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Identification of Milankovitch sedimentary cycle in Fengcheng Formation, Mahu depression: a case study of well Maye 1

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The sedimentary cycle of Fengcheng Formation in Junggar Basin changes rapidly and is difficult to identify. The low classification accuracy of high-frequency fine-grained sedimentary cycles restricts the exploration of unconventional shale oil and gas. Full-interval coring of well Maye 1 provides a solid foundation for small-layer research. In this paper, the high-frequency sedimentary cycle of Milan kovitch in Fengcheng Formation is studied by means of spectral analysis and wavelet transform, and the shale sweet spot is identified. The long period of eccentricity of 405ka, short period of eccentricity of 100ka and long period of axis slope of 42736a can be used as semi-quantitative basis for the classification of the fourth, fifth and sixth sequences. The Fengcheng Formation can be divided into 2 quaternary sequence cycles, 9 quaternary sequence cycles and 16 quaternary sequence cycles. A long period of eccentricity of 405ka can identify large-scale lake recessional and recessional, and there is a maximum lake flooding surface in the middle of the second Fengcheng Formation, which corresponds to high abundance of organic matter and high hydrocarbon generation potential. The 100ka short period eccentricity can identify the sweet spot layer, and there are 8 sweet spots in the well Maye 1, which is consistent with the results of nuclear magnetic interpretation. The research results provide a semi-quantitative basis for the classification of high-frequency sedimentary cycles and the identification of sweet spots of Fengcheng Formation in Mahu Sag, Junggar Basin.

KEYWORDS

Junggar basin, Fengcheng formation, shale oil, sedimentary cycle, Milankovitch, sweet spot recognition Junggar basin

1 Introduction

Milankovitch cycles (Ding, 2006) represent the response of paleoclimate variations in sedimentary strata. At the beginning of the 20th century, Milutin Milankovitch proposed that due to the rotation and revolution of the Earth, the parameters of the Earth's orbit, such as eccentricity, the slope of the Earth's axis, and the precession, change periodically, which in turn leads to cyclical changes in the Earth's climate over 10,000 and millions of years (Shi and Liu, 2006). This is still controversial because of the inability to date the Earth accurately geologically. It was not until the 1960s that the cyclic sea level changes corresponding to ice sheet dimensions were found to be consistent with glacier curves calculated by Milankovitch in several coral reef research conducted in various locations, including Hawaii (Mei, 2011). The existence of Milankovitch cycles has been confirmed. The important role of Milankovitch theory in delineating sedimentary cyclones on the scale of several centimeters to several meters was highlighted in 2010 by Mei Mingxiang (Mei, 2010) in the third research advance in stratigraphy. Subsequently, an increasing number of paleoclimate researchers have also corroborated the existence of the Milankovitch Cyclone several times in geological deposits (Raymo and Nisancioglu, 2003; Ding, 2006; Shi et al., 2017). At present, the Tarim Basin (Jia et al., 2018), Songliao Basin (Zhao et al., 2018), Bohai Bay Basin (Xu and Xie, 2012), Ordos Basin (Xie et al., 2016), and Sichuan Basin (Zhang et al., 2013) in China have all achieved good results in dividing the high-frequency stratigraphic sequences by Milankovitch cycles.

The advent of high-quality seismic reflection data in the 1970s led to a real rise in stratigraphy (Sloss, 1963). The current development of stratigraphy based on stratigraphic sequence under the control of tectonic factors can be summarized into four schools: firstly, the classical school represented by Vail et al. (1991); secondly, the diagenetic stratigraphy school represented by Galloway (Galloway, 1989); thirdly, the sea-advancing-sea-retreating stratigraphy school represented by Johnson (Johnson et al., 1985); and fourthly, the high-resolution stratigraphy school represented by Cross (Cross, 1988). The sequence stratigraphy division represented by Vail, Galloway, and Johnson makes it difficult to delineate sequences of less than 1 million years in duration. Van Wagoner and others (Wagoner et al., 1990) first proposed the concept of high-frequency sequence stratigraphy, specifically referring to sedimentary responses generated by sea-level cycles of fourth order and higher with periods of 0.1–0.5 million years. Despite the high-resolution sequence stratigraphy proposed by Cross et al., there is no clear method for defining the base-level cycle, with only a simple three-level division of long-term, medium-term, and short-term base-level cycles. In contrast, the fourth, fifth, and sixth-order sequence boundaries were precisely determined based on glacioeustatic sea-level changes caused by Milankovitch cycles, utilizing the long eccentricity cycle, short eccentricity cycle, obliquity cycle, and precession cycle (Imbrie et al., 1993; Shi et al., 2019; Berends et al., 2021). With the development of high-resolution stratigraphy, Vail and others (Vail et al., 1977) subdivided the stratigraphy into six classes based on durations according to sea-level change. Subsequently, domestic scholars proposed different division schemes based on the characteristics of terrestrial sedimentation in China. Mei et al. (2000) and others proposed two mechanisms of sea level change in 2010, which are tectonic sea level change with a long period and a slow rate, and glacial sea level change with a high frequency and a high rate. Zheng et al. (2001) and others also in 2010, generalized and summarized the relationship between the structural superposition styles and sedimentary dynamics of the datum cyclothems of several terrestrial basins, such as the Liaohe, western Sichuan, and Baise, and proposed six types of orogenic interfaces with different orogenic features, developmental scales and identifying markers, pointing out the important identifying markers for the interfaces of the corresponding cyclothems and comparing them with the Vail sequential stratigraphic unit.

The fine-grained sedimentary rocks of the Fengcheng Formation in the Mahu Sag of the Junggar Basin exhibit high-frequency sequence stratigraphic characteristics. Conventional sequence stratigraphic research methods often struggle to accurately reflect the true conditions of stratigraphic cycles. The Milankovitch theory provides an effective means for conducting high-precision cycle division and comparison, serving as a powerful supplement to traditional sequence stratigraphy. The Maye 1 well is on the north slope of the Mahu Sag, which is an important exploratory well for oil and gas exploration in the Fengcheng Formation. The continuous core of the Fengcheng Formation obtained from this well spans 348.37 m, with oil and gas shows observed throughout the entire core. A detailed on-site core description revealed the presence of 1,727 small layers, making it difficult to perform cycle division and regional cycle comparison, thus limiting its utility for exploration and production guidance. Therefore, there is an urgent need to establish an effective set of cycle division schemes as a reference for sweet spot identification research.

2 Geological setting

The Maye 1 well is in the Mahu Sag, which is the most prolific oil and gas-generating area in the Junggar Basin. It is situated near the Wuxia and Kebai fault zones, which serve as pathways for oil and gas migration (Figure 1). The stratigraphy of the Mahu Sag was deposited on a pre-Carboniferous basement and spans from the Carboniferous to the Quaternary, with a thickness exceeding 10,000 m. The deepest drilled well in the area, Hutan 1, has reached approximately 15,000 m in the Carboniferous system. Due to the early compression and nappe-thrusting of the Hercynian movement, the Permian strata tilt towards the interior of the basin with a steep angle. The Permian strata primarily consist of infill-type sediments and the dip angle becomes gentler for strata above the Triassic.

The internal stratigraphic relationships within the Permian consist mostly of unconformable contacts, with truncation phenomena observed in the western region. Towards the east, there is the presence of an “apparent downlap” towards the center of the depression, while the eastern strata exhibit thinning and “erosion an upper part and downlap at lower part”. The Fengcheng Formation, along with the overlying and underlying strata, form an independent and integrated sequence stratigraphic unit. The thickness of the stratum is 200–2000 m, and the distribution area is about 5,000 km^2, which is the most dominant and high-quality alkali lake hydrocarbon source rock of the depression, and the most important material basis for the discovery of the Northwest Marginal Multilayer System Baili Oil Zone.

The stratigraphy of the Mahu Sag is fully developed from the Carboniferous to the Cenozoic, with the Upper Permian locally missing in the tectonically high part of the slope. The Fengcheng Formation in Well Maye 1 exhibits a dual characteristic of both alkaline lake source rocks and fine-grained sedimentary rocks. Currently, widespread distribution of alkaline minerals such as searlesite, shortite, and nahcolite has been discovered. This holds significant importance for the study of paleoclimate, paleohydrology, geochemistry, biology, sedimentation, and structure, among other aspects. The reservoir rocks of the Fengcheng Formation are mainly composed of fine-grained sediments such as silt and clay. The continuity and high-resolution recording of lake-phase fine-grained sedimentation

TABLE 1 Pore structure data table of the Upper Wuerhe Formation reservoir in the Manan slope.

Cyclical levels	First-order	Second-order	Third-order	Fourth-order	Fifth-order	Sixth-order
Sequence	Mega sequence	Super sequence	Sequence	Para sequence set	Para sequence	rhythmite/meter-scale cycle
Forming duration (Ma)	200–400	10–40	1–10	0.4	0.1	0.02/0.04
(This article adopts)	>50	30–40	1–10	0.2–0.8	0.04–0.16	0.02/0.04
Sea level changes	Structural (tectonic sea level changes caused by plate movements)			Glacial (glacial sea-level changes due to the Milankovitch astronomical cycle)		
Cyclic period	Super galactic annual period	Galactic period	Asteroid belt orbital period	The long period of eccentricity	The short period of eccentricity	Period of earth axis slope or period of precession
Layer order level corresponding to Vail	Second-order sequence (suprasequence set)	Second-order sequence set (suprasequence)	Third-order sequence (sequence)	Fourth-order sequence (system tract/para sequence set)	Fifth-order sequence (para sequence)	Sixth-order sequence (rhythmic bedding)
Zheng Rongcai et al. Base-level cycles and duration (Ma)	Type I	Type II	Type III	Type IV	Type V	Type VI
	Mega-cycle	Super-long cycle	Long cycle	Mid-cycle	Short cycle	Ultra-short cycle
	30~>100	10–50	1.6–5.25	0.2~<1	0.04–0.16	0.02–0.04
Zheng Rongcai et al. Interface Identification markers	Weathering shell, pseudo-conformable surface characterized by angular unconformity or significant stratigraphic hiatus; abrupt changes in well logging parameters; major truncation surfaces of large-scale structures, sedimentary superimposition surfaces	Transitional surfaces that reflect changes in sedimentary systems and combinations of different logging facies; large-scale structural truncation and erosion surfaces, sedimentary superimposition surfaces, micro-angular or pseudo-conformable surfaces within the basin	Large-scale erosional unconformity surfaces in outcrops and rock cores; transitional surfaces of regional progradation to retrogradation logging facies combinations; erosion and truncation surfaces, and superimposition surfaces in seismic profiles	Large-scale bottom erosional surfaces in outcrops and rock cores; transitional surfaces of subaqueous progradation to retrogradation logging facies combinations; difficulty in identifying these features in conventional seismic profiles	Small-scale bottom erosional surfaces, amalgamation surfaces in outcrops and rock cores; abrupt surfaces in the transition zone between different logging facies types indicating unidirectional progradation to retrogradation shift, or accelerated gradational surfaces	Small-scale erosional and amalgamation surfaces in outcrops and rock cores; abrupt or gradual transitions in well log curves indicating a single logging facies type and unidirectional shift; pseudo-conformable and micro-angular unconformity surfaces in seismic profiles

(Continued on the following page)

TABLE 1 (*Continued*) Pore structure data table of the Upper Wuerhe Formation reservoir in the Manan slope.

Cyclical levels	First-order	Second-order	Third-order	Fourth-order	Fifth-order	Sixth-order
Interface Identification (This article adopts)	Structural unconformities in seismic profiles			Continuous strong reflector interfaces with abrupt changes in well-logging parameters that are inconsistent with seismic data; related to long Milankovitch cycles	Related to short Milankovitch cycles	Related to Milankovitch obliquity or precession cycles

TABLE 2 Periodic table of precession and slope of historical periods.

Geologic time	Age/Ma	Period of earth axis slope/a		Period of precession/a	
		Short period	Long period	Short period	Long period
Quaternary	0	41,000	54,000	19,000	23,000
Late Cretaceous	72	39,280	51,055	18,622	22,449
Middle Permian	270	34,778	43,703	17,545	20,902
Early Permian	298	34,163	42,736	17,387	20,678
Late Devonian	380	32,390	39,997	16,916	20,015
Early Silurian	440	31,134	38,099	16,567	19,529
Late Cambrian	500	29,885	36,245	16,207	19,029
Early Neoproterozoic	1,000	25,522	30,021	14,832	17,162
Early Mesoproterozoic	1,500	22,520	25,951	13,765	15,750
Early Paleoproterozoic	2000	19,590	22,136	12,612	14,258

provide valuable information on changes in lake climate, making it an ideal carrier for Milankovitch cycle analysis. Currently, the classification standards, sedimentary environments, and sweet spot prediction of fine-grained sedimentary rocks are hot topics and frontiers in petroleum geology research. The division of high-frequency sequences is the foundation for such studies. Therefore, the sequence stratigraphic study of the Fengcheng Formation in Well Maye 1 holds significant guiding significance for on-site production in the entire Junggar Basin oilfield and petroleum geological research.

3 Milankovitch cycle identification

3.1 Sequence stratigraphic levels and Milankovitch cycles

The Milankovitch cycles exhibit isochronism, providing a semi-quantitative reference for high-frequency sedimentary cycle correlation and comparison. In this paper, the stratigraphic division unit is further refined according to the stratigraphic sequence interface characteristics of the Fengcheng Formation in the Junggar Basin, to achieve the purpose of stratigraphic division and comparison of the Fengcheng Formation shale oils with high temporal precision (Table 1). We divided the sequence of the study area into six levels. The first three sequence interfaces are all tectonic unconformities in seismic profiles. The fourth-order sequence interface is a continuous and strong reflection interface with seismic incongruous changes in logging parameters, which is related to the long Milankovitch period and corresponds to the quasi-sequence set of classical sequence stratigraphy. The fifth order sequence interface is related to the short Milankovitch cycle and corresponds to the quasi-sequence of classical sequence stratigraphy. The sixth level sequence interface is related to the Milankovitch slope or precession period and corresponds to the rhythmic layers of classical sequence stratigraphy.

3.2 Theoretical orbital cycles

Berger and others concluded that there are regular variations in the obliquity and the period of precession in different geohistorical

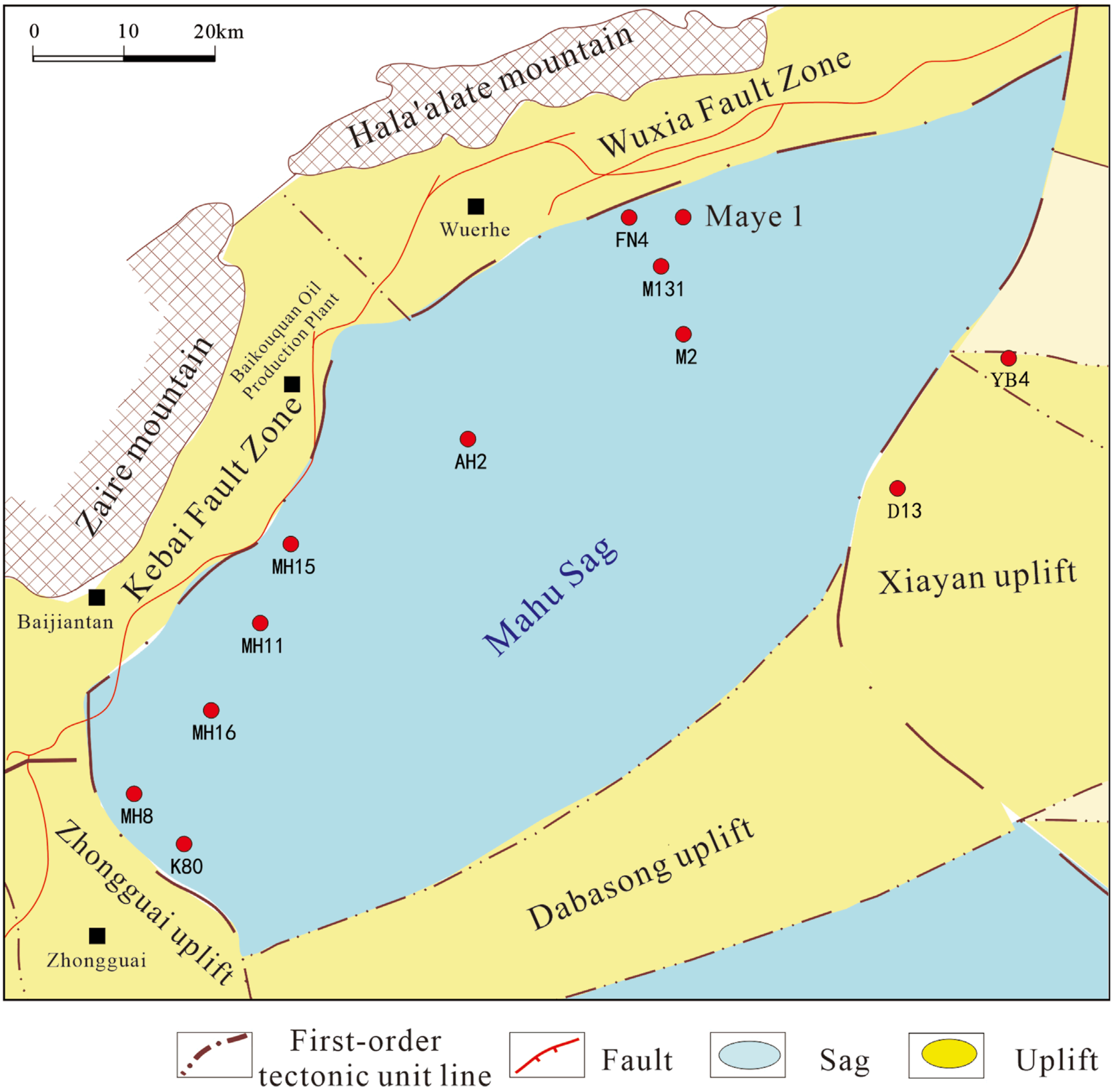

FIGURE 1
Structural location map of well Maye 1 in Mahu Sag, Junggar Basin.

periods and that the ratio between the orbital parameters is fixed (Berger et al., 1992), which was measured and corrected based on satellite measurements (Table 2). The slope cycle and precession cycle have a linear relationship during the geohistory. The cycle time for any period since 2,000 Ma can be obtained by linear interpolation. According to the investigation, the deposition age of the Fengcheng Formation is 283–272 Ma, corresponding to the early Permian. The short period of the earth axis slope is 34,163 a, the long period of the earth axis slope is 42,736 a, the short period of precession is 17,387 a, and the long period of precession is 20,678 a. In the past 250 Ma, the long eccentricity cycle is about 405 ka, and the short eccentricity cycle is about 100 ka. When the Earth is at aphelion, the Earth's surface receives less insolation; when the Earth is at perihelion, the Earth's surface receives more insolation; the eccentricity cycle mainly affects the distribution of the insolation by adjusting the amplitude of the precession cycle. The larger the eccentricity, the larger the amplitude of the precession cycle, corresponding to colder winters and hotter summers. The final astronomical period of the Milankovitch Cycle of the Fengcheng Formation was determined from the sedimentary age isochronism method as the ratio of the eccentricity short period, the earth axis slope long period, the earth axis slope short period,

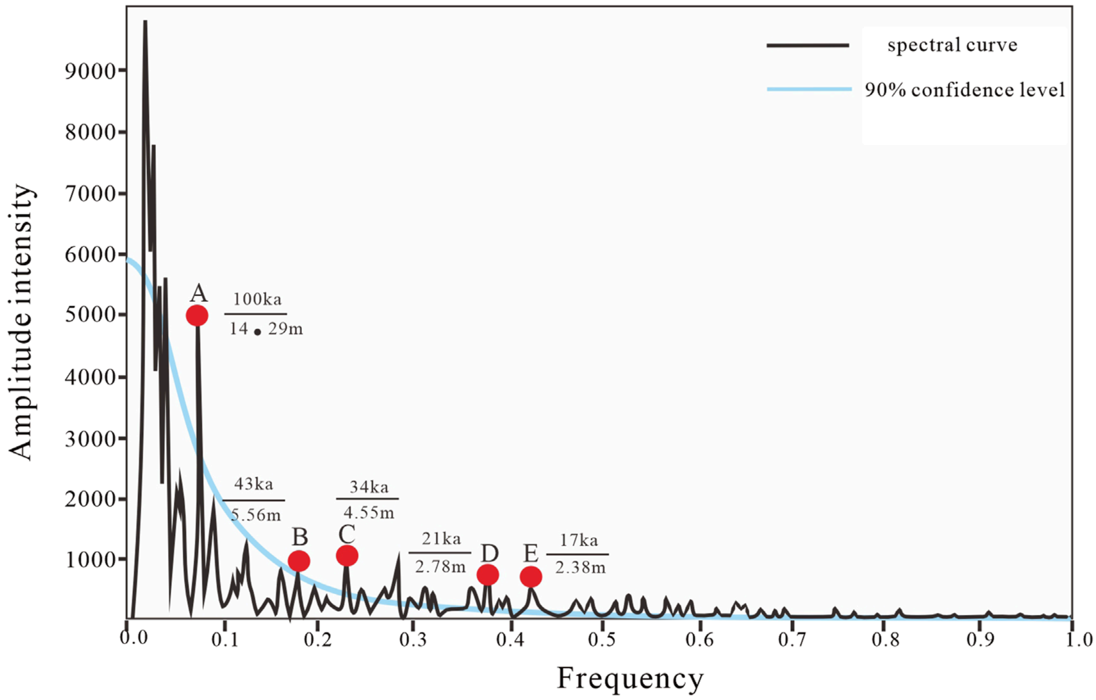

FIGURE 2
Spectral analysis of natural gamma curve of well Maye 1 in Mahu Sag, Junggar Basin.

the precession long period, and the precession short period are 1.0 : 0.43: 0.34: 0.21: 0.17.

3.3 Spectral analysis for extracting Milankovitch cycles

Spectral analysis is to show the stratigraphic rotation information contained in the GR curves through mathematical transformations. The eccentricity cycle, earth axis slope cycle, and precession cycle curves extracted from the well-logging data after filtering are used as the basis for the delineation of high-frequency stratigraphic sequences. Spectral analysis is a complex process that requires repeated comparisons and identifications. Its purpose is to discover frequencies where the wavelength ratios within the analyzed stratigraphic interval are similar or identical to the cyclical period ratios of climate variations during geological periods. Figure 2 shows the results of the spectrum analysis for Well Maye 1. The five peak points, labeled as A, B, C, D, and E, correspond to the eccentricity short period, earth axis slope long period, earth axis slope short period, precession long period, and precession short period, respectively. The corresponding values for the five points in Well Maye 1 are 0.07, 0.18, 0.22, 0.36, and 0.42. Calculating the corresponding sedimentary cyclicity thickness yields 14.29 m, 5.56 m, 4.55 m, 2.78 m, and 2.38 m, respectively. The thickness ratio is approximately 1.0 : 0.39: 0.32 : 0.19: 0.17. The ratios closely approximate the astronomical cycle ratios with an error within 10%, indicating that the fine-grained sedimentation in the Fengcheng Formation of the Mahu Sag exhibits Milankovitch cyclicity.

3.4 Wavelet transform for partitioning Milankovitch cycles

Smoothing the whole natural gamma curve (Figure 3, low frequency). The lower part of the Feng 2 section exhibits strong and significant amplitude variations, while the upper part shows weaker and less pronounced amplitude changes. The middle part has lower content and obvious variation from the upper and lower parts, corresponding to a fourth-order sequence unconformity interface. Through Table 1, the three fourth-order stratigraphic interfaces correspond to the Milankovitch eccentricity 405 ka long period, representing a long-term cyclical pattern.

According to the spectrum analysis, the eccentricity short period and axial tilt long period correspond to frequencies of 0.07 and 0.18, respectively. A higher frequency value indicates a faster amplitude superposition change. The frequency of 0.18 is sufficient to characterize the meter-scale sequence variation features, and a more detailed sequence division does not have practical geological significance. Therefore, the frequencies of 0.07 and 0.18 are chosen to divide the section into five and six-order sequences. Spectrum analysis only reflects the average spectral structure within a specific time (or depth) and cannot extract information about how a particular frequency changes over time. Wavelet analysis is a novel technique in time-scale analysis and multiresolution analysis, which effectively captures the time (or depth) variations in the frequency domain. Wavelet variation pumping of the natural gamma curve of the Maye 1 well was carried out using MATLAB software to present two amplitude curves of medium and high frequency with frequency values of 0.07 and 0.18 (Figure 3, medium

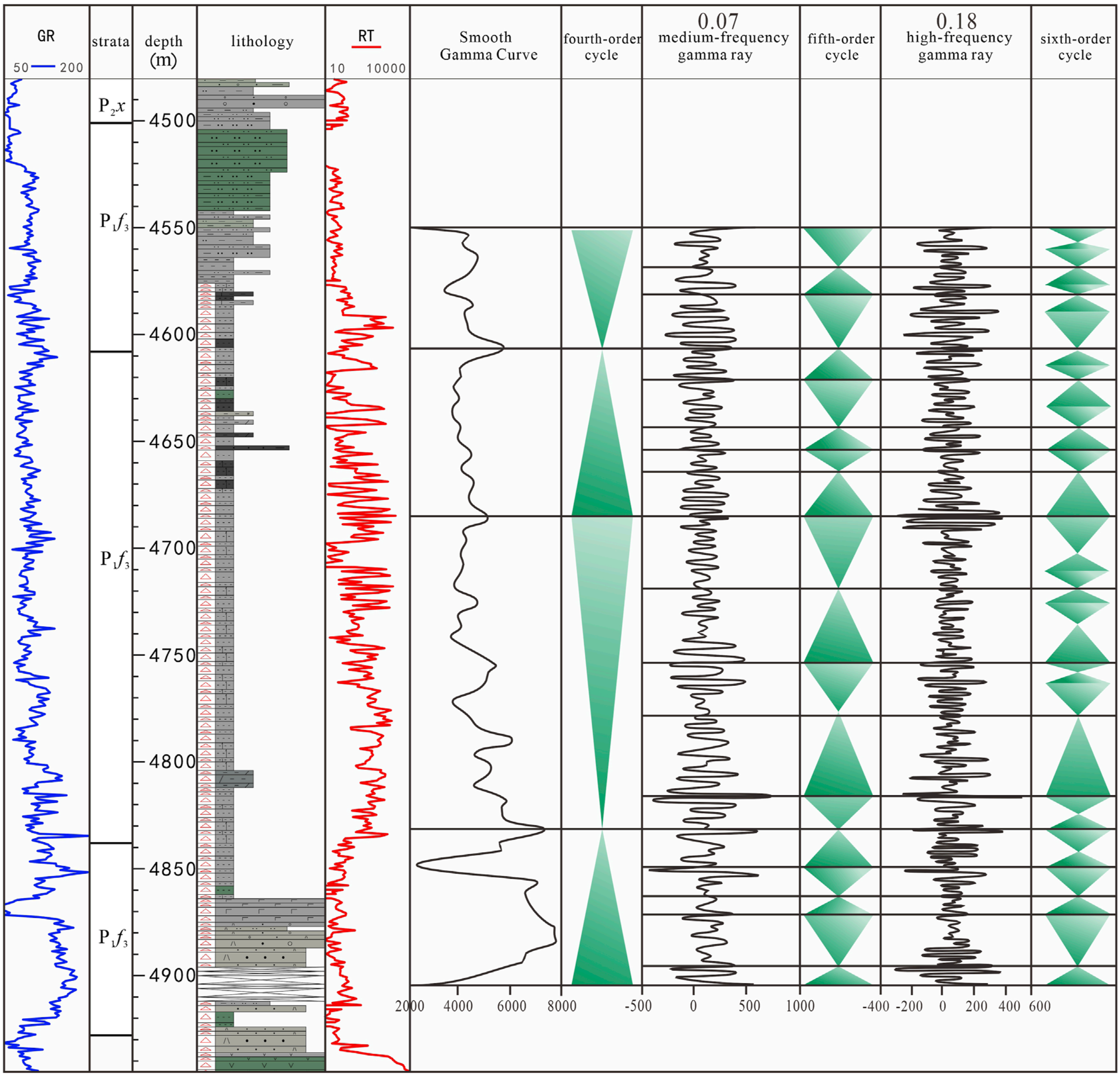

FIGURE 3
Wavelet transform results of well Maye 1 in Mahu Sag, Junggar Basin.

and high-frequency). The medium-frequency amplitude curve is an eccentricity 100 ka period, which is equivalent to a fifth-order sequence and represents a medium-term cyclone; the high-frequency amplitude curve is a ground-axis slope 42,736 a long period, which is equivalent to a sixth-order cyclone and represents a short-term cyclone.

Based on the spectral analysis of natural gamma curves and wavelet variations in the Fengcheng Formation of the Maye 1 well, two phases of lake recession-lake advance cyclicity were developed. Two long cycles with an eccentricity of 405 ka, nine short cycles with an eccentricity of 100 ka, and sixteen long cycles with earth axis slopes of 42,736 a were identified. The division of cycles corresponds well to core logging, logging sensitivity curves, and trace element measurement data.

4 Applications of Milankovitch cycles

4.1 Comparative analysis of regional cycles

The identification of Milankovitch cycles in the Fengnan 14, Fengnan 1, and Fengnan 4 wells of the Permian Fengcheng Formation of the Mahu Sag, all of which have two long cycles with an eccentricity of 405 ka, reflects that there are two large-scale lake retreat-lake advance cycles in the Fengcheng Formation (Figure 4). Additionally, a prominent maximum lake flooding surface in the middle of the deposition corresponds to the paleoclimate of the warmest and most humid environment. These conditions are conducive to the proliferation of salt-tolerant bacterial algae organisms and provide a favorable environment for the formation

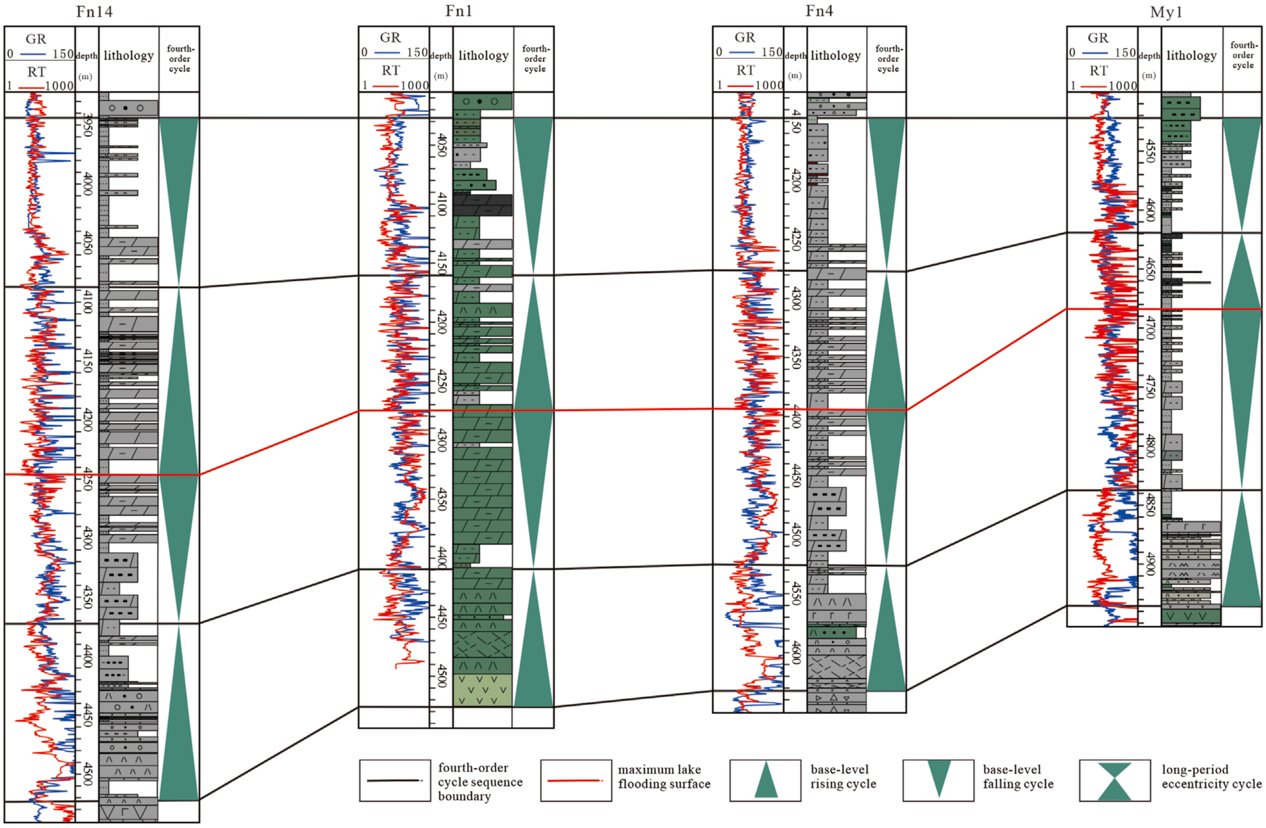

FIGURE 4
Regional comparison of Milankovitch cycle of Fengcheng Formation, Mahu Sag.

of organic matter. The Fengcheng Formation is dominated by lacustrine source rocks with good organic matter types, mainly II1 and II2.

Petrological characterization shows that longitudinally the rock grains change from coarse to fine and then from fine to coarse. A process of lithologic change dominated by mixed deposition of clastic and volcanic rocks at the base, with a gradual transition to chemosynthetic salt deposition, and dominated by clastic deposition at the top. This process also reflects that there is an important high-order sequence boundary during the period of chemical salt deposition, which corresponds to the identification of Milankovitch eccentricity long-period cycles. It further demonstrates that Earth's orbital periods have a controlling effect on the rich organic shale sedimentary cycles. Based on the eccentricity of long-period cycles, a unified cyclostratigraphy pattern can be established, which is of great significance for the planar study of sedimentary facies.

4.2 Sweet spot recognition

The Milankovitch cycle of the Fengcheng Formation in the Maye 1 well-identified nine short cycles with an eccentricity of 100 ka (Figure 5), whose cyclic cycles correspond to the process of climate change from warm-wet-dry-cold-warm-wet. The warm-wet environment is favorable for the propagation of fungal and algal organisms, with increased organic matter abundance and high hydrocarbon potential; on the contrary, organic matter abundance is low in the dry-cold environment. By recovering the climate characteristic curve from the cycle changes, assuming that the lowest and highest points of each climate change are the same value, and using the semi-floating-point position for division, eight intervals with high organic matter abundance were identified.

The lithology, porosity, and oil saturation curves were interpreted through nuclear magnetic resonance logging to comprehensively explain eight sweet spots. These sweet spots have strong correspondence with the high-organic-matter intervals identified by the Milankovitch cycles. The correspondence of sweet spots at depths 1 and 8 is slightly poor, primarily due to the coarse-grained sedimentation at the top and bottom of the Fengcheng Formation, which is less influenced by climatic conditions and therefore less suitable. In contrast, the sweet spots identified in the fine-grained sedimentation of intervals two to seven correspond better. The analysis suggests that the Milankovitch cycles reflect the climatic variations in geological deposition due to the change of the earth's axis orbit cycle. This climate variation is manifested in the sedimentary environment's temperature and humidity, which directly affect the growth and reproduction of organic organisms, and subsequently, the abundance of organic matter. Since shale oil has the characteristic of being self-generated and self-stored or self-generated and neighboring stored, meaning that the reservoir and hydrocarbon-generating layer are the same layer or closely adjacent layers, the segments with high organic matter abundance exhibit better correspondence with the sweet spots.

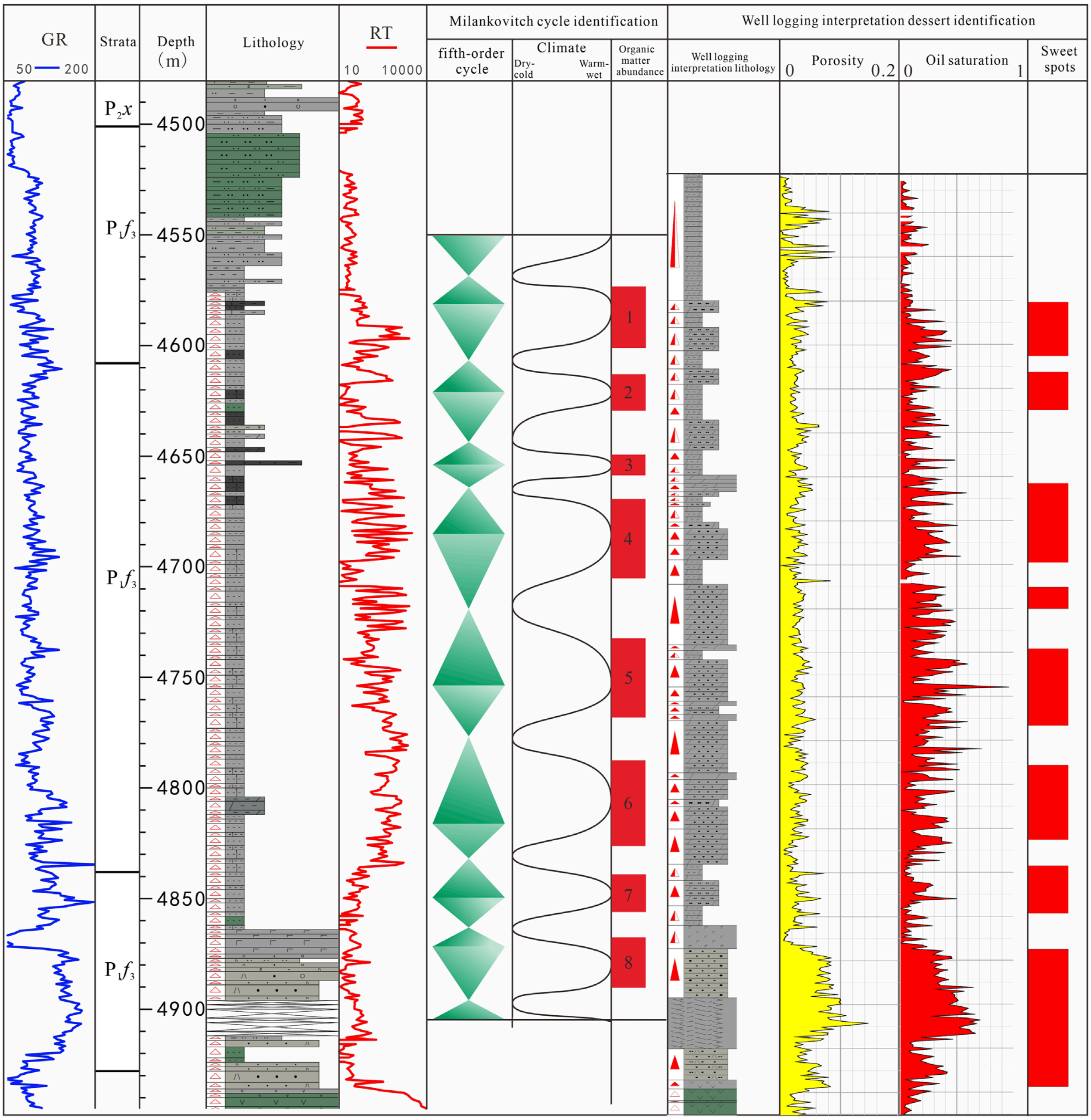

FIGURE 5
Milankovitch dessert identification of Fengcheng Formation in Well Maye 1, Mahu Sag.

This also demonstrates that the Milankovitch cycles' eccentricity 100ka short period can be used to identify sweet spots in the Fengcheng Formation.

5 Conclusion

(1) Spectral analysis and wavelet transform analysis of the natural gamma curve of the Well Maye 1 found that the shale formation in the Fengcheng Formation is characterized by Milankovitch's high-frequency cyclicity. These cycles are controlled by the long period of eccentricity 405 ka, the short period of eccentricity 100 ka, and the long period of earth axis slope 4,2736 a. This provides quantitative evidence for delineating the shale oil minor layer of the Fengcheng Formation in later stages. The eccentricity with a long period of 405 ka, eccentricity with a short period of 100 ka, and obliquity of the Earth's axis with a long period of 42,736 a are considered as reference curves for the subdivision of high-frequency sequence cycles at the fourth, fifth, and sixth order levels, respectively. The Fengcheng Formation exhibits two long eccentricity cycles, nine short eccentricity cycles, and 16 long earth axis slope cycles.

(2) The eccentricity 405 ka long period has regional applicability and divides the Fengcheng Formation into two phases of lake-retreat-lake-entry cyclones, providing a quantitative basis for establishing a unified stratigraphic grid of cyclones. A short period of 100 ka eccentricity can restore paleoclimate change. By establishing the relationship between paleoclimate and organic matter content, the abundance of organic matter can be predicted, which can indirectly identify desserts. The sweet spot prediction results are consistent with the identification of nuclear magnetic logging.

(3) The Milankovitch cycle is suitable for fine grained sediments affected by climate, but is not suitable for coarse grained sediments and volcanic sediments.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

RW: Writing–original draft. XC: Writing–review and editing. QC: Data curation, Formal analysis, Methodology, Writing–review and editing. XZ: Data curation, Formal analysis, Methodology, Writing–review and editing.

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Conflict of interest

Authors RW, QC, and XZ were employed by PetroChina Xinjiang oilfield Company.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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