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Stratigraphic Sequence Analysis of Palaeocene in the X Sag, East China Sea Shelf Basin

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Abstract: The X sag in the East China Sea Shelf Basin has great exploration potential and rich oil and gas resources, but the exploration degree is low, and the exploration process still faces the key geological problem of inconsistent sequence stratigraphic framework. Therefore, this study is based on regional geology, logging, seismic and analysis data, using well-seismic correlation, spectrum analysis, wavelet transform, relative sea level change analysis and other methods, through the identification of sequence boundaries of seismic and drilling at all levels, supplemented by stratigraphic sequence cycle and relative sea level change analysis. According to different sequence stratigraphic models, the Paleocene stratigraphic division scheme of X sag is determined. The Paleocene strata are divided into five third-order sequences, namely Y Formation, lower L Formation, upper L Formation, lower M Formation and upper M Formation, thirteen fourth-order sequences are further identified, which Y Formation and upper M Formation are divided into transgressive system tract and regressive system tract, the lower L Formation, upper L Formation and lower M Formation are divided into lowstand system tract, transgressive system tract and highstand system tract, and a unified stratigraphic sequence framework of the whole region is established. It provides geological support for the study of sedimentary facies and its development law under the control of Paleocene stratigraphic sequence in X sag, promoting the unification of basic geological understanding of X sag and the selection of favorable areas in the next exploration work.

Keywords: Stratigraphic Sequence, Palaeocene, X Sag, East China Sea Shelf Basin

1. Introduction

Sequence stratigraphy is the most modern revolutionary innovation in the field of sedimentary geology. The emergence and development of this discipline has greatly changed the research thinking of geologists. Since Sloss (1949) put forward the concept of sequence, sequence stratigraphy has developed rapidly in the past few decades, especially the comprehensive research of a variety of data, research methods and disciplines, which has made sequence stratigraphy progress and widely used. In this process, the research work of a large number of scholars has continuously enriched the theory of sequence stratigraphy and put forward different sequence stratigraphic models [1, 2]. Different schools such as sedimentary sequence school, genetic sequence school, T-R sequence school and high-resolution sequence stratigraphy theory proposed by Cross in recent years have emerged and developed greatly. Among them, sedimentary sequence theory has continuously evolved different sedimentary sequence models [3-5]. The boundaries and system tracts of different sequence models are slightly different. The sedimentary sequence is bounded by the continental unconformity and the corresponding integration surface in the basin. According to the interface generated in the migration and change process of shoreline, the sequence is divided into lowstand system tract (LST), transgressive system tract (TST) and high stand system tract (HST), the model after the subdivision is different in the division of LST and HST, the key is that the starting position of LST is the end and beginning of base level decline. The genetic sequence is divided into early LST, late LST, TST and HST. T-R sequence is related to transgressive and regressive cycles, which is subdivided into HST and regressive system tract (RST). The core of the difference of sequence models proposed by different schools is that the sequence boundaries used in the establishment of sequence cycles are at different geological times, resulting in different conceptual packaging methods [1]. The typical interpretation basins and sequence boundaries selected by different sequence theories are different, but they all focus on the main controlling factors of sequence stratigraphic formation and the distribution of sedimentary systems in different sequence units. In the process of practical application of various theories, it is necessary to comprehensively explain the sedimentary system developed in the stratigraphic sequence framework and reasonably determine the sequence boundary according to the specific data of the study area, such as seismic, drilling and logging, analysis test and outcrop data. Only a certain model has a good effect in specific cases, and it is not a method that is applicable in all cases, each method has certain limitations. In the 1990s, a series of new theories and viewpoints were introduced into sequence stratigraphy. The proposal of relative sea level made the influence of heterologous control factors in the development of sequence stratigraphy attract the attention of researchers. At the same time, sequence stratigraphy has been comprehensively developed in theoretical research and production application. At present, the principles and research methods of sequence stratigraphy have been accepted by most geologists, and have been widely used in the exploration and development of oil and gas resources. It has played an important role in the development of sequence stratigraphy, fine characterization of sedimentary system and prediction of sand body distribution in petroliferous basins.

Sequence stratigraphy was introduced into China in the early 1990s. From basic theory to production practice, it has attracted the attention of more and more domestic scholars. At the same time, it has developed and enriched new theories and methods suitable for exploration practice in China, and also promoted the development of sequence stratigraphy [6-9]. The research results and viewpoints of these scholars jointly promote the development of sequence stratigraphy in China and the application of sequence stratigraphy in the exploration of petroliferous basins.

Predecessors have also carried out a lot of research on the sequence stratigraphy in the exploration process of X sag. Wu et al (2000) carried out the research on the Paleogene relative sea level change curve and sequence division of the East China Sea Shelf Basin based on the analysis of sea level change, paleontology and seismic interface, it is considered that L Formation and M Formation can be divided into three third-order sequences and eight fourth-order sequences [10]. Zhang et al (2012) divided the sequence boundary based on drilling, logging and seismic data, and proposed the division scheme of Paleocene stratigraphic sequence in X sag, which is divided into four third-order sequences, corresponding to Y Formation, lower L Formation, upper L Formation and M Formation respectively, they believe that sea level change and tectonism are the main controlling factors of sequence stratigraphic development [11]. Chen et al (2013) believe that the Paleocene in X sag can be divided into five third-order sequences and eleven fourth-order sequences, of which Y Formation, lower L Formation, upper L Formation and M Formation are divided into two system tracts (TST and HST), and lower M Formation are divided into three system tracts (LST, TST and HST) [12]. The previous research results and understanding of sequence stratigraphy in X sag play an important role in promoting the exploration and development of X sag. However, there are still some problems to be solved, such as the previous division scheme is not systematic and complete, the impact of relative sea level change on sequence stratigraphy is not fully considered, and the Paleocene sequence division scheme in X sag is not unified, these basic geological problems seriously restrict the overall exploration of the depression in the next step.

Therefore, in the process of practical use, the specific geological conditions of the study area should be considered, the appropriate sequence stratigraphic model should be selected, and different theoretical models should be adopted to divide the sequence according to the characteristics of relative sea level changes during the development of stratigraphic sequence in X sag.

2. Data and Methods

This paper was based on drilling, logging, micro paleontological data, geochemical element data and seismic data derived from 18 wells in the X Sag. A total of 141 samples from the M Formation and L Formation were used for geochemical analysis by X-ray diffraction and ICP-AES, paleontological indicators were used to analyze the paleontological abundance analysis, these results were used for water paleosalinity analysis to identify characteristics of relative sea level change of X Sag. The logging from 18 wells and 11 seismic interpretation profiles were used to analyze characteristics of different sequence boundaries, sequence cycles and relative sea-level change of X Sag. In particular, the spectrum properties and wavelet analysis method were used to establish the relative sea-level change curve, these data and methods will help us to understand the basic characteristics of stratigraphic development and establishment the stratigraphic framework.

3. Geological Background

The East China Sea Shelf Basin (ECSSB) is located on the continental shelf of the East China Sea, adjacent to the Minzhe Uplift in the West and the Diaoyu Island Uplift Belt in the East, it distributed in NE-SW direction, the ECSSB is the largest offshore oil and gas basin in China [13]. The X Sag is a typical Cenozoic faulted basin with the characteristics of east fault and west overlap, developed on the basement of Mesozoic residual basin. It is located in the southwest of the ECSSB, adjacent to the Zhemin Up-lift in the west, Qiantang Sag and Yushan Uplift in the north, and separated from Fu-zhou Sag in the east by Yandang Uplift. It can be divided into five secondary tectonic units: X West Sub Sag, X East Sub Sag, Linfeng Uplift, X South Sub Sag and X South Uplift (Figure 1-a) [13-15]. The sag is mainly controlled by the NE-SW multi-stage fault system. The study area is mainly distributed near the East-West Sub Sag and Lingfeng Uplift. At present, there are 18 wells in the study area, mainly located near the West Sub Sag, East Sub Sag and Lingfeng Uplift (Figure 1-b).

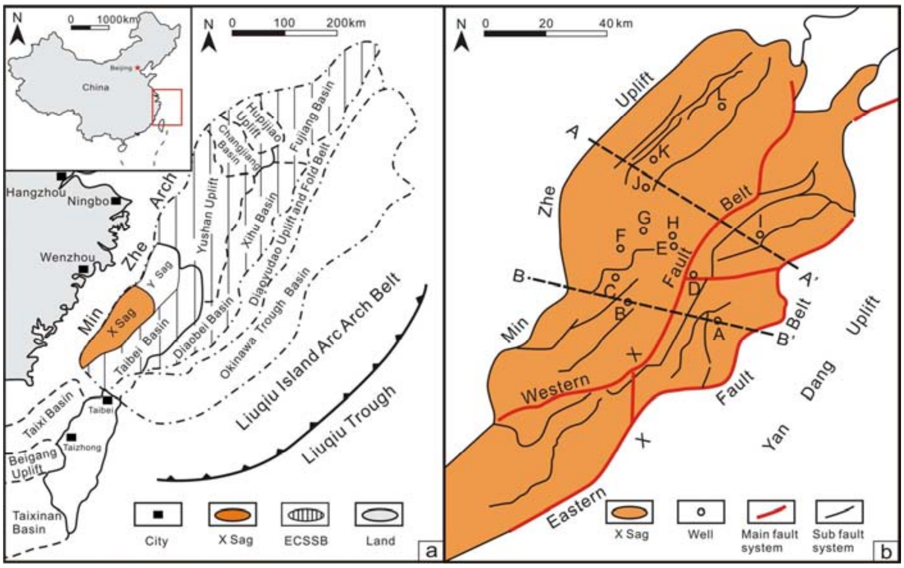


Figure 1. *(a) Tectonic location of the X Sag; (b) Structural units and well positions of the X Sag [16].*

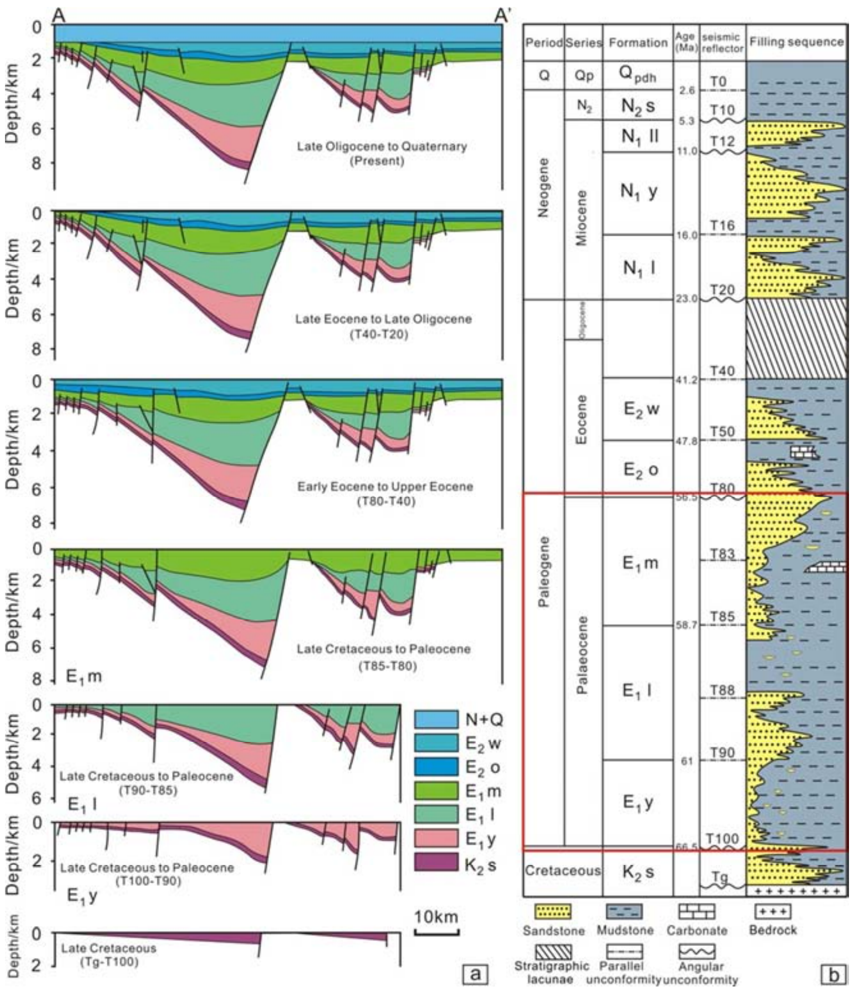


Figure 2. *(a) Evolutionary history of tectonics in X Sag; (b) Sequence stratigraphic chart of X Sag [16, 18].*

The tectonic geological background of X Sag is consistent with that of the ECSSB and can be roughly divided into five tectonic evolution stages, including: initial fault depression stage of Late Cretaceous, strong fault depression stage from Late Cre-taceous to Paleocene, fault depression transition stage at the end of Paleocene, depres-sion stage from early Eocene to late Eocene and regional subsidence stage from Neo-gene to Quaternary (Figure 2-a) [17-21]. Drilling data show that the basement of X Sag is Mesozoic extrusive rock, intrusive rock and Mesoproterozoic metamorphic rock. At present, the sedimentary stratum encountered from old to new mainly include Cre-taceous, Paleogene, Neogene and Quaternary [17-20]. The target stratum of this study is mainly the Y Formation, L Formation and M Formation of Paleocene in Paleogene, in which L Formation is divided into the upper L Formation and the lower L Formation, and M Formation is divided into the upper M Formation and the lower M Formation (Figure 2-b).

4. Results

4.1. Sequence Boundary Identification

As X sag belongs to few well exploration area, there are few coring wells drilled into Paleocene strata, and the coring is not continuous enough. Therefore, the identification of Paleocene sequence stratigraphic boundary in X sag is mainly based on geophysical data, paleontological and geochemical analysis data.

4.1.1. Logging Sequence Boundary Identification

Logging data is the reflection of underground geological information, which has the advantages of convenient acquisition, rich information, high resolution and good continuity. Through the characteristics of logging curves, some key interfaces in the process of stratigraphic deposition can be effectively identified, which is of great significance for dividing sequence stratigraphy and analyzing stratigraphic cycles [2, 22, 23]. The response characteristics of sedimentary strata during the change of relative sea level and other environmental factors can be effectively identified by logging data.

(1) Identification of maximum regression surface

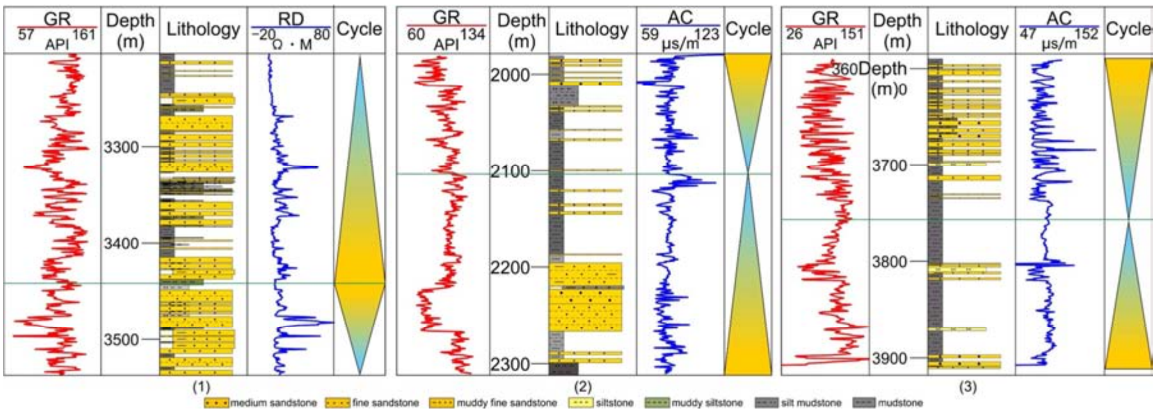
The maximum regression surface is defined according to the process of transgression and regression. This interface marks the end of normal regressive deposition and begins to change into a process of transgressive deposition. Below it is the lowstand system tract before the end of regression, and above it is the transgressive system tract after the beginning of transgressive process [2]. The sediments below the interface are aggradation to a certain extent, with medium to thick sandstone and mudstone interbedding deposition. The sediments above the interface are retrograde sequences as a whole, which is characterized by the gradual transformation of continuous thick sandstone and mudstone interbedding deposition into mudstone with thin sandstone deposition (the gradual change from yellow to blue indicates the rise of sea level, on the contrary, it indicates the decline of sea level). The GR curve transits upward from the overall toothed box or bell shape at the lower part to the sawtooth or local peak shape, the RD curve shows more right deviation peaks at the lower part and less at the upper part (Figure 3).

(2) Identification of maximum flooding surface

The most flooding surface is also defined according to the transgression and regression process, and appears in the marine sedimentary environment. The appearance of this interface marks the end of the transgression process. Below this interface is the transgression deposition process, and above the interface is the normal regression deposition process [23, 24]. According to the drilling data, the thicker sandstone or sandstone and mudstone interbedding deposits under the interface are often transformed into mudstone deposits, while the mudstone deposits above the interface are gradually transformed into sandstone and mudstone interbedding deposits, and the thicker mudstone deposits are often near the interface. In the logging curve, the natural gamma (GR) curve at the lower part of the interface shows a box or serrated transition to a toothed flat shape, while the upper part of the interface shows a gradual transition to a serrated shape and gradually increases to the left (Figure 3).

(3) Identification of maximum water surface

The interface mainly appears in the strata of the upper member of Y Formation and M Formation, corresponding to the maximum flooding surface in the process of transgression regression, and appears in the continental sedimentary environment. Below the interface is the transgressive system tract, and above the interface is the regressive system tract. Y Formation, the stratum where the interface is located, is rarely encountered in the whole area due to structural movement and other factors. At the initial stage of stratum sedimentation, it is mainly characterized by interbedding deposition of thin sand layer and mudstone. After overall water advance, it enters the water regression process, and thick interbedded deposition of sandstone and mudstone is developed. The drilling core shows coarse-grained sediments. For example, well C and other wells encounter this set of strata, and the thick sand body is relatively developed. Through the overall transgression process of the sedimentary period of L Formation and the lower M Formation, the regression occurred at the beginning of the deposition of the upper member of M Formation. This interface can also be identified in the upper M Formation (yellow to blue gradient indicates that the water level rises, on the contrary, it indicates that the water level falls). The GR curve gradually transits from the sharp peak sawtooth in the lower part to the frequent sawtooth or overall box shape in the upper part. The AC curve has similar characteristics. At the same time, the appearance of thin coal seams in the stratum indicates the lake sedimentary characteristics after the withdrawal of seawater (Figure 3).



(1) Mmaximum flooding surface, (2) Mmaximum flooding surface, (3) Identification of maximum water surface

Figure 3. *Sequence boundary of Paleocene in X Sag.*

4.1.2. Seismic Sequence Boundary Identification

(1) Characteristics and identification of third-order sequence boundary

The identification of the third-order sequence boundary of Paleocene strata is mainly manifested in the identification of a series of key seismic axes T100, T90, T88, T85, T83 and T80 seismic boundaries in the seismic profile of X sag [25].

T100 interface is the reflection of the stratigraphic boundary between S Formation of Upper Cretaceous and Y Formation of Paleocene on the seismic profile. It often shows pinch out characteristics at the boundary close to the basement, which can not be completely tracked in the whole region, and mostly changes with the fluctuation of the basement. The seismic profile shows the reflection characteristics of medium to strong amplitude, medium to low frequency, medium continuous to local intermittent (mostly affected by faults). Under the interface, the reflection is disordered and fuzzy due to the rapid deposition caused by basement uplift or fault, which is difficult to track. The erosion and undercutting characteristics caused by transgression or water intrusion can be seen locally above the interface (Figure 4).

T90 interface is the boundary between the strata of Y Formation and L Formation. This boundary cannot be completely tracked in the whole region due to the lack of strata caused by tectonic movement. On the seismic profile, the characteristics of medium frequency, relatively continuous, medium to strong amplitude reflection mainly appear near the bulge or slope zone, and the characteristics of low frequency, low continuous, weak amplitude reflection mainly appear in the middle of the sag. Due to the transgressive process, the interface has the characteristics of onlap reflection in the western slope zone (Figure 4).

T88 boundary is the internal boundary of L Formation, which can be divided into two third-order sequences, namely the lower L Formation and the upper L Formation. When the boundary is close to L Uplift, it is interrupted due to the overlying stratum overlap. Other areas can be tracked continuously, often showing the characteristics of medium to strong amplitude, medium frequency, medium continuous reflection. In some areas, especially near the uplift and east and west slope zone, it is difficult to compare due to the existence of faults. In addition, in the deep part of the sag, due to rapid sedimentation, the reflection is weak or chaotic to a certain extent, so it is necessary to track and compare carefully (Figure 4).

T85 interface is the boundary between the upper L Formation and lower M Formation. The seismic profile shows medium to strong amplitude, medium frequency, medium continuous reflection, which can be tracked and compared in the whole region. This interface is close to L Uplift and is overlapped or truncated by the overlying strata, and some discontinuities occur in the parts with strong fault activity (Figure 4).

T83 interface is part of the interface in M Formation, which separates the lower and upper parts. The seismic profile shows medium amplitude, medium frequency, relatively continuous reflection characteristics. The whole area can be tracked and compared. It is close to the middle of the sag, and the reflection characteristics of aggradation and progradation often appear on the interface (Figure 4).

T80 interface is the top boundary of M Formation, showing the characteristics of medium to strong amplitude, medium to high frequency, continuous reflection. The interface is cut off by the overlying Eocene stratum in the slope zone, showing unconformity contact, which corresponds to the regional unconformity formed by Oujiang movement, which can be identified and tracked in the whole region for the determination of sequence boundary (Figure 4).

(2) Characteristics and identification of fourth-order sequence boundary

On the premise of determining the third-order sequence boundary, in order to establish a relatively fine stratigraphic framework, it is necessary to identify the fourth-order sequence boundary (system tract). Since there are few drilling wells in X sag, the stratigraphic units of system tract are mostly divided according to seismic data (seismic reflection characteristics). Due to the different sedimentary environments of different stratigraphic units, the corresponding factors such as sediment supply and relative sea level change are also different, especially for the differences of sea or lake sedimentary environments, it is difficult to apply a certain stratigraphic sequence model or theory to identify the interface or explain the sequence cycle, when dividing the system tract, we should use the appropriate theory and model to divide the system tract according to the seismic data and the actual situation of stratigraphic development, especially the influence of the relative sea level change process on the stratigraphic development characteristics.

The seismic profile shows that during the sedimentary period of Y Formation, obvious onlap and large-scale progradation reflection characteristics can be seen from bottom to top on the western slope of the sag. The appearance of onlap reflection characteristics reflects the continuous aggradation of the stratum and can indicate the water rise process. The appearance of progradation reflection characteristics indicates the sediment accumulation process and can indicate the withdrawal of water. In view of the sedimentary environment [26] of the faulted lake basin of the Y Formation, the TST and RST of the T-R sequence model are used to characterize the regressive and transgressive systems tract in this study. The top of the onlap or the bottom of the progradational reflection is the location of the greatest lake flooding surface (Figure 4) [12].

On the seismic profiles of L Formation and lower M Formation, the occurrence of a series of foreset above the bottom boundary and foreset on the same phase axis indicates that the lower and upper of L Formation have experienced the initial regressive deposition, subsequent transgression and late slow regressive process respectively, and further divided into LST, TST and HST.

During the sedimentary period of the upper M Formation, L Uplift has been covered by the overlying strata due to the influence of tectonic movement. The strata of this period are distributed in the whole sag, and the seismic profile shows the reflection characteristics of high amplitude and high continuity, which is easy to be compared in the whole region [2]. Due to the large-scale regression after transgression, the stratum of this period has experienced a process water rise to normal water retreat in the sedimentary period of Y Formation. Therefore, the TST and RST of T-R sequence model are used to characterize the water rise and retreat in the lake. The top of the onlap or the bottom of the foreset is the position of the maximum water rise surface, the same phase axis with high amplitude and high continuity can be used as a sign of the maximum water rise surface or the initial water retreat surface (Figure 4).

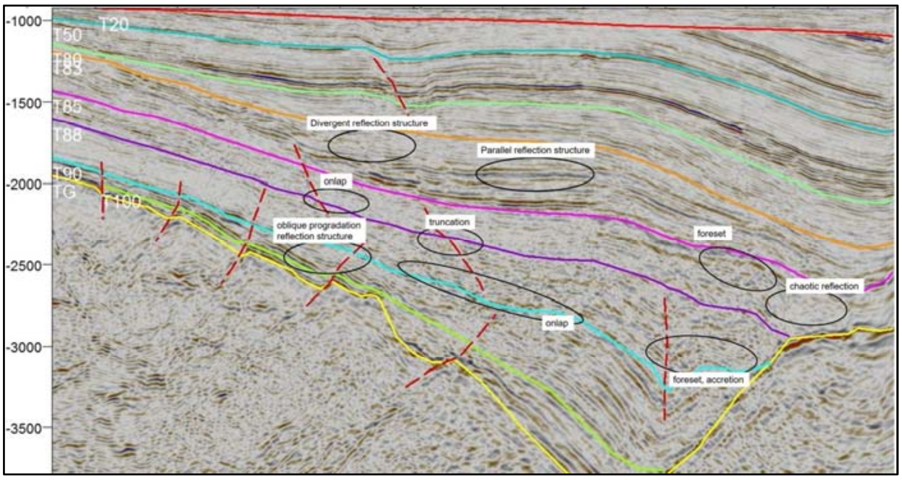


Figure 4. *Characteristics of fourth-order sequence reflection in X Sag (Inline10129).*

4.2. Analysis of Stratigraphic Sequence Cycle Characteristics

4.2.1. Spectrum Analysis

The logging curve contains the information of stratigraphic cycle. The information contained in the complex waveform of logging curve can be fully explained by relying on the spectrum analysis method. The available spectrum analysis methods include maximum entropy spectrum analysis (MESA), fast fourier transform (FFT), gabor wave conversion (GWAV), improved waveform conversion (CycloLog) and walsh conversion (WALT) And other methods [27].

By comparing the curve characteristics and drilling lithologic profile, it is found that the GR curve can accurately reflect the change of sandstone and mudstone content in the formation and is most sensitive to the change of stratigraphic sequence. Therefore, the GR curve is used to study the cycle characteristics of stratigraphy sequence by using the spectrum analysis method. Taking well A as an example, the spectrum characteristics of GR curve are analyzed by the above five methods respectively, and the MESA, Wavelet, Mod. Wavelet, FFT and Walsh spectrum with windows of 30m, 40m and 50m are obtained. The MESA spectrum with windows of 40m is the best, which can better reflect the spectrum change characteristics on the logging curve, and the effect is the most obvious. In addition, the Wavelet and Walsh spectrum are not sensitive to the logging information in the study area. The Mod. Wavelet and FFT spectrum have a good overall reflection effect and can be used as auxiliary analysis indicators (Figure 5).

Prediction error filter analysis (PEFA) is to replace the real value of each point with the value predicted by the maximum entropy spectrum, so as to obtain useful information on the continuity of stratigraphic boundary under different wavelengths [28, 29]. The PEFA curve under the condition of 9m window after median filtering is the best, and the smaller the prediction error is, the subsequent integrated prediction error filter analysis is carried out on this basis. Integrated prediction error filter analysis (INPEFA) is the integration of PEFA, which reflects the specific trend in the logging curve. The increase of INPEFA curve to the right is defined as the positive trend, and the increase to the left is defined as the negative trend [28, 29]. In the process of sequence stratigraphic interpretation of INPEFA curve, the positive trend represents an increase in the content of mudstone deposited in the stratum in an integration process or geological time period, indicating a transgression process, and the negative trend represents an increase in the content of sandstone deposited in the stratum, indicating a regression process, stratigraphic cycle analysis can be carried out according to this feature [27-29].

The spectrum analysis results show that the INPEFA trend of Paleocene strata in X sag is characterized by the trend of first positive and then gradually turning to negative. Therefore, the target strata can be divided into five third-order half cycles, corresponding to four sea-level rising half cycles and one sea-level falling half cycle respectively, which can be further subdivided into 13 fourth-order half cycles, the comprehensive spectrum analysis of each well shows that the characteristics of stratigraphic cycles are basically the same, which can be used as the basis for sequence division (Figure 5).

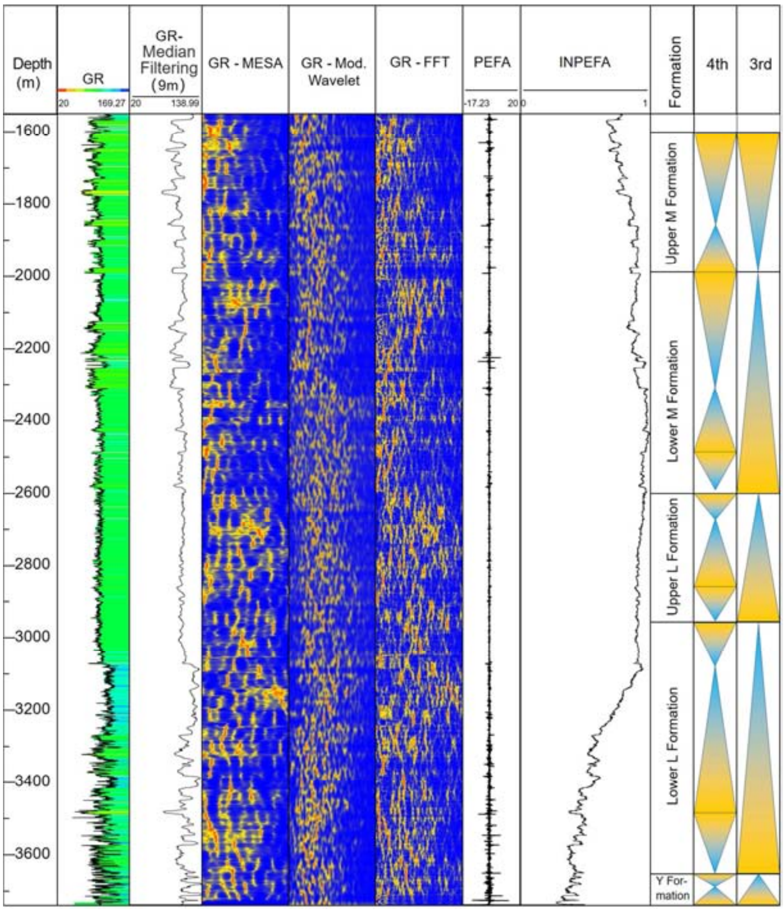


Figure 5. *Different spectrum analysis of Palaeocene in X Sag.*

4.2.2. Wavelet Analysis

The analysis of time series is often encountered in geoscience research, time domain and frequency domain are the most common forms, but these two forms have certain defects, time domain analysis can not deeply analyze the deep information of time series changes, frequency domain analysis is suitable for the stationary time series [30-31]. However, many geological problems, such as sequence stratigraphy, are the result of the comprehensive action of many factors and are a non-stationary time series. Sequence stratigraphy often has a certain tendency, periodicity and mutation in time profile. For example, sequence stratigraphy often has cycles and interface mutations due to the influence of sea-level changes and structural factors. Aiming at the time and frequency domain information required in the study of non-stationary time series between sequence stratigraphy and geological age, this study studies the time series of logging curves with the help of wavelet analysis proposed by Morlet, and makes a qualitative analysis on the change cycle and trend. The high-frequency series corresponds to the short-term stratigraphy sequence cycle, low frequency sequences correspond to long-term sequence stratigraphic cycles [30-33].

(1) Wavelet transform analysis

After the boundary effect of the logging curve is eliminated, the wavelet transform of the curve is carried out by using the Wavelet1-D function of MATLAB, and the db5 order 12 order wavelet transform is selected to obtain a group of db5 order wavelet transform curves of different levels. The transformation curves of different levels can correspond to the actual geological situation reflected by the actual sand-mud ratio, among the transformed curves with different scales, d12 curve can basically reflect a long-term sedimentary sequence of well F, d11-d9 can basically reflect the medium-term sedimentary sequence, and d8-d6 can basically reflect the short-term sedimentary sequence. After wavelet transform, wavelet coefficient analysis is needed to select appropriate coefficients to assist in the analysis of sequence cycles. Select the Morlet complex wavelet function of continuous Wavelet1-D in MATLAB to calculate the wavelet coefficients of the transformed logging curve data series, and the wavelet coefficients a at different scales can be obtained (Figure 6). It can be seen from Figure 6 that the wavelet modulus average curve under different coefficient conditions can reflect different sequence cycles (a=64, 128, 250 and 500). After comparison, a=128 can basically reflect the fourth-order sequence cycle, and a=250 can basically reflect the third-order sequence cycle.

(2) Wavelet time spectrum analysis

Wavelet coefficient a=250 is selected for time-frequency chromatogram analysis. Where the color is bright in the time-frequency chromatogram, the modulus of wavelet coefficient is large and the energy is high, where the color is dark, the modulus of wavelet coefficient is small and the energy is low. The gradual change of color from bright to dark represents the retrograde sequence cycle. At this time, the deposition rate gradually decreases and the sand-mud ratio decreases, it indicates the sedimentary process of transgression or transgression. On the contrary, it represents the progressive sequence cycle, the deposition rate increases gradually and the sand-mud ratio increases, indicating the sedimentary process of regression or transgression. Therefore, the Paleocene strata of X sag can be divided into third-order and fourth-order sequences of different levels, such as well F sequence, which can be divided into three third-order sequences and further subdivided into seven fourth-order sequences (the bottom of the target strata is not drilled) (Figure 6).

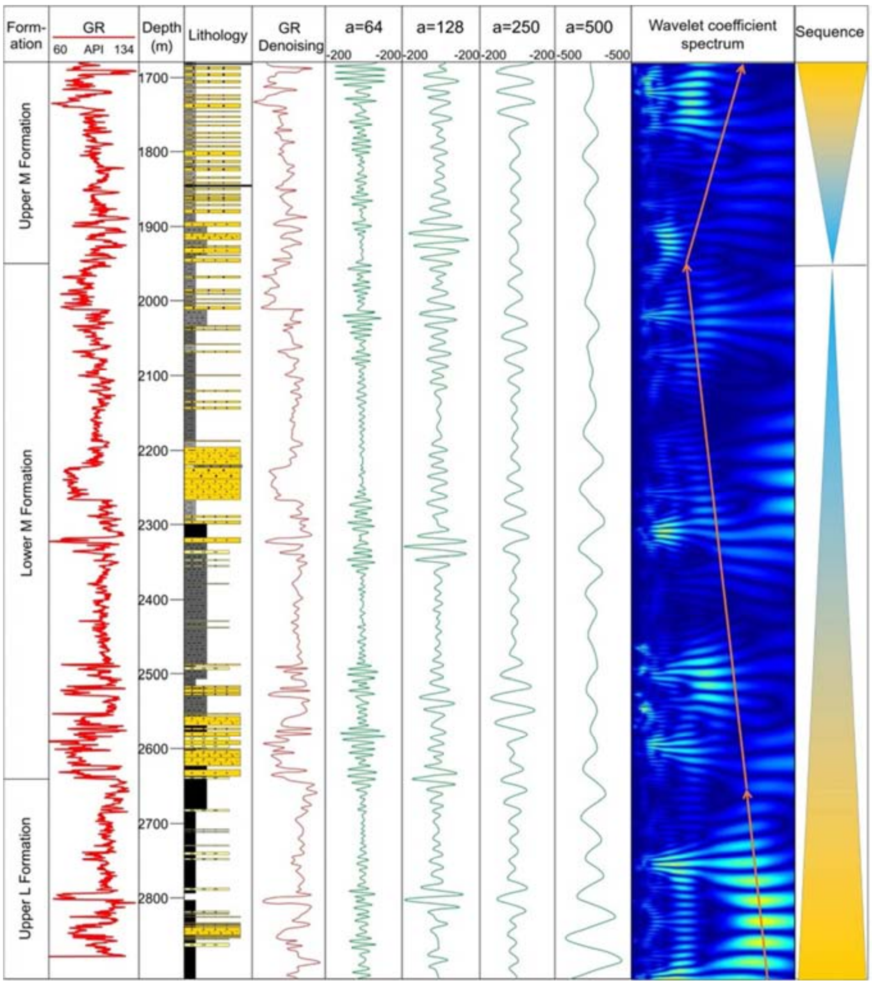


Figure 6. Seismic reflection characteristics of Paleocene in X Sag (Positions of A-D were shown in Figure 5).

4.3. Analysis of Relative Sea Level Change

Sea level change analysis plays an important role in the study of sequence stratigraphy, mainly including global sea level change analysis and relative sea level change analysis. Vail et al. (1991) considered that global sea level change is one of the main factors controlling base level change, and established and corrected the famous global sea level change curve [2, 34].

In this study, the paleontological and geochemical method are comprehensively used to establish the relative sea level (water depth) change curve in the sag, compare the change trend of it with the global sea level change curve.

4.3.1. Paleontological Abundance and Relative Sea Level

Using the paleontological identification data such as foraminifera, we can indirectly analyze the change of relative sea level (relative water depth change). Foraminifera are divided into planktonic foraminifera and benthic foraminifera. Among them, planktonic foraminifera are sensitive to the depth of water body, and their abundance often changes with the change of water depth. The deeper the water depth, the higher the abundance, and some specific species and genus combinations of planktonic foraminifera will appear in deep-water environment. In this study, the number and species of foraminifera in drilling data are identified and counted in detail, and the Paleocene planktonic foraminifera and benthic foraminifera abundance profile in X sag is established. It can be seen that the foraminifera abundance in Y Formation, the lower L Formation and the upper M Formation is low, the abundance of benthic foraminifera is about 10-20, a higher value appears in some depths, and the abundance of planktonic foraminifera is about 20, the high abundances of the two mainly occur in the lower L Formation and M Formation. The high abundances of benthic foraminifera in L Formation are about 40 and the high abundances of planktonic foraminifera in L Formation are between 40 and 80, indicating that the water depth in the study area is large during this period. From the bottom Y Formation to the upper M Formation at the top, it first increases and then decreases. Therefore, it can be inferred that the relative sea level (water depth) of Paleocene strata changes from bottom to top, which first deepens and then decreases, that is, it has experienced the process of transgression and then regression (Figure 7).

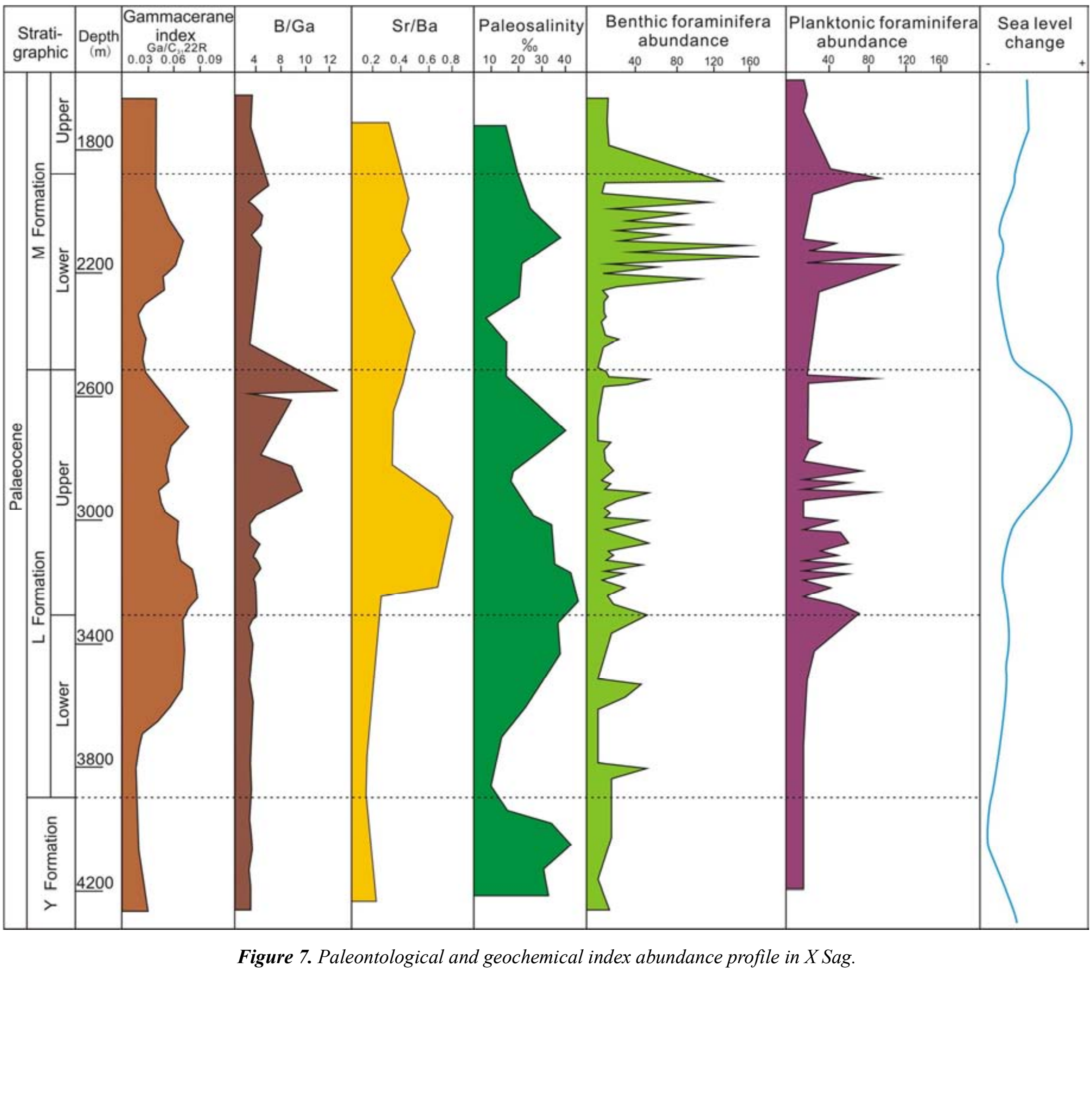


Figure 7. *Paleontological and geochemical index abundance profile in X Sag.*

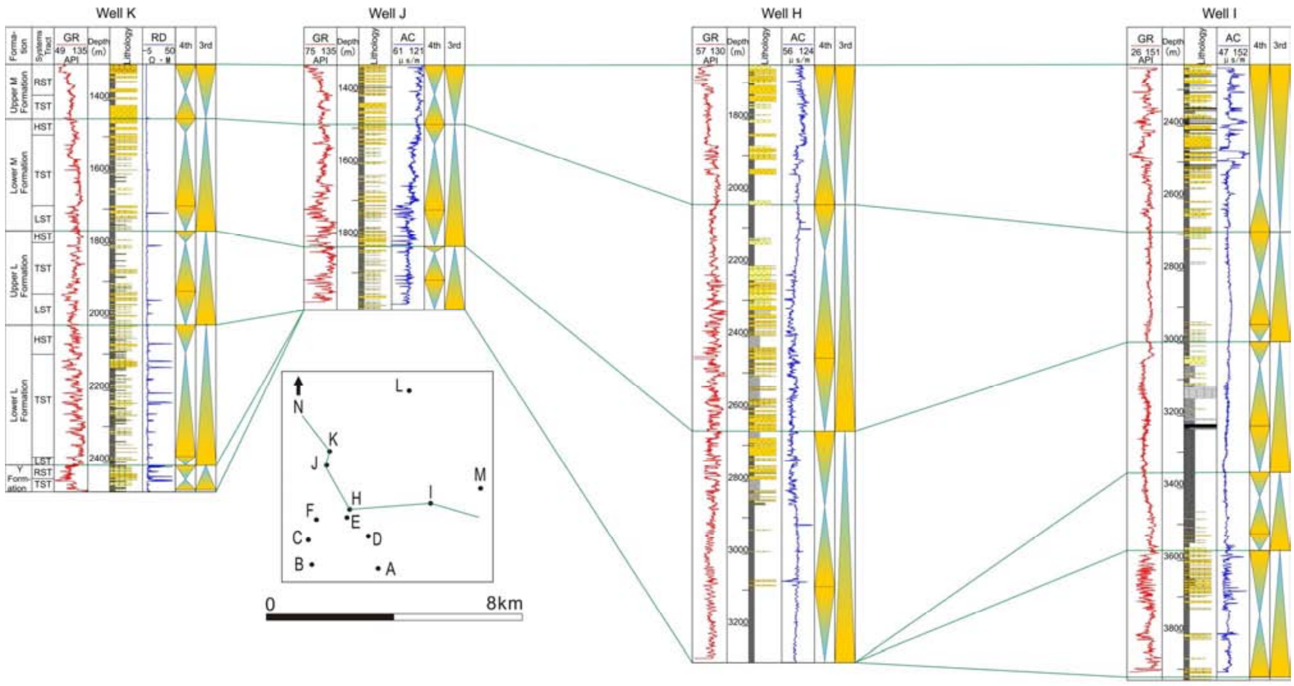


Figure 8. *Stratigraphic sequence framework in X Sag (profile 2).*

4.3.2. Geochemical Element Index and Relative Sea Level

Geochemical elements such as organic, major and trace elements in the stratum are deposited in specific sedimentary geological bodies with or after sediment deposition, which can reflect the environment of sediment deposition period to a certain extent. For example, the boron/calcium (B/Ga) and strontium/barium (Sr/Ba) ratio of mudstone can indicate the paleosalinity of sedimentary water body to a certain extent, and its ratio increases, it usually indicates the increase of paleosalinity, high salinity may indicate deep-water environment, and low salinity may indicate shallow water environment. Organic such as gammacerane index in the formation can also indicate certain environmental information. Gammacerane index greater than 0.05 often indicates marine sedimentary environment, and less than 0.05 often indicates continental environment. The higher the value, the deeper the water body may be [35-36]. From the abundance profile of paleontological and geochemical indexes, it can be seen that the high values of gammacerane index appear in the lower L Formation and M Formation, the B/Ga and Sr/Ba ratios also have the same characteristics, the paleosalinity values are slightly different, and there are some high values in Y Formation. It can be seen from various geochemical indexe, the relative depth of the water body is basically consistent with the results of spectrum attribute analysis and paleontology analysis (Figure 8).

The analysis of the relative sea level change curve during the Paleocene stratigraphic deposition period in X sag shows that the water depth from Y Formation to the upper M Formation first increases and then decreases, and the results of various analysis methods are relatively consistent. It can be compared with the global sea level change curve established by Haq (1988) and Miller (2005) [37-38]. The relative sea level change curve of sag X and the global sea level change curve have experienced the overall rising trend of sea level between 54.5ma and 60ma, but they are different on a smaller scale, indicating that the relative sea level change of sag X has a good corresponding relationship with the global sea level change at this time, which can assist in dividing the overall sequence stratigraphic cycle, After 54.5ma and before 60ma, the overall trend of the two is different, indicating that the relative sea level (or relative lake level) in the depression is less affected by the global sea level change, indicating that the sedimentary environment may be transformed into a lake basin or a basin not completely connected with the sea basin. Therefore, different sequence models can be adopted for comprehensive analysis in the process of sequence stratigraphic division.

4.4. Sequence Stratigraphic Division Scheme

According to the results of sequence boundary identification and sequence cycle analysis, assisted by the analysis of relative sea level change, the Paleocene stratigraphic division scheme in X sag is determined. The Paleocene strata are divided into five third-order sequences, namely Y Formation, lower L Formation, upper L Formation, lower M Formation and upper M Formation, and thirteen fourth-order sequences (system tracts) are further identified, the upper Y Formation and M Formation are divided into transgressive system tract and regressive system tract, and the lower L Formation and M Formation are divided into lowstand system tract, transgressive system tract and highstand system tract.

4.5. Sequence Stratigraphic Framework

Based on the single well sequence division scheme, the unified sequence stratigraphic framework of connected wells and the sequence stratigraphic interpretation framework based on seismic line and section are established.

As there are few drilling wells in X sag, the process of establishing the sequence stratigraphic framework profile of well connection follows the principle that the wells should basically cover the existing drilling and cover the main areas of east and west susag. In this study, three profiles are selected, profile 1 passes through well C-F-H-J-K-L (NE-SW), this profile is located in west subsag, Y Formation strata are encountered in well C and well K, other wells mainly encountered L Formation and M Formation. Profile 2 passes through well K-J-H-I (NW-SE), the profile crosses the east and west subsag, Y Formation is encountered in well K and I, and L Formation and M Formation are encountered in other wells (Figure 8). Profile 3 passes through well C-F-H-D-A (NW-SE), the profile is located in the southwest of the sag and crosses the east and west subsag, well C and well A encounter Y Formation. The third-order and fourth-order sequences of each connected well section are divided according to the sequence stratigraphic division scheme, and the connected well correlation is carried out at the same time. The subsequent division of sedimentary facies types and development law can be carried out in the stratigraphic framework (Figure 8).

5. Discussion

Due to the strong tectonic movement in the basin formation and stratigraphic development period, tectonic factors also play an important role in the development of sequence stratigraphy. Tectonic factors and sea-level change factors jointly control the formation of sequence stratigraphy (climate and other energy flux factors have little influence and can be ignored), therefore, the study can comprehensively reflect the relative sea level change of global sea level change and tectonic subsidence, which is more meaningful [2, 22].

Relative sea level change (which can be approximately regarded as base level change) is the change of the distance between sea level and base level (an imaginary reference plane in order to reflect all settlement relative to sedimentary compaction) [39]. Since the relative sea level change is based on the base level and the global sea level change is based on the geocenter, they do not always correspond [37]. Relative sea level change is the key to control base level and sequence division. In the analysis progress of relative sea level changes using paleontological and geochemical indicators. It is worth noting that there is a positive correlation between paleosalinity and paleowater depth, which generally occurs in the lake basin or open sea connected with the sea. For the water body not connected with the sea, due to the influence of fresh water injection, evaporation or glaciation, the relationship between paleosalinity and paleowater depth may be different. In addition, organic geochemical indicators and paleontological indicators can also be applied to the environmental analysis of continental lake basin, which is different from marine environment. Therefore, it may be better that the geochemical index and paleosalinity method be used with other methods to comprehensively judge the relative sea level change (relative water depth change) in the study area.

In addition, for the study of sequence stratigraphy in offshore oil and gas basins, due to the difficulty in obtaining core and analytical data, and more technical means need to be used to interpret seismic and logging data to help us to classify sequence.

6. Conclusion

Through the analysis of Paleocene stratigraphic sequence in X Sag, it is considered that:

(1) Through the analysis of logging sequence interface, the maximum regressive surface, maximum flooding surface and maximum water surface are identified.

(2) According to the seismic interface analysis, T100, T90, T88, T85, T83 and T80, six third-order sequences boundary are identified, 13 system tracts are also distinguished.

(3) Analysis of stratigraphic sequence cycle characteristics and relative sea level change show that the Paleocene strata experienced the process of transgression and then regression.

(4) The Paleocene strata in X sag are divided into five third-order sequences, namely, Y Formation, lower L Formation, upper L Formation, lower M Formation and upper M Formation, 13 fourth-order sequences are further identified, of which Y Formation and upper M Formation are divided into transgressive system tract and regressive system tract, and the upper and lower L Formation and lower M Formation are divided into lowstand system tract, transgressive system tract and highstand system tract have established a unified sequence stratigraphic framework in the whole region.

Conflicts of Interest

The authors declare that they have no competing interests.

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