, 39(5): 699–704 (in Chinese).

Liu Guangding，Li Qingmou and Liu Shaohua, 1999. Geophysical well log in global change. *Progress in Geophysics,* 14(2): 1–8 (in Chinese with English abstract).

Liu Hefu, 1996. Evolution of Chinese sedimentary basins and their cyclic dynamic environment. *Earth Science*, 21 (4): 345–356 (in Chinese).

Liu Wanzhu and Wang Pujun, 1997. Genesis and environmental significance of the dolomite concretions from the Nenjiang formation in the Songliao basin, Northeastern China. *Sedimentary Facies and Palaeogeography*, 17(1): 22–26 (in Chinese).

Liu Zechun, Chen Ye and Yuan Linwang, 2001. The paleoclimate change of Qaidam Basin during the last 2.85 Ma recorded by Gamma-ray logging. *Sci. China (D)*, 44(2): 133–145.

Milankovtich, M., 1941. Kano der Erdbestrahhlung und seine Anwendung auf das Eiszeitenproblem. *Academic Serbe,* 133: 1–633.

Niebuhr, B., 2005. Geochemistry and time-series analyses of orbitally forced Upper Cretaceous marl–limestone rhythmites (Lehrte West Syncline, northern Germany). *Geol. Mag.*, 142 (1): 31–55.

Prokoph, A., Villeneuve, M., Agterberg, F.P., and Rachold, V., 2001. Geochronology and calibration of global Milankovitch cyclicity at the Cenomanian-Turonian boundary. *Geology*, 29 (6): 523–526.

Rampino, M.R., Prokoph, A., and Adler, A., 2000. Tempo of the end-Permian event: High-resolution cyclostratigraphy at the Permian-Triassic boundary. *Geology*, 28(7): 643–646.

Schulz, M., and Mudelsee, M., 2002. REDFIT: Estimating red-noise spectra directly from unevenly spaced paleoclimatic time series. *Compu.t Geosci.,* 28(3): 421–426.

Schwarzacher, W., 2000. Repetitions and cycles in stratigraphy. *Earth-Sci. Rev.*, (50):51–75.

Stage, M., 1999. Signal analysis of cyclicity in Maastrichtian pelagic chalks from the Danish North Sea. *Earth Planet. Sci. Lett.*, 173: 75–90.

Stage, M., 2003. Recognition of Cyclicity in the Petrophysical Properties of a Maastrichtian Pelagic Chalk Oil Field Reservoir from the Danish North Sea. *AAPG Bulletin*, 85(11): 2003–2015.

Van der Zwan, C.J., 2002. The impact of Milankovitch-scale climatic forcing on sediment supply. *Sedimentary Geology*, 147: 271–294.

Wan Xiaoqiao, Li Gang, Chen Piji, Yu Tao and Ye Dequan, 2005. Isotope Stratigraphy of the Cretaceous Qingshankou Formation in Songliao Basin and its correlation with marine Cenomanian Stage. *Acta Geologica Sinica*, 79(2): 150–156.

Wang Chengshan, 2006. Coupling of the Earth Surface System: inferring from the Cretaceous major geological events. *Advances in Earth Science*, 21(8): 838–842 (in Chinese).

Wang Pujun, Du Xiaodi, Wang Jun and Wang Dongpo, 1995. The chronostratigraphy and stratigraphic classification of the Cretaceous of the Songliao Basin. *Acta Geologica Sinica*, 69 (4): 372–381 (in Chinese).

Wilson, P.A., Norris, R.D. and Cooper, M.J., 2002. Testing the mid-Cretaceous greenhouse hypothesis using "glassy" foraminiferal calcite from the core of the Turonian tropics on Demerara Rise. *Geology,* 30: 607–610.

Ye Shufen and Wei Kuisheng, 1996. Condensed section and new evidence of marine inundation in Cretaceous, Songliao basin. *Earth Science-Journal of China University of Geosciences*, 21 (3): 267–271 (in Chinese).

Zhang Minman and Zhou Jiajian, 1978. Discussions on the fish fossils in Meso-Neozoic oil strata and there depositional environment in eastern China. *Vertebrate and Anthropology*, 16(4): 229–237 (in Chinese).