Research Article

A Study on Astronomical Cycle Identification and Environmental Response Characteristics of Lacustrine Deep-Water Fine-Grained Sedimentary Rocks: A Case Study of the Lower Submember of Member 3 of Shahejie Formation in Well Fanye-1 of Dongying Sag, Bohai Bay Basin, China

Ledan Yu,1 Jun Peng,1 Tianyu Xu,1 Yubin Wang,1 and Haodong Han2

1School of Geoscience and Technology, Southwest Petroleum University, Chengdu, Sichuan 610500, China
2Chengdu Geological Survey Center, China Geological Survey, Chengdu, Sichuan 610081, China

Correspondence should be addressed to Jun Peng; 445371976@qq.com

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With the further exploration and development of shale oil and gas, cycle division of fine-grained sedimentary rock strata has been increasingly highly focused on by scholars. Owing to the application of the theory of classical sequence stratigraphy based on water depth changes and its technical methods being unsatisfactory in the isochronous division and correlation of deep-water fine-grained sedimentary strata, the cycle division of fine-grained sedimentary rock strata has always been a difficult point in the study of sequence stratigraphy. In this paper, the Milankovitch cycle recorded from the study interval and the environment response characteristics were studied, with the lacustrine shale in the lower third submember of the Paleogene Shahejie Formation (lower Es3 submember) in Well Fanye-1 of the Dongying sag, Bohai Bay Basin, as the object of study, by such technical means as thin section identification and X-ray whole rock diffraction, based on such data as logging data and geochemistry, combining the methods of spectral analysis, wavelet transform, and modulus extremum. The results showed that the stratigraphic cycle thicknesses caused by long eccentricity, short eccentricity, and obliquity periods were 38.95 m, 12.98 m, and 4.10 m, respectively, and a total of 16 short eccentricity periods and 4.5 long eccentricity periods were identified in the study interval. Thus, it was further calculated that the sedimentation time was approximately 1.905 Ma, and the average sedimentation rate was estimated to be 0.105 m/ka. Studies have shown that the sedimentary environment of lacustrine fine-grained sedimentary strata is controlled by the astronomical period, based on which the climate as a whole changes from relatively dry and cold to warm and wet when the eccentricity increases. The identification of the Milankovitch cycle of the lacustrine fine-grained sedimentary strata will provide references for the study of high frequency sequence and the division of high-resolution sequence strata, which can effectively solve the scientifically difficult isochronous division and correlation of lacustrine shale strata.

1. Introduction

Great strides have been made in the exploration of fine-grained sedimentary oil and gas in recent years, with the constantly improved fine-grained sedimentary oil and gas reservoir theory and the fast-growing well drilling and completion technology. The cycle division of fine-grained sedimentary strata is an important basic work for the exploration of fine-grained sedimentary oil and gas and has been a worldwide problem in the study of cyclic stratigraphy [1–3]. Previous studies indicate that the high frequency cycle in fine-grained sedimentary strata is formed under the influence of the Milankovitch cycle [3–5], and the application of the theory of classical sequence stratigraphy based on water depth changes and its technical methods is not satisfactory in the isochronous division and correlation of deep-water fine-grained sedimentary strata [6–13]; the control of the fine-grained sedimentation process by Milankovitch cycle-
effected climate changes is also poorly studied. Therefore, there is a crying need for feasible methods to realize the isochronous division of fine-grained sedimentary strata and to analyze in detail the relationship between the fine-grained sedimentation process with frequent lithological changes and the paleoenvironmental changes.

Cycle division of fine-grained sedimentary strata has always been a focus in the field of cyclic stratigraphy. In recent years, many scholars have tried different data and different methods to extract the Milankovitch cycle in sedimentary strata [14–22]. Wu and Liu performed the wavelet transform analysis using logging data to study the high-resolution sequence lacustrine strata in the North Yellow Sea Basin [23]; Sun et al. performed the wavelet transform analysis using natural gamma ray logging data and identified the Milankovitch cycle in the upper Es4 submember in Niuye Well 1 and discussed the significance of the Milankovitch cycle to the exploration of shale oil [24]; Shi et al. studied the high frequency sequence of lacustrine fine-grained sedimentary rocks by the spectrum and mean spectrum fitting difference analysis on magnetic susceptibility data [3]; Ruhl et al. studied the carbon cycle in the Pliensbachian of Early Jurassic by astronomical tuning, finding an obvious Milankovitch cycle period in the time series of concentration of the Fe element [25]; Hüssing et al. corrected the Miocene astronomical framework in the Mediterranean region by astronomical tuning using the magnetic susceptibility of the La Vedova profile in the north of Italy and the Ca/Al data [20]; Renne et al. calibrated the astronomical chronicle of the Cretaceous–Paleogene boundary of the Zumai profile in Spain and calculated the age of cyclic strata [26]; and Nie et al. presented in their study the precipitation record of a lake in the Late Miocene, suggesting that the main short eccentricity period in the Qaidam Basin in Northern China is similar to the record of the East Asian summer monsoon in the Later Quaternary [27]. Wang et al. presented astronomically calibrated gamma-ray log and CGR curves from the clastic and carbonate successions of well GFD-1 in the Pingle Depression of South China. A high-resolution astronomical time scale and high-resolution sedimentation rate curve of the Lopingian from well GFD-1 were constructed by cyclostratigraphic analysis [28]. Chen et al. passed the power spectrum/fast Fourier transform (FFT) and gamma rays of 4 wells including Liu 8 wells of the Lower Cretaceous Xiagou Formation in the Jiuquan Basin (GR) correlation coefficient analysis of series. It reveals the existence of astronomical periods such as long eccentricity, short eccentricity, slope, and precession in the study interval [29]. Zhao et al. used spectrum analysis and wavelet transform to reveal that the Milankovitch cycles are reflected in the third reservoir of the Saertu Formation (SIII). Evidently, the astronomical orbital period had an impact on SIII [30]. In many alternative indicators used for Milankovitch cycle analysis, logging data and magnetic susceptibility data are often used in previous studies, and the studies are performed by spectral analysis method, wavelet transform method, or the combination, and these studies have played an important role in promoting enriched sequence division of fine-grained sedimentary strata. However, there are few studies on environmental response characteristics of Milankovitch cycles. In this study, the logging data sensitive to cyclicity were still selected, and a modulus extremum analysis was further conducted on the basis of previously used spectral analysis method or wavelet transform method. This analytical method was added to mutually verify the accuracy in cycle division, thus perfecting the study methods for the Milankovitch cycle of lacustrine shale, improving the accuracy of sequence unit division and making the division results more consistent with reality. At the same time, previous studies have been less involved in the environmental responses with a very low level. Therefore, the environment response characteristics of Milankovitch cycles were further discussed in this paper based on the study of Milankovitch cycles.

A large suite of fine-grained sedimentary rocks develop in the Paleogene Shahejie Formation in Dongying sag, Bohai Bay Basin, China. This sag has abundant oil and gas resources, with a high degree of exploration [24], complete logging series, and rich geochemical test analysis data, thus being the best region for astronomical cycle identification using logging data. Achievements of many scholars in such aspects as lithofacies and sedimentary environment of this suite of fine-grained sedimentary rocks in recent years have vigorously promoted the exploration and development of shale oil and gas. However, there is a lack of a more perfect method for lacustrine shale sequence division now, and few studies focus on the relationship between the sedimentation process of lacustrine fine-grained rocks with frequent lithological changes and the paleoenvironmental changes. On the basis of previous studies, the author explored the identification of the Milankovitch cycle of logging information-based fine-grained sediments and its environment response characteristics in the case of the lower Es3 submember in Well Fanye-1, predicated on Milankovitch cycle theory, based on such data as rock core observation, thin section identification, X-ray whole-rock diffraction, element geochemistry, and logging data, combining the methods of spectral analysis, wavelet transform, and modulus extremum, thus providing a widely accepted study means and method for the isochronous cycle division and correlation of fine-grained sedimentary rocks such as shale and the environmental response characteristics of the cycle and the promoting the advance in cyclic stratigraphy of fine-grained sedimentary strata.

2. **Geological Setting**

2.1. **Tectonic-Sedimentary Evolution Characteristics.** Bohai Bay Basin, located in the east of China, is a Mesozoic-Cenozoic fault basin developing from the North China Plate through Paleozoic sedimentation and based on the Indosinian and Yanshanian movements (Figures 1(a) and 1(b)). Jiyang depression is located in the southeast of Bohai Bay Basin, in which four secondary sags, namely, the Chezhen sag, Zhanhua sag, Huimin sag, and Dongying sag, have developed (Figure 1(c)) [31–34]. The Dongying sag, inheriting the tectonic evolution characteristics of the Jiyang depression, has experienced four periods, namely, the initial period, development period, peak period, and decline period, and can be divided into four stages of episodic evolution, namely,
the Kongdian Formation, Es4, Es3-lower Es2 submember, and upper Es2 submember-Dongying Formation; the sedimentary center moves from south to north after each stage of extensional sedimentation, and this period is also an important period of oil and gas production. The fault depression period of tectonic evolution of the Dongying sag occurs in the Paleogene; this period is the main extensional rifting period of the sag, during which many extensional faults develop, with strong activity, forming a typical asymmetrical dustpan-like sag style, with an exploration area of appropriately 5,800 km². Many highs develop around the sag, and a series of synsedimentary normal faults inside the sag further divides the sag into four main oil-generating sub-sags (Boxing, Lijin, Niuzhuang, and Minfeng) and secondary tectonic units such as the North Steep Slope, Central Anticline Zone, and South Gentle Slope and multiple faulted tectonic zones (Figure 1(d)) [31–34].

2.2. Strata Development Characteristics. The Dongying sag strata developing from bottom to top are Paleozoic (Pz), Mesozoic (Mz), Paleogene (E), Neogene (N), and Quaternary (Q). Among them, Paleogene strata have a wide distribution, with a large sedimentary thickness (a maximum thickness of more than 7,000 m), which is gradually thinned and pinched out from the depocenter to the edge of the basin. Paleogene strata can be divided into the Kongdian Formation, Shahejie Formation, and Dongying Formation from bottom to top (Figure 2) [32, 33, 35, 36]. Es3 is characterized by lacustrine dark grey and grey shale sedimentation, with a general thickness of 700-1,000 m and up to over 1,200 m in the central sag. Es3 can be further divided into lower Es3 submember, middle Es3 submember, and upper Es3 submember from bottom to top, respectively, of which the lower Es3 submember has interbedded layers of dark grey mudstones, oil shale, and grey brown oil shale with different thicknesses, with deep lacustrine sedimentation of a small amount of thin sand layer, grey limestone, and dolomite (Figure 2). The lower Es3 submember stratum accurately records the
information of lake environment and climate changes and is an ideal carrier for Milankovitch cycle analysis.

3. Data and Experimental Methods

3.1. XRF Rock Core Scanning and X-Ray Diffraction Whole-Rock Mineral Analysis. Based on the elaborate description of rock cores of the lower Es3 submember (3,052-3,251 m) in Well Fanye-1, concentration, content, and types of various elements in the rock core samples were tested using the NITON XL3t-950 handheld mineral element analyzer (an instrument based on XRF spectroscopic analysis technology) developed by Thermo Scientific [37]. For observing the shortest cycle in the time series analysis, each cycle must be controlled by at least two points. Therefore, according to the Nyquist sampling theorem, the test density was appropriately 2.5 cm for each point and the test time was 20 s for each point to ensure the effectiveness of the collected data. In this study, such elements as Ti, Si, S, K, Ca, Fe, V, Ba, Zr, Mn, and Zn were mainly tested, and two methods were adopted, in which the mineral model was used for major elements and the soil model was used for minor elements less than 1%. Elements with an error of less than 10% in the test were selected in this paper.

X-ray whole-rock diffraction is a common method to determine the mineral composition of rocks. Rock samples were ground to powder with particle size less than 40 μm; a test block was made with the powder and tested by the analyzer. The integral intensity of diffraction peaks of minerals was calculated by reference to the K value of international standard samples to obtain the mass percentages of the minerals. The experimental analysis was performed using TTR-type X-ray diffractometer, and the test conditions were according to the industrial standard SY/T5163-2010 [38].

3.2. Natural Gamma Ray Logging Data. Natural gamma ray is the intensity of gamma rays emitted during the decay of radionuclides naturally existing in strata, and the natural gamma ray intensity in the logging curve is related to the contents of $^{40}$K, $^{232}$Th, and $^{238}$U in rocks. Such logging data have been widely used in the reconstruction of the paleoenvironment and the study of Milankovitch cycles [39, 40]. The logging data in this study were mainly obtained through the test of the CNPC Logging Engineering Co., Ltd., in which a data point was taken at an interval of 0.1 m and tested to obtain such logging data as GR, AC, SP, and resistivity.

4. Results and Discussion

4.1. Results of Milankovitch Cycle Analysis. The common methods in Milankovitch cycle study include logging spectral analysis, wavelet transform, digital filtering, and other methods, which can be used to extract the strata response information related to earth orbit parameters and thus determine the ages of strata in the millions of years and below [25, 41–44].

| System | Series | Group | Formation | Member | Thickness (m) | Lithology | Lithology description |
|--------|--------|-------|-----------|--------|--------------|-----------|----------------------|
| Paleogene system | Eocene | Es (Shahejie formation) | Es3 | M | 200–600 | Mud-limestone, Lime-limestone, Lime-containing mudstone, Mudstone |
| Paleogene system | Eocene | Es (Shahejie formation) | Es4 | U | 270–350 | Mud-limestone, Lime-limestone, Lime-containing mudstone, Mudstone |

Figure 2: Characteristics of stratum development in Dongying sag, Jiyang depression (revised by [32, 33, 35, 36]).
4.1.1. Logging Data Preprocessing. To reduce signal interference and ensure continuous stratum records and high credibility of the obtained results, a one-dimensional continuous wavelet toolkit provided by MATLAB was used in this paper to denoise and detrend the natural gamma ray logging data of the lower Es3 submember in Well Fanye-1 strata (3,051-3,251 m). Results are shown in Table 1.

| Depth (m) | GR/API | Denoise | Detrend | Depth (m) | GR/API | Denoise | Detrend |
|----------|--------|---------|---------|----------|--------|---------|---------|
| 3051     | 61.436 | 61.908904 | 0.0955567 | 3053.2   | 58.013 | 57.811148 | -3.957047 |
| 3051.1   | 61.614 | 61.889737 | 0.0696784 | 3053.3   | 57.739 | 57.548265 | -4.217877 |
| 3051.2   | 61.962 | 61.700265 | -1.089787 | 3053.4   | 58.012 | 58.065646 | -3.698444 |
| 3051.3   | 61.748 | 61.34055  | 0.46664   | 3053.5   | 58.373 | 59.093014 | -2.669024 |
| 3051.4   | 61.026 | 60.929643 | -0.875494 | 3053.6   | 59.625 | 60.081318 | -1.676867 |
| 3051.5   | 60.443 | 60.617078 | -1.186008 | 3053.7   | 60.369 | 60.446816 | -1.311117 |
| 3051.6   | 60.514 | 60.520643 | -1.28039  | 3053.8   | 60.8   | 60.481044 | -1.274836 |
| 3051.7   | 60.978 | 60.775733 | -1.023247 | 3053.9   | 61.044 | 60.637466 | -1.116362 |
| 3051.8   | 61.453 | 61.353604 | -0.443324 | 3054     | 61.525 | 61.381818 | -0.369958 |
| 3051.9   | 62.031 | 62.123047 | 0.3281717 | 3054.1   | 62.695 | 63.05363  | 1.303906 |
| 3052     | 63.047 | 63.13179  | 1.3389669 | 3054.2   | 64.923 | 65.440463 | 3.692792 |
| 3052.1   | 64.507 | 64.409128 | 2.6183577 | 3054.3   | 67.811 | 68.30927  | 6.563651 |
| 3052.2   | 66.004 | 65.723041 | 3.9343228 | 3054.4   | 70.531 | 70.709138 | 8.9655718 |
| 3052.3   | 66.955 | 66.844312 | 5.057646  | 3054.5   | 71.973 | 71.564115 | 9.8226015 |
| 3052.4   | 67.305 | 67.522101 | 5.7374873 | 3054.6   | 71.883 | 71.249998 | 9.5105364 |
| 3052.5   | 67.331 | 67.478868 | 5.6963065 | 3054.7   | 70.741 | 70.393862 | 8.6564526 |
| 3052.6   | 67.027 | 66.820185 | 5.0396762 | 3054.8   | 69.567 | 69.481237 | 7.7458803 |
| 3052.7   | 66.134 | 65.797358 | 4.0189016 | 3054.9   | 68.974 | 69.155916 | 7.4226116 |
| 3052.8   | 64.53  | 64.396162 | 2.6197579 | 3055     | 68.862 | 69.212349 | 7.4810974 |
| 3052.9   | 62.501 | 62.678237 | 0.903885  | 3055.1   | 68.84  | 69.146886 | 7.4176859 |
| 3053     | 60.507 | 60.855539 | -0.916761 | 3055.2   | 68.916 | 69.097946 | 7.3707986 |
| 3053.1   | 58.915 | 59.066436 | -2.703811 | 3055.3   | 69.287 | 69.173082 | 7.447987 |

4.1.2. Theoretical Periods and Characteristics of Paleogene Earth Orbit Elements. The Milankovitch theory is a method to describe the periodical changes of the three earth orbital elements (eccentricity, obliquity, and precession) caused by the changes in astronomical factors. In the current calculation methods of orbit elements, the representative solution was proposed by Bergen Berger and Laskar et al., and Laskar et al. provided an effective solution to the various influencing factors that have not been considered previously [45–47]. According to previous studies, the stratigraphic age of the lower Es3 submember in the Dongying sag is 30-40 Ma [48], so the solution of Laskar et al. [45] was used in this paper to calculate the theoretical values of changes in eccentricity, obliquity, and precession in 30-50 Ma at 38° north on summer solstice (June 21), thus finally calculating the proportional relationships between eccentricity, obliquity, and precession periods in the Jiyang depression in 30-50 Ma (Table 2). These proportional relationships were the key to identify the Milankovitch cycles.

4.1.3. Milankovitch Cycle Analysis

(1) Spectral Analysis. The REDFIT program in the Spectral Analysis module was selected for the spectral analysis on
preprocessed natural gamma ray logging data. Pink noise curve and 90% confidence interval (CI) curve, that is, the red line and green line in Figure 3, were selected in the Significance Lines window. Figure 3 is the result chart of spectral analysis of natural gamma ray logging data in Well Fanye-1, of which the x-coordinate represents the frequency and the stratigraphic cycle thickness corresponds to the reciprocal of the dominant frequency; the y-coordinate represents spectrum energy (i.e., spectrum amplitude), namely, the significance level of a certain frequency.

The spectral analysis result of natural gamma ray data of the lower Es3 submember in Well Fanye-1 showed an obvious periodicity (Figure 3), in which the cycle thicknesses of the main peaks were 38.95 m, 12.98 m, 4.10 m, 2.40 m, 1.95 m, and other values, and the cycle thickness ratio was 38.95 : 12.98 : 4.10 : 2.40 : 1.95 = 19.974 : 6.656 : 2.103 : 1.231 : 1, which is very close to 405 ka : 124.22 ka : 39.76 ka : 23.28 ka : 22 ka, the ratio of theoretical orbit periods of the Milankovitch cycle in the Paleogene (Tables 3 and 4). Therefore, the five main peaks were considered to be caused by long eccentricity (405 ka), short eccentricity (124.22 ka), obliquity (39.76 ka), and precessions (23.28 ka and 22 ka). According to the analysis, the cycle thicknesses of 38.95 m and 12.98 m corresponded to the long eccentricity period of 405 ka and the short eccentricity period of 124.22 ka, and the cycle thickness of 4.10 m corresponded to the obliquity period of 39.76 ka, while the cycle thicknesses of 2.40 m and 1.95 m corresponded to the precession periods of 23.28 ka and 22 ka. Spectral analysis results showed that the lower Es3 submember in the Well Fanye-1 may be controlled by the Milankovitch cycle, and the corresponding cycle periods and cycle thicknesses are shown in Table 4.
(2) Wavelet Transform. In this paper, the one-dimensional continuous wavelet toolkit provided by MATLAB was used for wavelet analysis. The method can provide a statistical significance test to ensure the high credibility of the obtained results. One-dimensional continuous wavelet transform was performed for the natural gamma ray logging data signal of the lower Es3 submember in Well Fanye-1 using the Morlet wavelet. Results of one-dimensional continuous wavelet transform of the logging signals of the lower Es3 submember in the Well Fanye-1 at the scale of 512 \((a = 512)\) are shown in Figure 4. The diagram shows, from top to bottom, the GR logging signal of the preprocessed lower Es3 submember in the Well Fanye-1, the time-frequency energy spectrum diagram (wavelet energy spectrum diagram) after the Morlet one-dimensional continuous wavelet transform, the wavelet transform coefficient curve at the current scale \((a = 512)\), and the wavelet transform coefficient contour map to which time-frequency energy spectrum diagram corresponds, in which the \(y\)-coordinate represents different wavelet scales.

The wavelet coefficient matrix was extracted on the basis of wavelet analysis to calculate the modulus extremum. When searching for the extremum in the average wavelet modulus value curve, to eliminate the errors and inaccuracy caused by human identification, the formula \(y = (\text{SUM}(\text{ABS}(1:n))/n\) was self-defined in Office Excel, including sum function, absolute value function, and average value operation, and \(n\) in the formula is the data value at the \(n\)th column. The modulus extremum was obtained by the formula and then was determined according to the data near the extremum for whether it is a maximum or a minimum. Figure 5 shows the modulus extremum diagram of the lower Es3 submember in Well Fanye-1 obtained by matrix calculation of

![Figure 4: Diagram of results of one-dimensional continuous wavelet transform of the lower Es3 submember in Well Fanye-1 \((a = 512)\).](image)

![Figure 5: Modulus extremum diagram of wavelet analysis of GR curve of lower Es3 submember in Well Fanye-1.](image)
the energy spectrum of different scales, and the appropriate extremum scale is selected to analyze the wavelet period of the signal.

There are two obvious modulus maximum points in the modulus extremum diagram of wavelet analysis of the GR curve of the lower Es3 submember in Well Fanye-1, corresponding to the wavelet scales of 108 and 331, and their ratio of 3.10 is almost identical to the ratio of 3.26 between the short eccentricity period (124.22 ka) and the long eccentricity period (405 ka) of the astronomical orbit period. Since the main astronomical period identified by spectral analysis also includes these two eccentricity periods, it can be concluded

| Stratum       | System  | Series | Group | Member | GR/API | Depth (m) | Lithology          | Wavelet spectrum | Eccentricity (La, 2004) | Wavelet coefficient |
|---------------|---------|--------|-------|--------|--------|-----------|-------------------|-------------------|-----------------------|----------------------|
|               | Paleogene | Eocene | Es (shahejie formation) | Lower third of shahejie | 20 | 62 |                     |                   |                       | a=108 e=124.22 ka | 108 105 |
|               |         | 1st member |        |        |        |            |                   |                   |                       | a=331 E=405 ka | 105 105 |
|               |         | 2nd member |        |        |        |            |                   |                   |                       |                      |            |
|               |         | 3rd member |        |        |        |            |                   |                   |                       |                      |            |
|               |         | 4th member |        |        |        |            |                   |                   |                       |                      |            |

**Figure 6**: Results of cyclostratigraphy analysis of the lower Es3 submember in Well Fanye-1.
that this suite of strata has preserved obvious astronomical orbit periods and is mainly controlled by long eccentricity period and short eccentricity period. The wavelet energy spectrum diagram also shows that bright energy rings are mainly concentrated near the lines with the scales of 108 and 331, indicating that the frequency near these two scales is the dominant frequency in the signal, that is, it corresponds to the short eccentricity period of 124.22 ka at the scale of 108, and the long eccentricity period of 405 ka at the scale of 331, and their wavelet curves can be seen as the cycle curves of the long eccentricity period and short eccentricity period.

(3) Cycle Period Analysis. The wavelet coefficient curves at the scales (a) of 108 and 331 were extracted, respectively, based on wavelet analysis to represent the period cycle curve of the lower Es3 submember in Well Fanye-1 (Figure 6). The number of cycle periods of the two cycle curves could be directly identified from the graphical results of cycle analysis. The number of cycle periods was 16 and 4.5, respectively, and their ratio of 3.5:1 was exactly close to the ratio of 3.26:1 between the long eccentricity period (405 ka) and short eccentricity period (124.22 ka), which further confirmed that the lower Es3 submember in Well Fanye-1 was driven by the obvious Milankovitch cycle and the main influencing factor was eccentricity.

The composite bar graph of the cyclic stratigraphic division of Well Fanye-1 was drawn based on the GR data, depth, lithology, period curves with the scales of 108 and 331 and wavelet energy spectrum map of the Lower Es3 submember in Well Fanye-1 (Figure 6). According to the figure, the long and short eccentricity periods of the strata in the Lower Es3 submember are well preserved, and the short eccentricity cycle curve is significantly modulated by the long eccentricity cycle curve, suggesting that there is a good correspondence between the two eccentricity cycle curves and the dominant component in the energy spectrum map. Appropriately 4.5 long eccentricity periods and 16 short eccentricity periods were identified in the study interval. The strata thickness of this interval was 200 m, based on which the sedimentation time of the lower Es3 submember in Well Fanye-1 was calculated to be approximately 1.905 Ma, and the average sedimentation rate was estimated to be 0.105 m/ka. In previous studies, the absolute age of the top of the upper Es4 submember in the Dongying sag was about 42 Ma according to the isotopic dating data of paleomagnetism and volcanic rocks [49], and thus, the absolute geological age of the top of the lower Es3 submember was determined to be 40.095 Ma. Then, a float geological age ruler for the study area lower Es3 submember can be established.

Cycle period analysis performed based on logging data and the methods of spectral analysis, wavelet transform, and modulus extremum contributes to cycle (sequence) division of fine-grained sedimentary strata, establishes the float geological age ruler, and determines the absolute age of strata at a certain depth point, thus calculating the sedimentation
rate. At the same time, the isochronous division and correlation of strata provides a solution to the sequence division and correlation of shale fine-grained sedimentary strata, as well as an effective method for the fine stratigraphic division and correlation, thus promoting, enriching, and improving the theory of sequence stratigraphy and its application, and promoting the exploration and development of unconventional shale oil and gas.

4.2. Environmental Response Characteristics of the Milankovitch Cycle. Semideep lake-deep lake environment of the Dongying sag is dominated by fine-grained sedimentation. Previous studies on lacustrine fine-grained rocks have shown that the sedimentation process of lacustrine fine-grained rocks with frequent lithological changes is closely related to the changes in the paleoenvironment. The evolution of the paleoenvironment tends to lead to the changes in the chemical composition of rocks, mineral composition, content of organic matter, rock type, and other aspects [50–58], so indicators such as geochemistry and mineral composition can be used to study the paleoclimate, paleowater depth, paleoredox conditions, paleosalinity, paleoproducitivity, and other aspects [56–60]. In this paper, various indicators for the changes in the sedimentary environment were selected to further explore and confirm that the sedimentary environment of lacustrine fine-grained rocks in the lower Es3 submember of the Paleogene Shahejie Formation in Well Fanye-1 of the Dongying sag was affected by the Milankovitch cycle. The results showed that there was a good correspondence between the vertical changes of some indicators and the Milankovitch cycle.

4.2.1. Environmental Response Characteristics of Long Eccentricity Cycle. A total of 4.5 long eccentricity cycles were
identified from bottom to top in the fine-grained sedimentary rock strata in the lower Es3 submember in Well Fanye-1. Based on the indicators of sedimentary environment analysis, the evolution of the sedimentary environment of the study interval is periodical (Figures 7 and 8). The environment response characteristics of the Milankovitch cycle were studied based on the results of the sedimentary environment analysis.

In a long eccentricity cycle period, eccentricity increases, due to which the amount of sunshine on the surface increases, the climate as a whole becomes warm and wet from dry and cold, and the seasonal change enhances. Thus, the long eccentricity cycle period is divided into a dry-cold climate half-period cycle and a warm-wet climate half-period cycle (Figures 7 and 8). In the warm-wet climate half-period cycle, the paleowater depth increases, the Na/Al value is low, the C value of the dry-wet index is high, the calcite content is small, the pyrite content increases, the ratios of such element combinations as Ba/Al and Al/Ti are high. The relative content of calcite sensitive to the climate environment is an important source of paleoenvironmental information. When the climate tends to be dry, the water evaporates strongly and the content of carbonate minerals (mainly calcite) is high; when the climate tends to be humid, the content of carbonate minerals is low, suggesting that the calcite content is negatively correlated to the eccentricity value. The changes of the above indicators further illustrated that the climate will develop from relatively dry and cold to warm and wet, the typical types of lithofacies associations of the lower Es3 submember in Well Fanye-1 from bottom to top are massive argillaceous limestone-bearing organic matter—bedded calcareous clay—bedded calcareous clay rich in organic matter—lamellar calcareous clay rich in organic matter—bedded lime mudstone rich in organic matter—bedded lime mudstone rich in organic matter—bedded calcareous clay rich in organic matter—bedded calcareous clay rich in organic matter (Figure 8).

According to the analysis of environmental changes in the long eccentricity period and the sedimentary environment evolutionary stages, warm and wet climate is conducive to the proliferation of organisms, that is, in the interval with a high eccentricity value, the average TOC content is relatively high, the Na/Al value is low, the C value of the dry-wet index is high, the ratios of such element combinations as Fe/Mn and (Fe + Al)/(Ca + Mg) are low, and the ratios of such element combinations as Ba/Al and Al/Ti are high. The relative content of calcite sensitive to the climate environment is an important source of paleoenvironmental information. When the climate tends to be dry, the water evaporates strongly and the content of carbonate minerals (mainly calcite) is high; when the climate tends to be humid, the content of carbonate minerals is low, suggesting that the calcite content is negatively correlated to the eccentricity value. The changes of the above indicators further illustrated that the climate will become warm and wet when the eccentricity increases and that the sedimentary environment of lacustrine fine-grained rocks is controlled by the Milankovitch cycle.

4.2.2. Environmental Response Characteristics of Short Eccentricity Cycle. Due to the significant modulation of the short eccentricity cycle by the long eccentricity cycle, environment response characteristics of the short eccentricity cycle were analyzed according to the different climate half-period backgrounds of the long eccentricity cycle. When
the long eccentricity is small, that is, when in the dry-cold climate half-period cycle, the overall background is that the Na/Al value and calcite content are low, the content of organic matter is low, the productivity is relatively low, and the sedimentary structure is mainly a bedded-massive structure. Under this background, in a short eccentricity cycle period, the climate changes from dry and cold to relatively warm and wet, thus causing the increase of Na/Al value, the decrease of TOC content, the gradual increase of paleoproductivity, the increase of calcite content, and the decrease of the C value of dry-wet index decreases, but the change is not significant as a whole. The typical types of lithofacies associations from bottom to top are massive argillaceous limestone bearing organic matter—bedded argillaceous limestone bearing organic matter (Figure 9); when the climate is very dry and cold (the top of the upper Es4 submember), bedded argillaceous rocks poor in organic matter often develop in the early stage of the short eccentricity cycle. When the long eccentricity is large, that is, when in the warm-wet climate half-period cycle, the overall background is that the Na/Al value and calcite content are low, the content of organic matter is high, and the sedimentary structure is mainly a bedded-lamellar structure. Under this background, in a short eccentricity cycle period, the short eccentricity cycle becomes large, and the climate changes from relatively dry and cold to warm and wet, thus causing the decrease of Na/Al value, the increase of TOC content, the increase of paleoproductivity, the decrease of calcite content, and the increase of the C value of the dry-wet index. At the same time, the short eccentricity cycle changes, which is accordingly reflected in the lithofacies of fine-grained sedimentary rocks, that is, the sedimentary structure changes from clearly lamellar to weakly lamellar, bedded or massive. Owing to the changes of the above material composition and sedimentary structure, corresponding types of lithofacies are formed. The typical types of lithofacies associations from bottom to top are bedded calcareous clay bearing organic matter—bedded calcareous clay rich in organic matter (Figure 9).

5. Conclusions

In this paper, the Milankovitch cycle recorded from the study interval and the environment response characteristics were studied, with the lower Es3 submember of the Shahejie Formation in Well Fanye-1 of Dongying sag, Bohai Bay Basin, as the object of the study, combining the methods of spectral analysis, wavelet transform, and modulus extremum. The study concluded that

(1) The spectral analysis, wavelet transform, and modulus extremum analyses of natural gamma ray logging data of the lower Es3 submember stratum in Fanye-1 showed that the Milankovitch cycle drove and controlled the sedimentary period of Paleogene Dongying sag

(2) A total of about 4.5 long eccentricity periods and 16 short eccentricity periods were identified in the study interval, based on which the sedimentation time of the lower Es3 submember in Fanye-1 was calculated to be appropriately 1.905 Ma, and the average sedimentation rate was estimated to be 0.105 m/ka

(3) Sedimentary environment of the lacustrine fine-grained rocks was controlled by the astronomical periods. The interval with high eccentricity values generally had higher average TOC content and C value of dry-wet index and smaller content of carbonate mineral (mainly calcite), Na/Al value, and ratios of such element combinations as Fe/Mn and (Fe + Al)/(Ca + Mg). The change of each indicator further illustrated that the climate will become warm and wet when the eccentricity increases.

Data Availability

All data in the article is presented in the form of tables and graphs. All the data in this article is accessible to readers.

Additional Points

**Highlights.** (1) Methods of spectral analysis, wavelet transform, and modulus extremum were combined to identify the Milankovitch cycle preserved in lacustrine shale strata, providing a theoretical basis and actual reference for the study of the cycle in the lacustrine deep-water fine-grained sedimentary strata. (2) Sedimentation rate of the study interval was calculated based on the absolute age of the strata determined by the isotopic dating data of paleomagnetism and volcanic rocks, facilitating the establishment of the float geological age ruler of the study area lower Es3 submember. (3) Environment response characteristics of astronomical periods were analyzed in detail, further confirming the effect of Milankovitch cycles on the evolution of the sedimentary environment of the lacustrine deep-water fine-grained sedimentary strata, thus contributing to understanding the influence of earth orbital forcing on climate and environment changes.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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