

Research Article

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Utilizing Maximum Entropy Spectral Analysis (MESA) to identify Milankovitch cycles in Lower Member of Miocene Zhujiang Formation in north slope of Baiyun Sag, Pearl River Mouth Basin, South China Sea

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Abstract: Logs in the petroleum boreholes indirectly records the sedimentary cycles in the deep burial formation. In order to extract and understand the periodicity and cyclicity, it is necessary to process the data by digital signal analysis method. Taking the gamma ray (GR) log as the primary material, an identification approach of Milankovitch cycles in boreholes is proposed in this paper, which is based on the Maximum Entropy Spectral Analysis (MESA). The first stage chooses the appropriate windows for calculating the frequency spectral properties in a short section of the data. In each depth window, the second stage generates the two-dimension frequency spectrum utilizing the MESA. At each depth point, the third stage finds the potential Milankovitch cycles in the one-dimension frequency spectrum, in which the average amplitude spectrum peak would be matched to the ratio of Milankovitch period. According to the frequency and wavelength of the maximum amplitude in Milankovitch cycles, the fourth stage estimates the sedimentation rate controlled by cyclical factor. Finally, the Milankovitch cycles in Lower Member of Miocene Zhujiang Formation in north slope of Baiyun Sag, Pearl River Mouth Basin, are identified and the cyclical sedimentation rate is estimated. The results demonstrate that the proposed method is feasible and effective to identify Milankovitch cycles in boreholes, which may contribute to the other geological researches.

Keywords: Maximum Entropy Spectral Analysis; Milankovitch cycles; cyclical sedimentation rate; Lower Member of Zhujiang Formation, Pearl River Mouth Basin

1 Introduction

Quasi-periodicity or periodicity is the common phenomenon for almost every object in the universe. Derived from the astronomical cyclical movement, the deposition processes and sediment sequences of the Earth are within the cyclicity and periodicity as well. The quasi-periodic variations of the precession, obliquity and eccentricity of the Earth orbital parameters generate different features and rhythmicity records in the sedimentary rocks, called Milankovitch cycles in geology [1]. However, the outcrops in fields and cores in petroleum wells just provide a small part of the formation. It is impossible to directly view and observe the cycles in the deep burial sedimentary rocks continuously. Fortunately, logs in the boreholes can continuously collect the features of the underground sediments, which offers other indirect materials to research the Milankovitch cycles [2–4]. These digital signals may consist by various stacked cyclical indexes, and one of the challenges is how to analyze the sedimentary records and to find the information that indicate the cyclicity in the stratigraphy and cyclostratigraphy.

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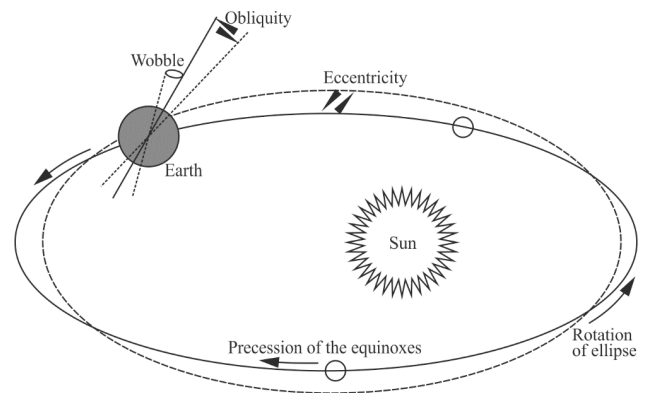
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Table 1: Part Milankovitch periods in different geological age [25].

Geological age	Eccentricity period		Obliquity period	Precession two major period	
	long	short			
Recent	413.000	100.000	41.000	23.000	19.000
Tertiary	413.000	100.000	40.000	22.500	19.000
Cretaceous	413.000	100.000	39.300	22.500	18.600
Upper-Jurassic	413.000	100.000	38.100	22.000	18.300
Lower-Jurassic	413.000	100.000	37.600	21.800	18.200
Triassic	413.000	100.000	37.000	21.000	18.000
Lower-Permian	413.000	100.000	35.145	21.034	17.638
Carboniferous	413.000	100.000	34.200	20.700	17.400

Recent advances in signal analysis provide many approaches in different theories for this problem, such as Multitaper method (MTM) [5–7], Average Spectral Misfit (ASM) [8, 9], first-order autoregressive (AR1) [10], Evolutionary Harmonic Analysis (EHA) [11], Time Scale Optimization (TimeOpt) [12, 13], Wavelet Transform (WT) [14–18], Fast Fourier Transform (FFT) [2, 4, 19] and so on. However, MTM, ASM, AR1, EHA and TimeOpt prefer discrete astronomical and climatological experimental data sampled in regularly-space [5–13], and WT and FFT, spectral analysis methods, are generally applied to continuous data in boreholes [14–18]. The primary reason for using spectral methods is the understanding that cyclical climatic changes are recorded in strata, which can therefore be expected to contain information in the frequency domain [19–21]. If a wireline log is viewed as a series of data points and a regularly-spaced sampling of a complex waveform, then spectral analysis methods are required to fully understand it.

However, WT methods have advantages in the original data with very spiky-large spikes which would dominate the frequency spectra to the point and lead to the obscure of the interesting frequencies. Although FFT may be the most familiar method in other applications, it attempts to decompose the data into exact sine waves, which are very rarely in the geological data. Maximum Entropy Spectral Analysis (MESA), another widely used spectral analysis approach, is much more tolerant of any imperfections in the expression of an underlying periodicity, such as Milankovitch cyclicity, by generating a model of the data rather than an exact decomposition mathematically [22]. Based on the MESA, a method of identifying the Milankovitch cycles and estimating the cyclical sedimentation rate in the Lower Member of Miocene Zhujiang Formation in north slope of Baiyun Sag, Pearl River Mouth Basin, is introduced in this paper.

**Figure 1:** Sketch of the Earth's orbit. The precession, obliquity and eccentricity are three important orbital parameters [24].

2 Milankovitch cycles

The Earth's orbit around the Sun is influenced by gravitational attractions of the Moon and the other planets in the solar system, which produces the quasi-periodic variations, termed Milankovitch theory, in the orbital parameters: precession, obliquity and eccentricity (Figure 1) [23, 24]. At present, the precession of equinoxes refers to the wobble of the Earth on its axis with major periods of ~23.00 and ~19.00 kyr. The obliquity, varies between 22.1° and 24.5° , is oscillation of the Earth's axial tilt with major periods of ~41.00 kyr and secondary period of ~29.00 and ~54.00 kyr. As the elliptical orbit, eccentricity varies between 0.0005 and 0.0607 with long period of ~413.00 kyr and short period of ~95.00 and ~123.00 kyr (average in 100.00 kyr) [23, 24]. At different geological age, these orbital parameters would be slightly changed (Table 1) [25].

The quasi-periodic variations of the orbital parameters directly control the all of the environment changes on the Earth [26]. Then, the environment influences all intimately linked factors eventually that directly or indi-

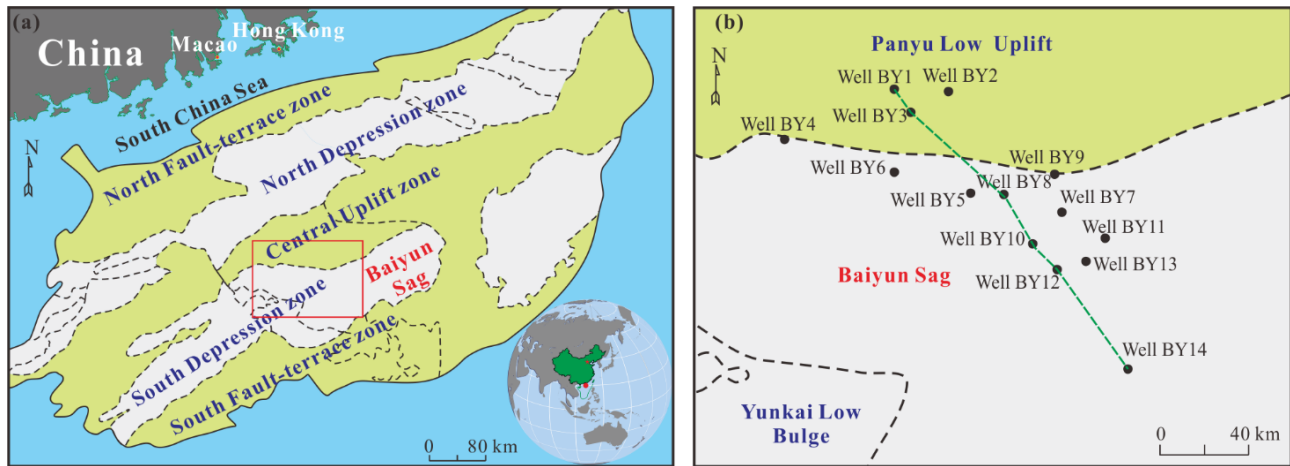


Figure 2: Tectonic features of Pearl River Mouth Basin. (a) Five major structural units in Pearl River Mouth Basin. The Baiyun Sag is in the South Depression zone. (b) Fourteen wells in research region.

rectly control sediment production, transportation and accumulation. Depending on the sensitivity of the sedimentary systems, environment forcing may exist in the stratigraphic records in continuous depositional settings where the preservation potential is high. It is clear that the strata thus indirectly reflect the orbital parameters. Although the orbital changes are not truly cyclical but quasi-periodic, it is commonly accepted by the geological community to call as “Milankovitch cycles” in the stratigraphy and cyclostratigraphy [25].

3 Geological setting

Pearl River Mouth Basin, in the continental shelf northern South China Sea, is a representative rift basin of passive continental margin. Strike in NE-SW, the basin is approximately paralleled with the shoreline of south China continent [27–29]. It is a vital offshore petroliferous basin of China. In tectonic, Pearl River Mouth Basin is divided into five major structural units from north to south: North Fault-terrace zone, North Depression zone, Central Uplift zone, South Depression zone and South Fault-terrace zone (Figure 2a) [27–29]. Each unit include several sags and uplifts furtherly. As one of the significant oil-rich sags, Baiyun Sag is in North Depression zone, encircled by Panyu Low Uplift, Yunkai Low Bulge and South Fault-terrace zone (Figure 2b).

Under adequate sediment supplying, steady formations are developed in Baiyun Sag from Eocene to Quaternary. From 32 myr, for the continuous expansion of the South China Sea, the depositional environment changed from lakes to shoreland in Eocene and Oligocene [30].

Then the Pearl River Mouth Basin turned into marine sedimentary stage, when shelf slope break zone maintained at the south of Panyu Low Uplift and north slope of Baiyun Sag (Figure 3a) [30]. Therefore, between 23.8 myr and 18.5 myr, shelf marginal delta was primarily developed to form Lower Member of Zhujiang Formation in Lower Miocene [30]. Constituted by various sands, silts and clays, the thickness of Lower Member of Zhujiang Formation is ranged from 150 m to 400 m (Figure 3b) [30, 31].

4 Database and methodologies

4.1 Database

There are over 150 petroleum wells in Pearl River Mouth Basin. As a key exploration area, dozens of wells are being drilled in Baiyun Sag in recent years. Fourteen petroleum exploitation wells crossed over the Miocene Formation in the north slope (Figure 2b). In these boreholes, besides mud log, conventional comprehensive logging programs were completed, including gamma ray, self-potential, borehole diameter, resistivity, neutron, sonic and density. As a lithological log, the natural gamma ray (GR) logging values reflect the radioactivity induced by radioactive elements U, Th and K of the rocks. In sand-shale stratigraphic sequence, during long transport, the clay and organic particles would adsorb more radioactive elements from the depositional environment, which are closely related with the change of environment and climate. For the GR log, it shows that high value in mudstones and low value in sandstones (Figure 3b). It means that the GR logging values are sensitive to the lithology which may records the sedimen-

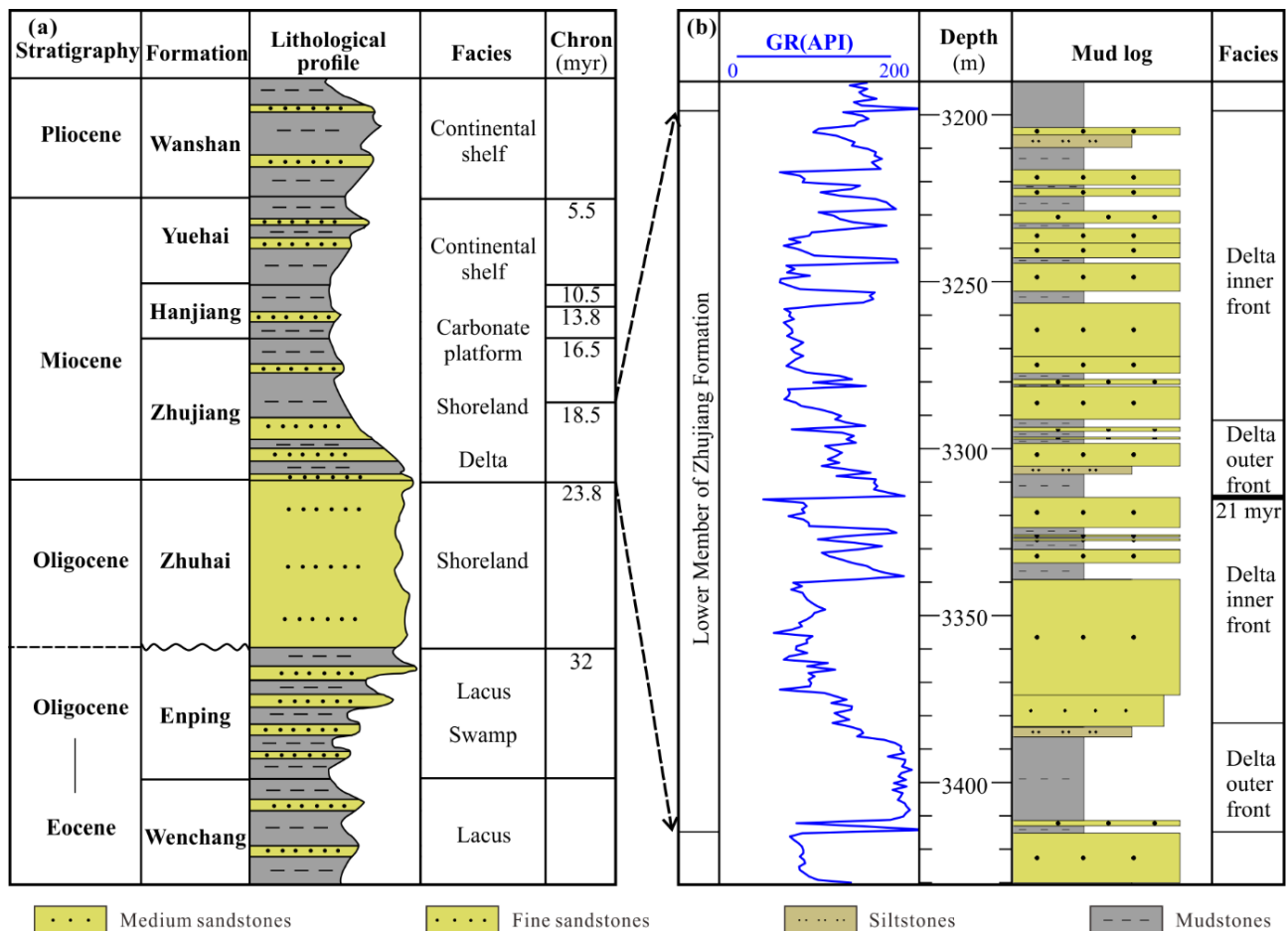


Figure 3: Formations in Baiyun Sag. (a) Formations from Eocene to Quaternary. The Zhujiang Formation is mainly formed by shelf marginal delta. (b) Lower Member of Zhujiang Formation in north slope of Baiyun Sag, Well BY9. Delta front is the dominated depositional environment.

tary cycles [3, 17, 32]. With the sampling interval in 0.1 m, this kind material provides a more detail record of sedimentation history than that determined solely based upon cuttings and limited core analyses in the overall intended formation. For these reasons, GR log is the primary material of this paper. In addition, a three-dimension seismic profile is cited in correlation wells in the discussions.

4.2 Maximum Entropy Spectrum Analysis

In information theory, entropy is defined as a measure of signal uncertainty. Proposed by Burg [33], MESA extracts the periods of different frequency from the time series, which generates the minimum of the power spectrum error and increases the resolution. It is equivalent with the autoregressive model [34]. The prediction error of logging

record x_i ($i=1, 2, \dots, N$) could be regarded as

$$e_j = x_j - \sum_{k=1}^m \alpha_k x_{j-k}, \quad j = m+1, m+2, \dots, N.$$

Taken $1, -\alpha_1, \dots, -\alpha_m$ as filtering factors and e_j as the output of the digital filter, a prediction error filter is just designed. In frequency domain, the filter is expressed by

$$E(\omega) = A(\omega) \cdot X(\omega)$$

$E(\omega)$ is the frequency spectrum of prediction error e_j , $A(\omega)$ is the frequency spectrum of prediction error filter and $X(\omega)$ is the frequency spectrum of the logging x_i . The frequency spectrum of the x_i is thus

$$S(\omega) = |X(\omega)|^2 = \frac{|E(\omega)|^2}{|A(\omega)|^2} = \frac{2\sigma_a^2}{|1 - \sum_{k=1}^m \alpha_k e^{-i2\pi\omega k}|^2}$$

σ_a^2 is the power of the prediction error filter and $S(\omega)$ is the maximum entropy frequency spectrum of the stochastic

process. It is outside the key points of this paper to derive all detail procedures that illustrate such spectral theory.

For example, a simulate log has been processed by MESA (Figure 4). The simulate log is synthesized by five logs with constant wavelengths of 41.3 m, 10 m, 4.1 m, 2.3 m and 1.9 m respectively. In the MESA spectral band, frequency spectrum generated by MESA, there are five peaks whose wavelengths are 41.3 m, 10 m, 4.1 m, 2.3 m and 1.9 m respectively. It suggests that MESA is effective to unmix the cycle property in a composite log.

4.3 Used process

Based on the GR log in boreholes, the method using MESA to identify Milankovitch cycles and estimate the cyclical sedimentation rate requires primary depositional features and comprises four stages. During the first stage, the appropriate window is chosen. Computing the frequency spectrum of an entire log would be meaningless, as the statistical properties of geological data are highly variable downhole, “non-stationary” in statistical terms. Consistency of frequency properties is much more likely in a short section of the data. Therefore, frequency spectral is analyzed in a large number of short windows, 30 m, in this paper. In the second stage, two-dimension frequency spectrum in each depth window is calculated upwards. The spectral results are characteristic for the window, and not for the window center. During the third stage, potential Milankovitch cycles in the one-dimension frequency spectrum are found. According to the geological period, the most appropriate orbital parameters should be selected first. At each depth point, average amplitude spectrum peaks would be checked whether match to the ratio of Milankovitch period carefully. If the conformance of the both is good, it will consider that the strata may dominate in the Milankovitch cycles. In the fourth stage, the sedimentation rate controlled by cyclical factor is estimated. In the Milankovitch cycles, the period in the maximum amplitude is regarded as the dominant periodicity that controls the cyclical sedimentary, and the wavelength of the maximum amplitude would imply the sedimentation thickness [25]. The approximated cyclical sedimentation rate is just the ratio of wavelength and period at the maximum amplitude [35].

5 Results

Without exposure and denudation, the sustaining marine sedimentary successions can often preserve more complete record of orbital cycles than lacustrine strata. From 23.8 myr, the north slope of Baiyun Sag was inundated by marine water and the slope break belt is appeared. Until 18.5 myr, Lower Member of Miocene Zhujiang Formation is developed in delta front facies. Between both times, there is another chronologic age recorded by seismic reflection, 21 myr, which divided Lower Member of Zhujiang Formation into two parts. Taking Well BY6 for example, each part comprises lower delta outer front and upper delta inner front (Figure 5). Thick sands would be deposited in delta inner front, and interbed of thick mudstone and thin sands may be developed in delta outer front.

In order to identify probable Milankovitch cycles in this borehole, GR log is processed utilizing MESA to generate two-dimension spectral band (Figure 5). The GR are high values in sandstone intervals and low values in siltstone and mudstone intervals. In the two-dimension spectral band, the ratio of wavelengths at each depth point should be checked carefully to judge whether match the Milankovitch periods approximating wavelengths ratio in 41.3: 10: 4.1: 2.3: 1.9. Finally, six typical one-dimension frequency spectrum at different depth point, whose wavelengths ratio of amplitude peak matches the Milankovitch periods well (Figure 5, Table 2). The maximum amplitude suggests the dominating Milankovitch period. Between the 23.8 myr and 21 myr, the dominating period is mainly ~100.00 kyr, while between the 21 myr and 18.5 myr, the dominating period is mainly ~413.00 kyr.

The abscissa axis of the amplitude peak is the wavelength, implying the sedimentation thickness during the dominating period. Taking the spectral amplitude at depth of 3432.24 m for example, five amplitude peaks are found distinctly. Their wavelengths are 40.14 m, 10.4 m, 4.03 m, 2.27 m, 1.89 m respectively, closing to the ratio of 41.3: 10: 4.1: 2.3: 1.9. What's more, the amplitude in wavelength of 40.14 m is the maximum value, which means that the major long eccentricity period ~413.00 kyr may dominate the cycles. Finally, in this interval, the sedimentation rate controlled by cycle is estimated about $40.14/413=0.0972$ m/kyr., Therefore, the cyclical sedimentation rates could be estimated at these six depth points (Table 2). Vertically, the cyclical sedimentation rates of thick sands in delta inner front are slightly greater than that of the delta outer front.

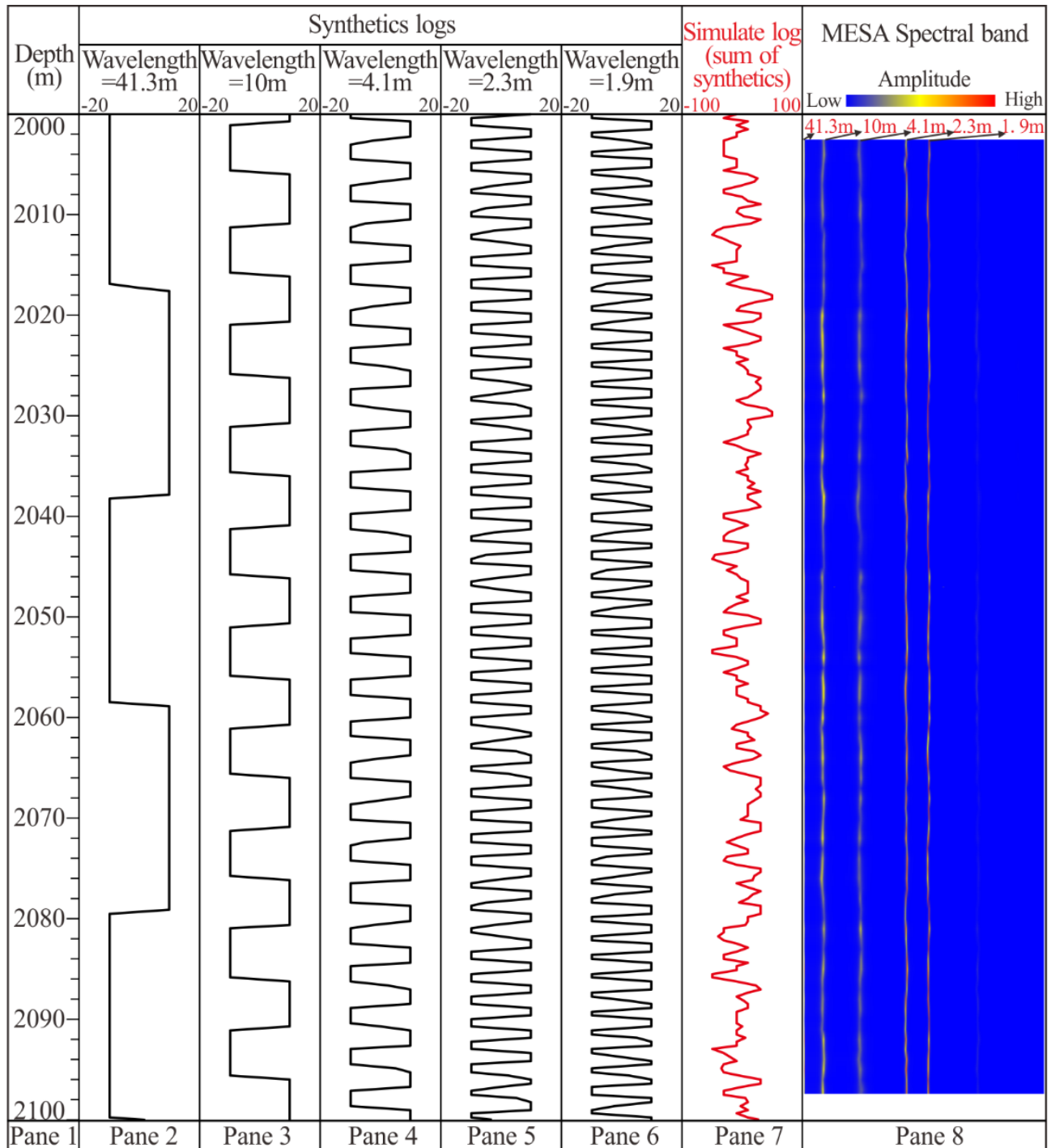


Figure 4: Spectral band of simulate log. From second to sixth pane show synthetic logs with wavelengths of 41.3 m, 10 m, 4.1 m, 2.3 m and 1.9 m respectively. The seventh pane shows the simulate log, sum of the synthetic logs. The eighth pane shows the two-dimension frequency spectral band calculated by MESA (window=30 m). High spectral amplitudes correspond to the wavelengths of 41.3 m, 10 m, 4.1 m, 2.3 m and 1.9 m respectively.

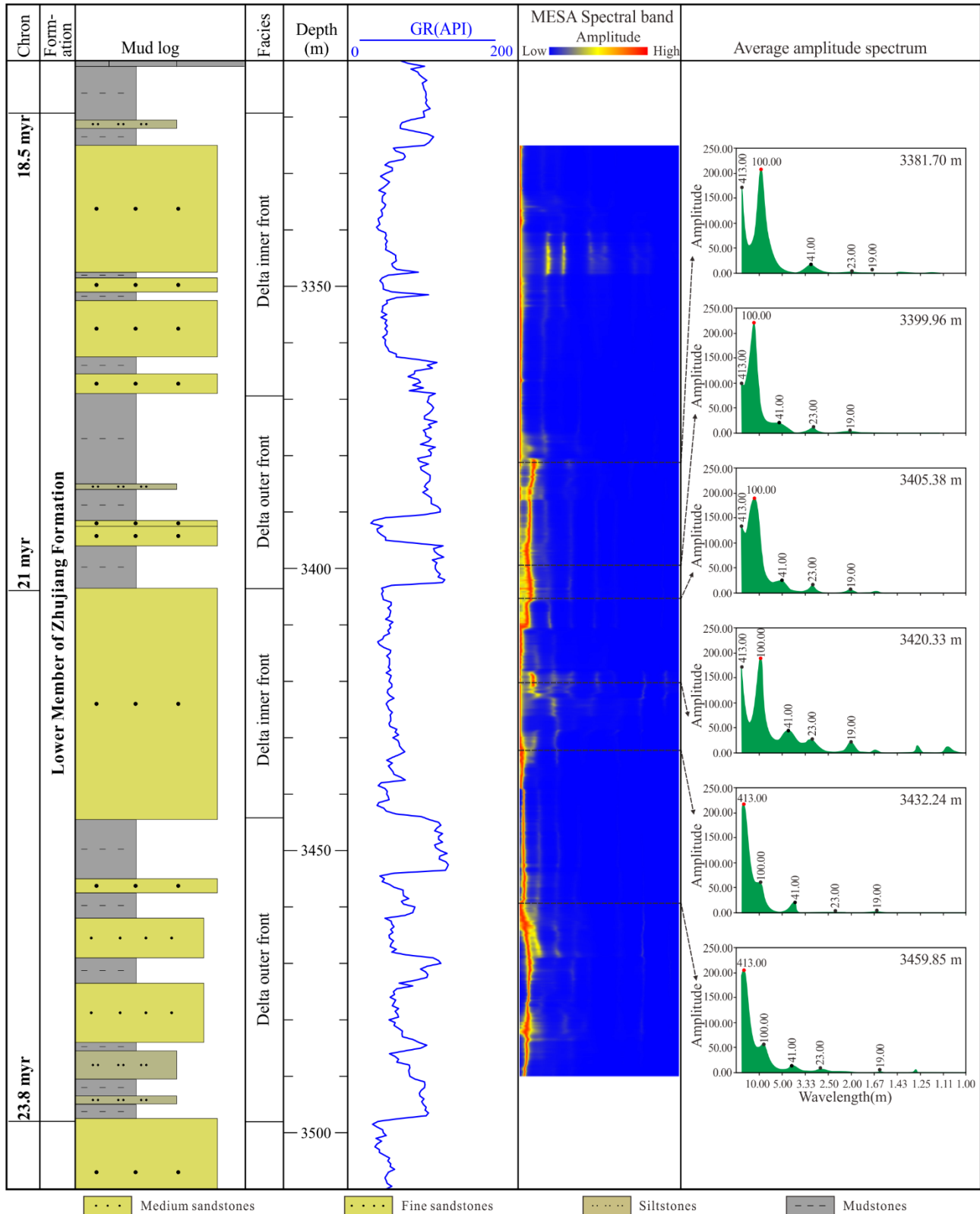


Figure 5: MESA result of Lower Member of Zhujiang Formation in Well BY6. The sandstones are in low GR values and siltstones and mudstones are in high GR values. The two-dimension frequency spectral band is calculated by MESA (window=30 m). Six typical one-dimension frequency spectrum at different depth match the Milankovitch periods.

Table 2: Parameters of Milankovitch cycles of Well BY6 in the Figure 5.

Depth (m)	Dominating frequency (kyr)	Wavelength (m)	Cyclical sedimentation rate (m/kyr)
3381.70	100.00	9.02	0.0902
3399.96	100.00	12.67	0.1267
3405.38	100.00	12.67	0.1267
3420.33	100.00	10.4	0.1040
3432.24	413.00	40.14	0.0972
3359.85	413.00	33.53	0.0812

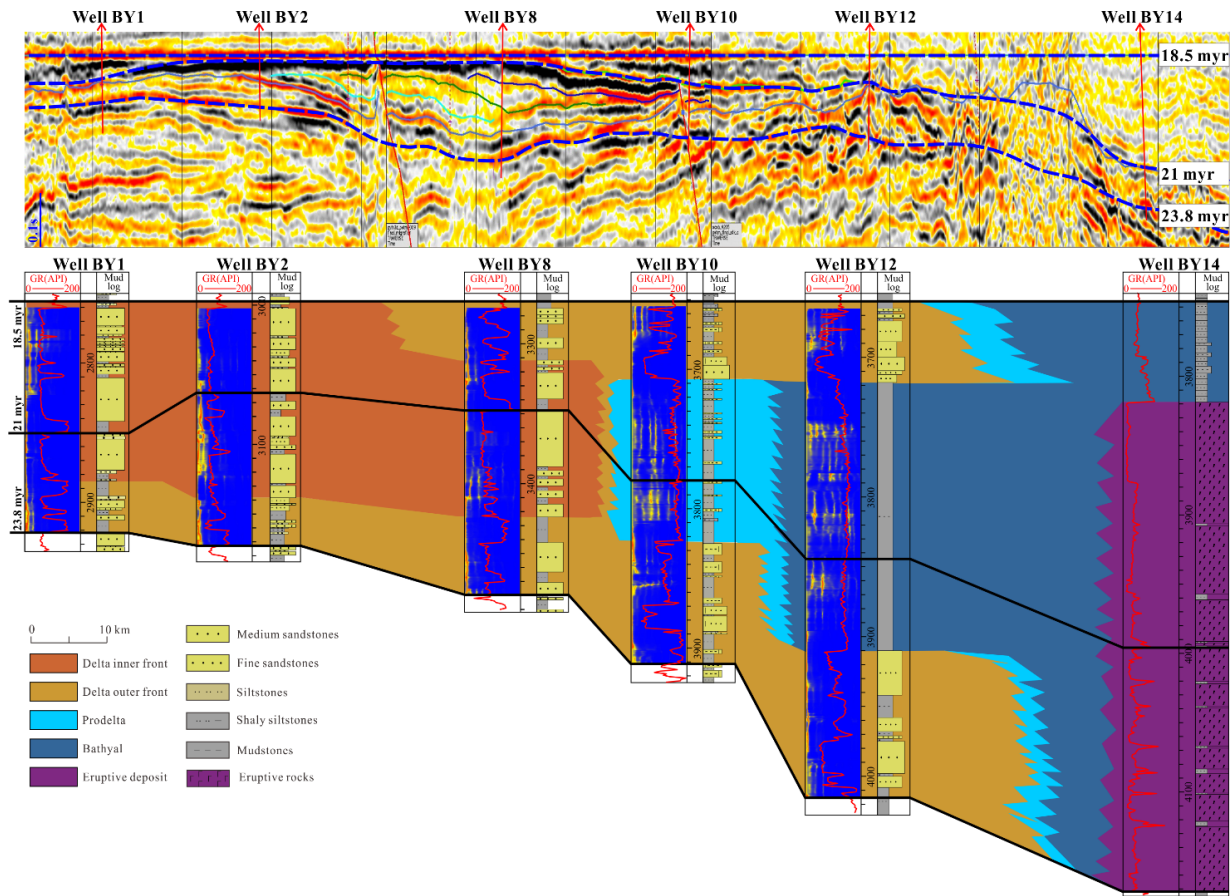


Figure 6: MESA result and microfacies of a correlation wells profile whose location can be found in Figure 2b. No MESA in Well BY14 for the eruptive deposit.

6 Discussions

The north slope of Baiyun Sag is a gently dipping monoclinal slope whose tilts towards southeast with abundant sandy sediments. Profit from three-dimension seismic data prospecting, three sedimentary boundaries are interpreted as 23.8 myr, 21 myr and 18.5 myr in the Lower Member of Miocene Zhujiang Formation. From depositional zone to bathyal region, a correlation wells profile involving six wells is built to discussed the Milankovitch

cycles in this formation (Figure 6). The linear distance between Well BY1 and Well BY14 is about 95 km. The depositional microfacies are extracted from conventional electrofacies [30, 31]. From Well BY1 to Well BY14, depositional environment changed from delta inner front to delta outer front, prodelta and bathyal gradually. The GR of five wells are processed by MESA, except Well BY14 for its partially interval is eruptive deposit. Using the method proposed in this paper, there are obvious seven, eight, six, eight and thirteen typical Milankovitch cycles found respectively in Well BY1, BY3, BY8, BY10 and BY12 (Table 2). The results

Table 3: Obvious Milankovitch cycles found in Well BY1, BY3, BY8, BY10 and BY12.

Well BY1	Well BY2	Well BY8	Well BY10	Well BY12
2778.32/100.00	3057.36/100.00	3295.19/100.00	3664.50/100.00	3687.31/100.00
9.93/0.0993	9.89/0.0989	8.99/0.0899	10.27/0.1027	10.21/0.1021
2787.56/100.00	3077.14/100.00	3317.16/100.00	3673.16/100.00	3692.31/100.00
9.74/0.0974	9.94/0.0994	9.95/0.0995	9.91/0.0991	10.18/0.1018
2808.78/100.00	3088.48/100.00	3329.56/413.00	3717.73/100.00	3755.26/41.00
12.53/0.1253	9.98/0.0998	41.13/0.0996	9.91/0.0991	3.62/0.0883
2812.73/100.00	3105.31/413.00	3353.98/413.00	3739.68/23.00	37874.91/23.00
12.62/0.1262	41.26/0.0975	40.16/0.0972	1.98/0.0861	1.92/0.0835
2895.12/413.00	3113.19/413.00	3392.19/100.00	3750.19/23.00	3811.62/100.00
39.36/0.0953	42.02/0.1017	9.94/0.0994	1.85/0.0804	8.88/0.0888
2907.69/413.00	3121.26/413.00	3426.34/100.00	3795.35/41.00	3855.62/100.00
/40.15/0.0972	40.98/0.0992	10.01/0.1010	3.59/0.0876	8.98/0.0989
2913.39/100.00	3142.25/100.00		3824.29/413.00	3863.98/41.00
10.47/0.1047	9.95/0.0995		42.19/0.1022	3.71/0.0905
	3153.35/100.00		3863.46/413.00	3886.72/413.00
	9.19/0.0919		44.08/0.1067	44.34/0.1074
				3911.83/413.00
				39.98/0.0968
				3938.39/413.00
				40.78/0.0987
				3965.51/100.00
				11.01/0.1101
				3980/72/100.00
				11.74/0.1174
				3993.47/100.00
				10.96/0.1096

Delta inner front	Delta outer front	Prodelta	Bathyal
Depth(m)/ Dominating frequency (kyr)/ Wavelength(m)/ Cyclical sedimentation rate (m/kyr)			

suggest that: 1) the dominating cycles frequency in delta inner and outer front is mainly ~413.00 kyr and ~100.00 kyr, and the concluded cyclical sedimentation rate is about 0.1 m/kyr; 2) in the mudstone of prodelta and bathyal, dominating cycles frequency is occasionally ~41.00 kyr and ~23.00 kyr, and the implied cyclical sedimentation rate is about 0.085 m/kyr.

In the stratigraphy, formation developed in the delta inner and outer front are thin than that in prodelta and bathyal, the average sedimentation rate of the former is less than that of the latter. For example, the average sedimentation rate of Lower Member of Zhujiang Formation in Well BY1 and Well BY12 is 0.0321 m/kyr and 0.0661 m/kyr respectively. However, the cyclical sedimentation rate estimated from Milankovitch cycles imply the inverse conse-

quence, which is more accord with principles of sedimentology.

7 Conclusions

A method of Milankovitch cycles identification and sedimentation rate estimation is proposed based on Maximum Entropy Spectral Analysis using GR log in the petroleum boreholes, which could be divided into four stages. Choosing the calculating windows is the first stage. Calculating the frequency and generates the two-dimension frequency spectrum in short data sections is the second stage. Finding the potential Milankovitch cycles in the one-dimension frequency spectrum at each depth point serves as the third stage. Estimating the sedimentation rate of forma-

tion in the borehole sites is as the fourth stage. In one-dimension frequency spectrum of Milankovitch cycles, the wavelength of average amplitude spectrum peak would be matched to the ratio of the Milankovitch period. The Milankovitch period of the maximum amplitude spectrum is regarded as the dominant periodicity that controls the cyclicity, and the ratio of the wavelength and period offers an approximated cyclical accumulation rate of the depth.

The proposed approach has been applied to the Lower Member of Miocene Zhujiang Formation in north slope of Baiyun Sag, Pearl River Mouth Basin. The dominating cycles frequency in delta inner and outer front is mainly ~413.00 kyr and ~100.00 kyr, and the concluded cyclical sedimentation rate is about 0.1 m/kyr. In the mudstone of prodelta and bathyal, dominating cycles frequency is occasionally ~41.00 kyr and ~23.00 kyr, and the implied cyclical sedimentation rate is about 0.085 m/kyr. This method may be feasible and effective to identify Milankovitch cycles and estimate the cyclical sedimentation rate in the marine depositional environment and be useful to other geological researches.

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