

Ordos Basin, Dingbian Brick Well Block, Chang 7 Member: High-resolution Sequence Stratigraphic Division Using INPEFA

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Abstract: The tuff marker bed of Chang 7 Member of Yanchang Formation in the Ordos Basin is superimposed in multiple periods, and the shale layer system has significant time-crossing filling characteristics. There is great uncertainty in the isochronous comparison of the sub-members of the traditional lithostratigraphic method. Based on the natural gamma logging curve of drilling in Dingbianzhuang well block, the comprehensive prediction error filtering analysis (INPEFA) technology is used, supplemented by the constraint of tuff marker layer, and the high-resolution sequence division is carried out for the sub-members of Chang 7₁, Chang 7₂ and Chang 7₃. The results show that the Chang 7 oil layer group belongs to a long-term base level descending half cycle as a whole, and two fourth-order sequences can be divided inside. The lower fourth-order sequence consists of a complete symmetrical cycle composed of the Chang 7₃ progradational sequence group and the Chang 7₂ regressive sequence group, with the maximum regressive surface located in the interior of Chang 7₂. The upper fourth-order sequence corresponds to Chang 7₁, and only the ascending half cycle is retained. The fifth-order sequence is divided into : 1 progradational parasequence developed in Chang 7₃, 2 parasequence developed in Chang 7₂, and 2 regressive parasequence developed in Chang 7₁. The INPEFA trend curve quantitatively reveals differences in cyclic structure among the three sub-members: a continuous negative trend in Chang 7₃ indicates progradation, with a positive trend shift at the top marking the terminal flooding surface; in Chang 7₂, the lower part continues the negative trend while the upper part shifts to positive, with the minimum at the trend transition pinpointing the maximum regressive surface; Chang 7₁ is dominated by a positive trend, with stepwise rise interrupted by two negative deflections, each corresponding to two brief provenance progradation events during the lake transgression. Sequence boundaries at all levels can be traced and correlated across the study area. This division scheme provides a quantitative basis for isochronous stratigraphic correlation in deep-water fine-grained sedimentary areas that does not rely on static lithological boundaries.

Keywords: Chang 7 oil-bearing formation; Dingbian Brick Well Block; INPEFA curve; high-resolution sequence stratigraphy.

1. Introduction

The concept of sequences originated from Sloss (1963), who formally named the giant cyclic sedimentary sequences bounded by unconformities within the North American Craton as stratigraphic units[1]. Vail et al. (1977), based on seismic stratigraphy, defined it as "a genetically related succession of strata bounded by unconformities or their correlative conformities" and established the Exxon model by linking a threefold division of systems tracts to global sea-level changes[2]. This model was systematically introduced into China through translation by Xu Huai-da and others in the late 1980s to early 1990s. Liu Bao-jun, Li Si-tian, and others pioneered its application in Mesozoic–Cenozoic continental basins in China, revealing the limitations of the marine model and promoting the development of continental sequence stratigraphy[3–5]. Deng Hong-wen, Zheng Rong-cai, and others introduced Cross's base-level cycle concept, advancing the application of high-resolution sequence stratigraphy in fine correlation and reservoir prediction in petroliferous basins[6,7].

The semi-deep lake-deep lake facies organic-rich dark shale is developed in the Chang 7 member of the Yanchang Formation in the Ordos Basin, which is the main source rock and the core layer of shale oil exploration in the Mesozoic basin. The accuracy of sub-stage fine stratigraphic division directly restricts the distribution tracking of high-quality source rocks, the prediction of gravity flow sand bodies and

the trajectory optimization of horizontal wells. The sedimentary facies of continental lake basin is characterized by rapid phase change, multi-stage superposition of tuff marker layers, wide distribution of zircon U-Pb age (about 226-241 Ma), and significant uncertainty in sub-stage isochronous correlation. Traditional rock stratigraphic methods are difficult to meet the accuracy requirements. Integrated prediction error filter analysis (INPEFA), as a numerical processing method of logging curves for cyclic stratigraphic division, was proposed by Nio (2005) on the basis of maximum entropy spectrum analysis. Through the autoregressive prediction of logging curves and the construction of prediction error integral sequence, the INPEFA curve representing the continuous change of sedimentary trend was obtained [8]. Domestic scholars have applied this technology to high-resolution sequence identification of multiple sedimentary backgrounds. Jin Si-ding et al. combined INPEFA with wavelet analysis to accomplish third-order sequence division of the Lower Carboniferous Dawuba Formation shale in southwestern Guizhou[9]. Liu Yu-feng et al. integrated continuous wavelet transform with INPEFA trend analysis in the Kalashayi Formation of the Tarim Basin to systematically divide long-term, medium-term, and short-term base-level cycles[10]. Li Yuan-liang et al. demonstrated in the Dongpu Depression that GR-INPEFA curves provide higher accuracy and resolution in identifying medium- and short-term cycle boundaries compared to raw GR curves[11]. Previous studies, based on

lithologic marker beds such as tuff interbeds and condensed sections of flooding surfaces, established a basin-wide, approximately parallel, constant-thickness lithostratigraphic framework for the Chang 7 Member. Three-dimensional seismic data reveal that progradational reflections in the northeast pinch out wedge-shaped toward the southwest deep-lake area, indicating that the strata are not isochronous. The originally defined shale series of the Chang 7 oil-bearing formation is in fact a diachronous succession composed of multiple medium-term cycles deposited from the lower slope to the basin-floor area. The wide range of zircon U-Pb ages of tuffs further confirms multi-phase superimposition and diachroneity, restricting the accuracy of regional isochronous stratigraphic division.

The advantages of INPEFA for sub-member sequence division of the Chang 7 Member are as follows: it uses conventional GR curves as input, does not rely on cores or

outcrops, making it applicable to exploration areas with high drilling density but uneven core distribution; the overall trend and local inflection points of the curve quantitatively indicate base-level rise–fall transitions, meeting the need for high-frequency cycle identification in intervals with scarce marker beds and complex facies changes; it replaces static lithological boundaries with continuous trend patterns for multi-order cycle identification, effectively overcoming the diachroneity challenge in isochronous correlation.

2. Regional Geological Setting

The study area is located in the central-western part of the northern Shaanxi slope, a first-order tectonic unit of the Ordos Basin, structurally belonging to the Dingbian platform[12–14]. The target interval is the Chang 7 sub-member of the Triassic Yanchang Formation. The overall structure presents an "east high, west low" pattern[15,16].

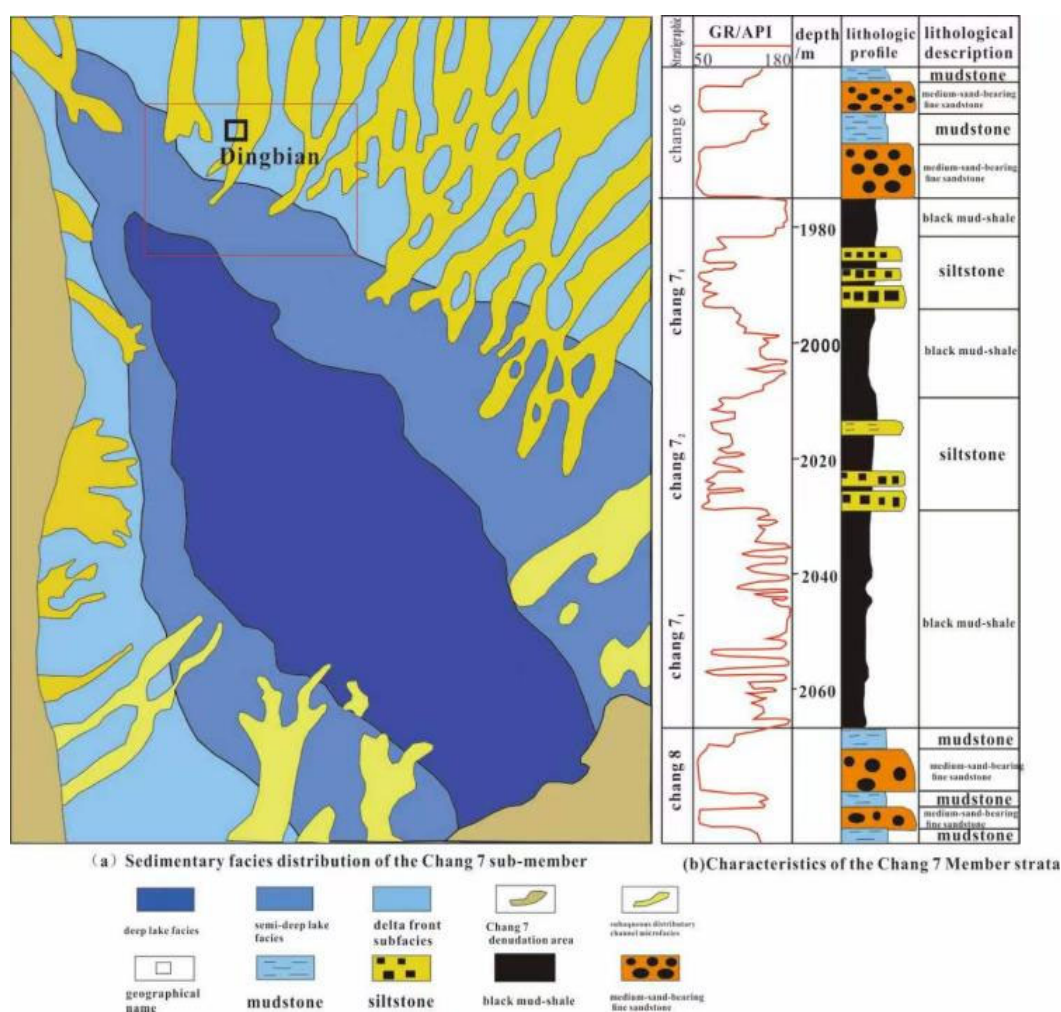


Figure 1. Sedimentary facies distribution of the Chang 7₃ sub-member (Fu Jinhua et al., 2023)

Regionally, 4–6nose-like structures are locally developed, distributed across various parts of the study area, but these structures have small amplitude, narrow width, and limited influence[13,15].

The Chang 7 Member was deposited during the Late Triassic maximum flooding period of the Ordos Basin, representing the product of the Yanchang Formation's lacustrine development peak[17–19]. During this period, semi-deep to deep lacustrine deposits were widely distributed, covering an area of approximately $6.5 \times 10^4 \text{km}^2$, with paleo-water depths estimated at 60–120m[18–20]. Sedimentary

facies are dominated by delta front and semi-deep to deep lacustrine settings[21,22]. Lithologically, a set of organic-rich dark mudstones and shales was deposited, interbedded with thin layers of siltstone and fine sandstone[17–23], forming the most important source rock series of the Mesozoic in the basin and also a key target interval for shale oil exploration [24–26].

3. Data Processing Methods

In the first half of the 20th century, Serbian astrophysicist Milankovitch systematically demonstrated from celestial mechanics the modulation effect of quasi-periodic

fluctuations in Earth's orbital geometry on global insolation distribution, and quantitatively defined the characteristic periods of three orbital parameters: eccentricity (~100kyr and ~400kyr), obliquity (~41kyr), and precession (~23kyr and ~19kyr)[27]. By driving glacial–interglacial alternations and sea-level changes, these parameters leave rhythmic lithological, grain size, or geochemical cyclic imprints in sedimentary systems, forming identifiable and correlatable isochronous stratigraphic records[28,29]. Thus, Milankovitch cycle theory serves as a natural astronomical "timer" for high-resolution stratigraphic division and global correlation[30,31]. In practical application, continuously measured well logs (e.g., natural gamma ray) convert lithological alternations into a quasi-time series in the depth domain, enabling the detection and extraction of orbital cycle signals using mathematical tools such as spectral analysis and wavelet transforms, thereby providing a quantitative basis for constructing floating astronomical time scales and inter-well isochronous stratigraphic correlation[32–34].

INPEFA (Integrated Prediction Error Filter Analysis) technology was proposed by Dutch scholar S.D.Nio in 2005. The core is to perform maximum entropy spectrum analysis on lithology-sensitive logging curves, implement prediction error filtering to obtain PEFA curves reflecting sedimentary discontinuities, and then integrate and normalize them to generate INPEFA curves, and quantitatively identify sequence boundaries and base-level cycles with trend inflection points [35]. This technology was introduced into China after 2008 [36], and was rapidly popularized in high-resolution sequence division and reservoir prediction in continental basins. The classical application of focuses on the fine identification of sequence boundaries and system tract boundaries, the establishment of high-resolution isochronous stratigraphic framework [37,38]. Its advantage is to transform qualitative cycle analysis into computable trends and inflection points, and is sensitive to hidden discontinuities. And only rely on conventional logging data, low cost and wide application [39]. In the analysis, the natural gamma curve is selected after preprocessing, the maximum entropy spectrum is calculated in the sliding window and the linear prediction filter is constructed. The difference between the measured value and the predicted value is obtained point by point to obtain the PEFA peak, and the cumulative integral is standardized to form the INPEFA curve. According to the positive and negative directions of the trend, the increase or decrease of the allowable space is indicated, and the sequence boundary and the flood surface are located by the inflection point, and the base level cycle division of different levels is completed [35-36].

4. Stratigraphic Division

4.1. Marker Bed Characteristics and Basis for Stratigraphic Division

In the long-term exploration and development practice, a total of 10 sets of K0-K9 marker layers that can be used for regional comparison have been identified in the Yanchang Formation. According to the lithology and genetic characteristics, these marker layers can be divided into two

categories : one is tuffaceous rocks related to volcanic eruption activities, and the other is gray-black mud shale and oil shale.

This fine division and comparison of small layers mainly uses K1 and K2 two sets of marker layers as the key basis for horizon identification and stratigraphic correlation. Its main features are as follows.

1) Marking layer

1 The K1 marker layer is located at the bottom of the Chang 7 member. The lithology is mainly black mudstone, carbonaceous mudstone and oil shale, and the thickness is generally 2-10 m. Its logging response is characterized by high acoustic time difference (AC), high natural gamma (GR) and high resistivity. The marker layer is stable in the study area and has a good contrast effect, which can be used as an important datum for profile comparison and structural mapping.

The K2 marker layer is located at the bottom of the Chang 6 section, which is an important interface for dividing the Chang 6 section and the Chang 7 section. Its lithology is mainly gray-black mudstone, tuffaceous mudstone, carbonaceous mudstone and silty mudstone. The logging response characteristics are characterized by high acoustic time difference, high natural gamma, high natural potential, low resistivity, low induction, low density and thin layer sharp knife-shaped large hole diameter. The marker layer is clearly identified in the study area and has good comparative significance.

2) INPEFA cycle recognition and fifth-order sequence division

INPEFA is a method for cycle signal enhancement and trend extraction from well logs. The basic procedure involves performing prediction error filter analysis on a well log (primarily GR in this study) and integrating to obtain the INPEFA trend curve. The overall direction of the INPEFA curve directly reflects the long-term change of base level: a negative trend (curve turning left) represents base-level fall, shallowing of water, and progradation of sediments toward the basin, recording a regressive semi-cycle; a positive trend (curve turning right) represents base-level rise, deepening of water, and retrogradation of sediments landward, recording a transgressive semi-cycle. A complete positive-to-negative trend shift often corresponds to a complete base-level rise–fall cycle. Trend inflection points (turning points) of the INPEFA curve correspond to positions where depositional regime fundamentally changes, and can be used to calibrate key surfaces in sequence stratigraphy: an inflection from negative to positive trend corresponds to the transition from base-level fall to rise, indicating a sequence boundary or maximum regressive surface, and is a preferred surface for sequence division; an inflection from positive to negative trend corresponds to the transition from base-level rise to fall, indicating the maximum flooding surface, enabling systems tract division. The order of an inflection is controlled by the integration window length of the INPEFA curve: a long window yields inflections corresponding to long-term cycle boundaries, while a short window corresponds to medium- or short-term cycle boundaries.

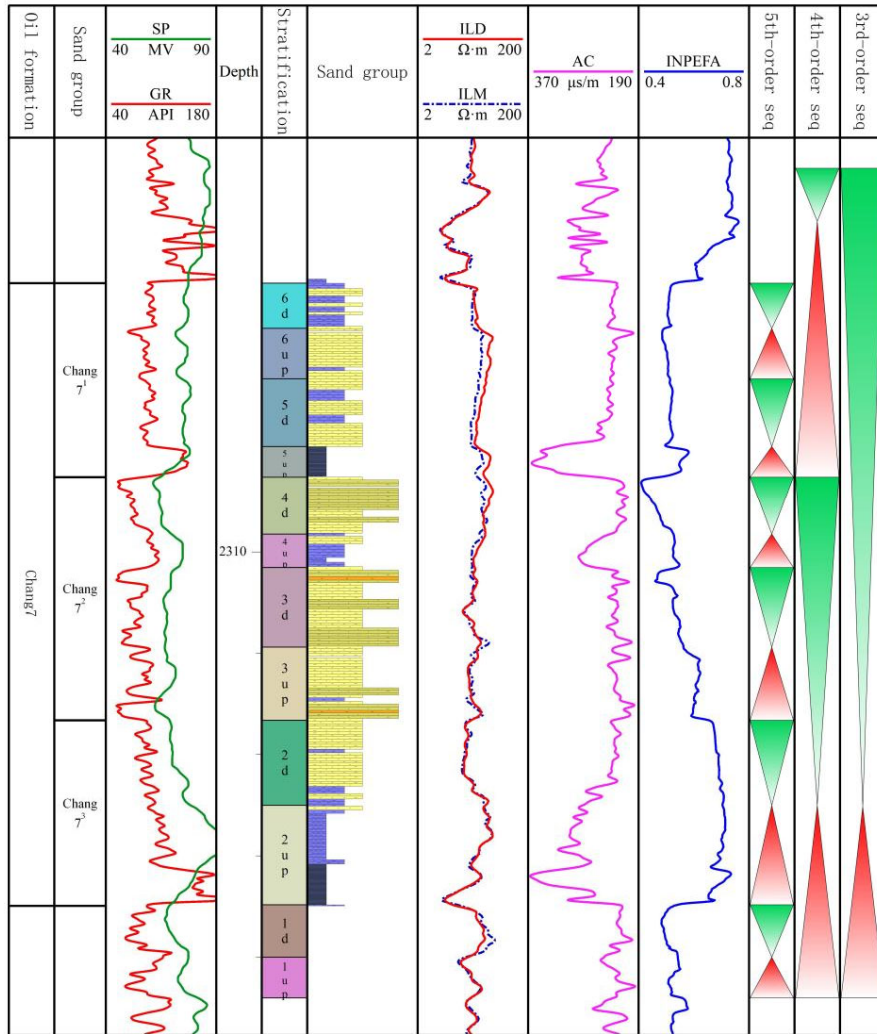


Figure 2. Single-well subdivision scheme in the Brick Well Block area

Combined with the characteristics of thin interbeds in the Chang 7 section of the study area and the fine correlation requirements of this study, this paper uses INPEFA curve to identify internal sedimentary cycles and fifth-order sequence boundaries. The specific identification process is as follows :

① Data preparation : Select representative wells (standard wells) with complete logging series and relatively stable borehole conditions for INPEFA processing ; the input curve is mainly GR, and combined with AC, SP, resistivity and other curves to review, identify and eliminate the local abnormal inflection points caused by non-formation factors such as hole diameter expansion and mud invasion.

② Interface identification : identify the transition position and significant inflection point of the trend segment of the INPEFA curve between the top and bottom interfaces of Chang 7 anchored by K1 / K2 ; the inflection point is taken as the candidate point of the cycle boundary, and its traceability in the adjacent well is taken as the validity criterion. In general, the larger inflection point corresponds to a higher level of sequence interface, and the smaller inflection point corresponds to a lower level of cycle interface. In thin interbeds, the inflection point position needs to be compared with the ' high GR / high AC mudstone section and sand-mud combination mutation section ' to avoid short-period noise as an interface.

③ The INPEFA identification characteristics of the base level cycle and the fifth-order parasequence of the Chang 7 submember :

The lithology of the Chang 7 third sub-section gradually changes from the lower dark mudstone and shale (high GR) to the upper siltstone and sandstone (low GR), forming a typical upward coarsening sequence, which belongs to the progradation cycle macroscopically. The INPEFA curve shows a negative trend of continuous decline, which corresponds to the continuous decrease of GR value, indicating that the water body is shallower and the sediment is advancing towards the lake basin. The bottom boundary of this sub-section is located at the top of Zhangjiatan shale, corresponding to a large-scale lake flooding event. In the INPEFA response, it is an inflection point from the maximum value to the minimum value, and it is the conversion surface from the rising to the falling base level. Under this progradation background, the five-stage cycle is superimposed on the overall negative trend, which is manifested by the multi-stage local small positive deflection during the decline of INPEFA. The vertex of each positive deflection is a secondary lake flooding surface, which constitutes the top boundary of the progradational parasequence. The inner part of the cycle has the characteristics of lower fine and upper coarse, from thin mudstone or silty mudstone to siltstone and fine sandstone,

showing a superimposed upward shallowing sequence.

The Chang 7_2 sub-member is a composite cycle, the lower part shows progradation, the upper part shows retrogradation, and there may be aggradation section in the middle, which constitutes a symmetrical regression-transgression sequence as a whole. The trend of INPEFA in the lower progradation section changes from stable to decreasing, corresponding to the half cycle of base level decline, and its minimum value is located at the most developed place of sandstone. The trend of INPEFA in the upper retrogradation section changes from decline to rise, corresponding to the semi-cycle of base level rise. The minimum value at the turning point indicates the maximum water regression surface, which is the key interface for dividing progradation and retrogradation. The top boundary of 7_2 is located at the end of the retrogradation section, and the INPEFA reaches the maximum value of the first order, which represents the rapid lake intrusion event. It is also the boundary between 7_2 and 7_1 . The characteristics of the fifth-order cycle are divided into two sections : the lower progradational semi-cycle is superimposed with multiple small positive deflections in the overall downward trend, and each vertex is the interface of the transient water deepening event ; there are several small negative deflections in the overall upward trend of the upper regressive semi-cycle, corresponding to small-scale water regression and short-term sand body progradation. The positive trend recovery point after each negative deflection is the starting surface of a lake flooding, which constitutes a regressive quasi-sequence boundary. The INPEFA valley floor where the maximum regression surface is located separates two sets of five-stage cycles with different superimposed styles.

The Chang 7_1 sub-member is dominated by fine-grained sediments, and the GR value is generally high, with thin-layer siltstone, showing an upward thinning sequence, which belongs to a retrograde cycle. The INPEFA curve is a positive trend of continuous rise, indicating that the accommodation space continues to increase and the sediment retreats to the shore. This section and the top retrograde section of the underlying length 7_2 form a step-like rise on INPEFA, which is composed of two continuous peaks, and there is a small negative deflection in the middle. The maximum value corresponding to the top boundary represents a higher level of lake flooding surface. The fifth-order cycles are superimposed on the positive trend background, which shows that the GR curve has a small low value section reflecting thin siltstone, and the INPEFA has a short negative deflection, which represents a short decrease in the growth rate of the accommodation space and an increase in the sand input. The end of each negative deflection and the start of the next positive trend are the top boundary of the fifth-order cycle corresponding to the intensification of a lake flooding. The cycle itself is mostly a regressive quasi-sequence with upward thinning, and the sandstone content of the single cycle decreases from bottom to top, and the positive trend of INPEFA generally increases.

4.2. Comparison with Previous Subdivision Schemes

The Chang 7 member of Yanchang Formation mostly adopts the empirical comparison framework of " marker layer constraint + approximate equal thickness " in oilfield practice. Among them, tuff event layer and typical mud shale section

are widely used for regional comparison anchoring because of their strong identifiability and stable comparison. This method has the advantages of strong engineering operability and low cost. However, in the context of long 7 thin interbedded layers, relying solely on conventional curve markers and thickness constraints is prone to problems such as unclear interface within the layer, strong multi-solution of interwell comparison, and limited subdivision resolution. In contrast, sequence stratigraphy emphasizes the identification of key interfaces under time constraints and the analysis of the response of stratigraphic accumulation patterns to changes in accommodation space and sediment supply. It organizes sedimentary records through units such as sequences, system tracts, and parasequences to achieve higher-precision chronostratigraphic correlation, sedimentary system tract restoration, and facies / sand body distribution prediction. Under the background of thin interbedding of Chang 7 reservoir group, only relying on the traditional " marker layer constraint + approximate equal thickness " unified layer experience framework, it is easy to cause unclear identification of intra-layer interface, multi-solution of interwell correlation and uncertainty amplification of wear time. Therefore, this paper adopts the mixed strategy of ' regional stable marker layer anchoring + logging cycle trend enhancement identification ' : firstly, a reliable comparison anchor point is established by using the regional identifiable marker layer, and then the INPEFA and other logging cycle signal enhancement methods are introduced to extract the characteristics of the trend section and inflection point in the layer, so as to improve the identification stability and traceability of the high-frequency cycle and the working-level sequence interface, so as to form a high-resolution sequence framework for sedimentary microfacies characterization and sand body configuration analysis.

4.3. Results of Stratigraphic Division and Correlation

The Chang 7 oil layer group corresponds to the descending half cycle of a long-term base level cycle, and two fourth-order sequences can be subdivided inside. The lower fourth-order sequence is composed of long 7_3 and long 7_2 , showing a complete symmetrical cycle structure in which the base level decreases first and then rises. The maximum regression surface is located in the most concentrated development section of sandstone in long 7_2 . The upper fourth-order sequence corresponds to a long 7-yr cycle, and the cycle structure is incomplete. Only the base-level rising half-cycle is retained, and the falling half-cycle is not developed due to sedimentary interruption or no deposition.

Under the constraint of the fourth-order sequence framework, the fifth-order sequence is divided step by step according to the trend fluctuation of INPEFA and the change of lithology combination. A fifth-order sequence is identified inside the Chang 7_3 , and the lithology gradually changes from the bottom dark shale to siltstone and fine sandstone, and the progradational parasequence is developed. Two fifth-order sequences are identified in the 7_2 section. The next one inherits the characteristics of progradation, and the last one turns into retrogradation. The boundary between the two is the maximum water regression surface. Two fifth-order sequences are identified inside Chang 7_1 , both of which belong to retrograde parasequences. The sandstone content decreases from bottom to top, and the scale of lake transgression increases step by step. Each fifth-order

sequence interface has inter-well comparability in the whole area.

The trend of INPEFA curve reveals the difference of cyclic structure in the Sanya section. INPEFA shows a continuous negative trend, indicating that the base level continues to decline, the sediment advances to the lake, and the top shows a positive trend turning point, which corresponds to the end of the lake flooding surface and limits the upper limit of the sub-member deposition. The lower INPEFA of Chang 7₂ continues to have a negative trend, and together with Chang 7₃, it constitutes a progradational parasequence set. The upper part turns into a continuous positive trend, reflecting the process of base level recovery and lake basin expansion. The INPEFA minimum point at the positive and negative trend conversion is the quantitative position of the maximum

regression surface in the fourth-order sequence. The overall trend of Chang 7 is mainly positive, and GR maintains a high value background. The INPEFA curve rises in a step-like shape, with two small negative deflections, corresponding to the fifth-order sequence boundary in turn, and records two short-term provenance progradation events during the lake transgression period.

The thickness of each fifth-order sequence changes significantly, and the sedimentary facies differentiation between wells is obvious, which is mainly controlled by the pre-existing difference of the lake basin bottom shape and the spatial heterogeneity of the supply intensity of multi-source direction, and some layers have the characteristics of penetrating and filling.

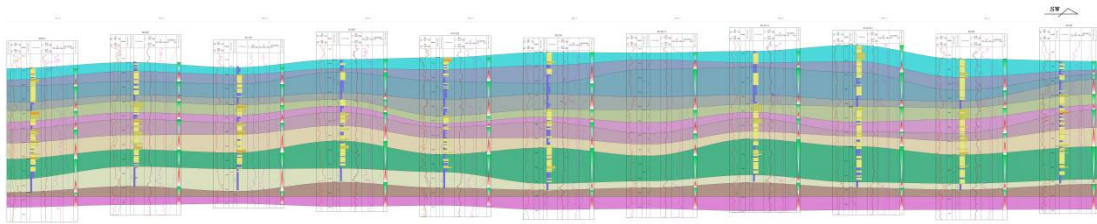


Figure 3. Dingtan 1877-Dingtan 1381 Chang 7 stratigraphic correlation profile

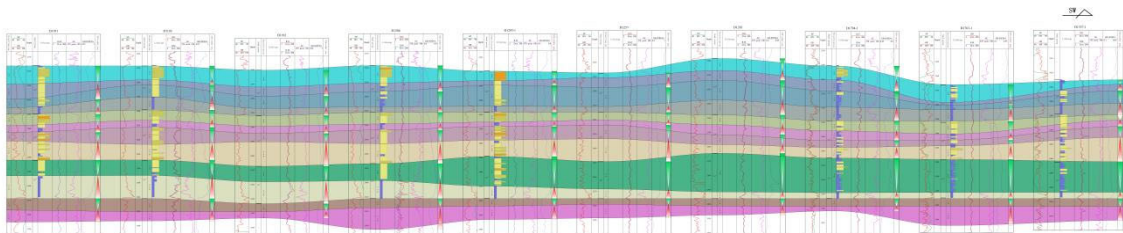


Figure 4. Prospecting 2179-Ding 1266-1 Chang 7 stratigraphic correlation profile

5. Conclusions

(1) Integrating marker bed constraints and INPEFA cycle analysis, the Chang 7 oil-bearing formation of the Yanchang Formation on the Dingbian platform is defined as a single long-term base-level falling semi-cycle, within which two fourth-order sequences are identified. The lower fourth-order sequence consists of Chang 7₃ and Chang 7₂, exhibiting a complete symmetrical structure of base-level fall followed by rise. The upper fourth-order sequence corresponds to Chang 7₁, preserving only the rising semi-cycle. Fifth-order sequence division results are: one progradational parasequence in Chang 7₃, two parasequences in Chang 7₂, and two retrogradational parasequences in Chang 7₁; all boundaries can be correlated across the study area.

(2) The INPEFA curve trends quantitatively characterize the spatial differences in cyclic structure among the three sub-members. The continuous negative trend in Chang 7₃ indicates a progradational succession; the positive trend shift at the top defines the terminal flooding surface. The lower part of Chang 7₂ continues the negative progradational trend, while the upper part shifts to a positive retrogradational trend; the minimum at the negative-to-positive transition precisely locates the maximum regressive surface within the fourth-order cycle. Chang 7₁ is dominated by a positive trend, with a stepwise rise interrupted by two negative deflections, which

sequentially record two brief provenance progradation events during the lake transgression.

(3) The thickness of each fifth-order sequence varies significantly in plan view, and inter-well sedimentary facies differences are jointly controlled by pre-existing lake-basin topography and uneven sediment supply from multiple provenance directions; some intervals exhibit diachronous filling characteristics. The INPEFA-based cycle division scheme provides a quantitative analytical approach for isochronous stratigraphic correlation in deep-water fine-grained sedimentary areas that does not rely on static lithological boundaries.

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