Fine Identification and Quantitative Characterization of Interlayers in Thick Oil Reservoirs of Bohai L Oilfield

Yujuan Liu, Jing Zhang, Qianping Zhang, Bin Zheng, Xiaoming Chen

CNOOC (China) Co., Ltd. Tianjin Branch, Tianjin 300459, China

Abstract: ***As water-flooded oilfields enter the stage of high water cut and high recovery degree, interlayers have an increasingly significant impact on the distribution of remaining oil in thick oil reservoirs. Taking the thick oil reservoirs of L Oilfield as the target, this paper comprehensively applies core, logging, and well logging data to analyze the types and genesis of interlayers in the oilfield. By adopting the core-calibrated logging method, quantitative identification criteria for interlayers are established, enabling quantitative interpretation of physical property interlayers. Through fine identification of interlayers at different hierarchical grades in L Oilfield, this study investigates the spatial distribution patterns of interlayers across various grades, quantitatively characterizes their distribution rules, examines their influence on remaining oil distribution, and provides guidance for later potential tapping.***

Keywords: Bohai Sea; Thick oil reservoir; Interlayers; Remaining oil.

1. INTRODUCTION

Interlayers refer to impermeable layers or ultra-low permeability rock layers in reservoirs that can block fluid flow. As water-flooded oilfields enter the "dual-high" stage (high water cut and high recovery degree), interlayers exert an increasingly significant influence on the distribution of remaining oil, with particularly prominent effects on thick oil reservoirs. Therefore, studying the fine identification and distribution patterns of interlayers in thick oil reservoirs during this dual-high stage, as well as analyzing their impact on the distribution patterns of remaining oil, holds great significance for enhancing oil recovery and conducting targeted potential tapping.

2. GENERAL OVERVIEW OF THE OILFIELD

The Bohai L Oilfield is a faulted half-anticline structure formed by sedimentary cover overlying a paleo-buried hill and controlled by boundary major faults. The oil-bearing formation series of the oilfield belongs to the lower second submember of the Dongying Formation (Paleogene), divided into five oil groups. Among them, Oil Groups II and III are the major oil groups, primarily developed with braided river delta front deposits. The reservoirs are well-developed, with individual layers characterized by large thicknesses. At present, the L Oilfield has entered the stage of high water cut and high recovery degree. After multiple rounds of adjustments, the planar distribution of remaining oil has become more scattered. Vertically, between layers, all intervals have been exploited but with uneven recovery; within layers, multi-stage waterflooding has occurred, resulting in complex distribution patterns of remaining oil.

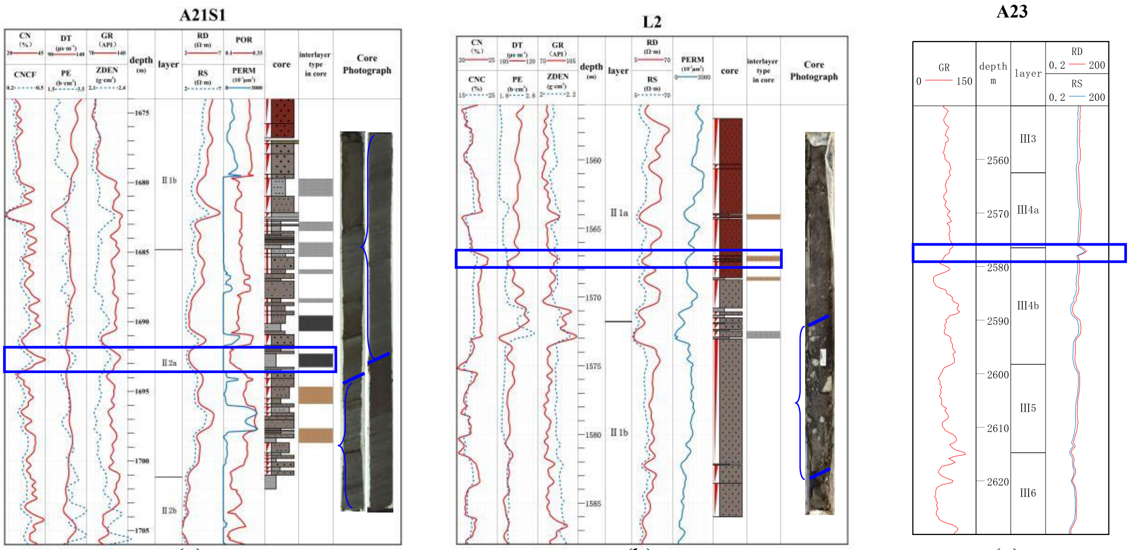
3. TYPES AND GENESIS OF INTERLAYERS

3.1 Types of Interlayers

Interlayers refer to impermeable layers or ultra-low permeability rock layers in reservoirs that can block fluid flow. They are generally classified by genesis into argillaceous interlayers, physical property interlayers, and calcareous interlayers. Through core observation, positioning, and detailed description of cores from two core-drilled wells (L2 and A21S1) in the L Oilfield, interlayers were identified. A total of 13 interlayers were identified in the core-drilled intervals of these two wells, mainly composed of argillaceous and physical property interlayers. No calcareous interlayers were identified in the core-drilled wells, but small amounts of calcareous interlayers could be recognized in the well logging data of other wells in the oilfield.

1) Argillaceous interlayers

Argillaceous interlayers are a type of formation with high clay content, which leads to deteriorated porosity and permeability. The lithologies of argillaceous interlayers in the study area include mudstone, silty mudstone, argillaceous siltstone, as well as sandy and gravelly mudstone. These interlayers exhibit low permeability and excellent sealing capacity. Their well-log response characteristics are close to the mudstone baseline: compared with adjacent reservoirs, their resistivity decreases, natural gamma increases, and density values rise, resulting in non-permeable interpretations in well-log analysis. A typical argillaceous interlayers occurs in Well A21S1 at a core depth of 1692.28–1693.16 m (Figure 1a). Between oil groups in the study area, argillaceous interlayers are thick and interpreted as non-permeable by well logs. interlayers between sub-layers and between units are also dominated by argillaceous interlayers, which are relatively thick and interpreted as non-permeable by well logs. Within units, argillaceous interlayers are fewer, thinner, and interpreted to have poor permeability based on well-log analysis.



(a) (b) (c)

mudstone interlayer mud interlayer petrophysical interlayer

Figure 1: Identification of interlayers in Wells A21S1 and 2

2) Physical Property interlayers

Physical property interlayers are a type of formation where porosity and permeability deteriorate laterally due to factors such as clay content in the formation and changes in sediment particle size. They are dominated by siltstone and fine sandstone, and also include matrix-supported fine conglomerate, mud conglomerate, and grain-supported conglomerate, with relatively high clay content. Within the study area, physical property interlayers are relatively well-developed, exhibiting certain porosity and permeability. However, their physical properties are degraded by two main factors: cementation of fine-grained thin sandstones in sandstone layers during deposition, and alteration or recrystallization of muddy clasts. Their well-log curve characteristics fall between those of argillaceous interlayers and normal reservoirs. Compared to adjacent reservoirs, they show low resistivity, high natural gamma, and high density, and are interpreted as having low permeability from well logs, with a significant difference in permeability compared to adjacent reservoirs. The permeability of physical property interlayers is mainly distributed between 10–300 × 10^{-3} μm²; interlayers with permeability exceeding 300 × 10^{-3} μm² hardly act as flow barriers. A large number of physical property interlayers have been identified in core-drilled wells. For example, a core interval at Well L2 with a depth of 1667.17–1667.57m is a typical physical property interlayers (Figure 1b), dominated by gravel-bearing fine sandstone with poor physical properties.

3) Calcareous interlayers

Calcareous interlayers are a type of formation where porosity and permeability deteriorate due to later-stage calcareous cementation diagenesis. Calcareous cements generally enrich in two locations: one is the contact surface between sandstone and mudstone (i.e., near the top and bottom surfaces of sandstone); the other is within medium-coarse sandstones with better early physical properties in thick sandstone layers. If fractures are present in thick sandstone layers, CO_3^{2-}-enriched solutions can more easily infiltrate the sandstone formations, making calcareous interlayers more likely to occur near the fractures.

The lithology of calcareous interlayers is dominated by calcareously cemented fine sandstone and fine-medium sandstone, with tightly cemented textures and essentially no permeability. They are generally thin (usually less than 2 m in thickness) and primarily distributed in thick sandstone layers of subaqueous distributary channels. Their electrical characteristics are primarily manifested as abnormally high deep and shallow lateral resistivity (presenting a sharp peak shape) and increased density curves.

These interlayers are sparsely distributed with strong randomness, rarely occurring in the L Oilfield and only encountered in a few wells. A typical example is the interval at 2577 m in Well A23 (Figure 1c).

3.2 Genesis of Interlayers

Interlayers can generally be divided into two major categories based on their genetic types: sedimentation and diagenesis.

1) Flood Period Deposition. During the flood period, accompanied by the rise of the lake level and the migration of effective accommodation space landward, the base level reaches its maximum elevation, with accommodation space significantly exceeding sediment supply. In the study area, the tops of Oil Group II and Oil Group III are characterized by pure and dense clay content, well-developed horizontal laminations, large single-layer thickness, and excellent continuity, thus acting as interlayers in this region.

2) Multi-Stage River or Bar Incision and Erosion. As the sediment transport hydrodynamic force weakens, a layer of relatively fine-grained silty mudstone or argillaceous siltstone is deposited over the gravelly sandstone in river channels, representing the deposition of fine-grained materials during the brief period between the end of one river channel deposition and the start of the next. Due to the superposition and incision of multi-stage rivers, the strong downcutting and scouring by later-stage rivers result in incomplete preservation of the fine-grained deposits at the tops of earlier-stage river channels. Consequently, the thickness of interlayers becomes locally thinner or even missing, with their distribution being random, small in scale, and chaotic. For example, Well A21S1 shows two sets of fine sandstone rich in oil, with a 31 cm-thick light-gray mudstone interbedded between them, forming a physical property interlayers that impedes hydrocarbon migration (Figure 1).

3) Argillaceous interlayers within river channels or bars, with limited distribution.

4) Calcareous interlayers generally form in restricted, shallow, and evaporative environments, developing at the bottom of subaqueous distributary channels. The presence of calcareous cementation indicates that after a river channel ceases development, the original riverbed water body becomes stagnant (non-circulating), and some river segments remain in a shallow evaporative environment over long periods, ultimately leading to the formation of a calcareous layer. When a flood occurs, the previously abandoned riverbed is reactivated by floodwaters, forming a new shallow channel at the upper part of the original river channel. The previously formed calcareous layer is then covered by sandy deposits transported by the river, forming a calcareous interlayers. Thus, the calcareous layers within sandstones can serve as important indicators for identifying two stages of river channel deposition.

4. QUANTITATIVE IDENTIFICATION OF INTERLAYERS

There are numerous methods for the identification and prediction of interlayers. Among them, core-based identification is intuitive, accurate, and operates at a scale as small as a few centimeters, making it the most effective approach. However, due to the limited availability of core well data, while well-log data are abundant and high-resolution, well-log methods are generally used as the primary means for interlayers identification. There are also multiple inter-well prediction methods, such as 3D seismic identification of inter-well barriers, geostatistical methods for predicting the distribution patterns of inter-well interlayers, or deterministic modeling and stochastic simulation methods for inter-well prediction and characterization of interlayers. Nevertheless, the understanding derived from these methods remains incomplete. In recent years, new methods with strong learning ability and high accuracy, such as wavelet neural network models, have emerged, though these new approaches have certain limitations. Based on a comprehensive review of domestic and international research status, and considering the data conditions of the study area, this research primarily adopts the core-calibrated logging method for the identification of interlayers.

4.1 Preprocessing of Well-Log Data

1) Statistical Analysis and Collation of Well-Log Curves

Statistical analysis of well-log curves from all development wells across different logging series was conducted. Among the oilfield's two core-drilled wells, there are 19 types of well-log curves. Statistics were compiled to analyze the shared well-log curves among all wells, including these two core-drilled ones. Based on the well-log data, it was ultimately determined that, under the premise of fully utilizing core data, conventional logging curves (including natural gamma [GR], deep dual-lateral resistivity [RD], shallow dual-lateral resistivity [RS], thermal neutron porosity [CN], density [ZDEN], acoustic time difference [DT], and photoelectric absorption cross-section index [PE]) would be effectively integrated with physical property parameters. Using the 13 reliable interlayers identified from cores, the core-calibrated logging method was adopted to establish interlayers identification templates, enabling quantitative identification of interlayers.

2) Normalization of Well-Log Curves

The application of well-log curve normalization processing techniques can effectively eliminate systematic biases between wells. The standard layer serves as the geological basis for well-log curve normalization, and its selection criteria should meet the following requirements: stable sedimentation, wide distribution, and a certain thickness; distinct lithological and electrical characteristics that facilitate regional tracking and correlation. Based on the specific conditions of the study area, a stable mudstone section with an average sediment thickness of 24 m above the top of Oil Group II in the Lower Dongying Formation was selected as the standard layer (Figure 2). Frequency histograms of well data for each standard layer were plotted, compared with key wells, and the difference between them was calculated as the correction value. Well-log curve normalization was then completed based on this correction value. The normalized curves not only retain the single-well geological response characteristics but also eliminate systematic biases, thereby ensuring the rationality and reliability of interlayers identification results using the corrected curves.

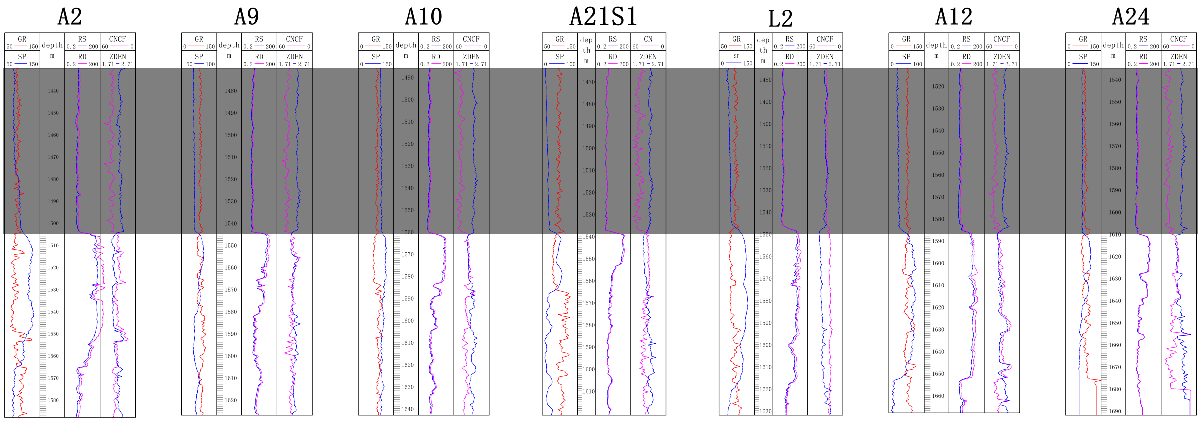


Figure 2: First-grade Marker at the Top of Oil Group II in Lower Submember II of the Dongying Formation

4.2 Establishment of Quantitative Identification Criteria for interlayers

Aimed at the characteristics of interlayers, this study establishes quantitative identification criteria based on the core-based identification of interlayers in core-drilled wells. By comprehensively considering factors such as well-log resolution, the number of well-log curves, and the sensitivity of curves to interlayers, and through the optimization of multiple cross-plots, it was preliminarily determined to use parameters such as lithology, electrical properties, and physical properties to develop interlayers identification templates. Gamma (GR), resistivity curves, and porosity are prioritized for the interpretation of interlayers (Table 1), with density and permeability appropriately referenced as needed. This approach enables the distinction between argillaceous interlayers and physical property interlayers.

Table 1: Well-Log Identification Criteria for interlayers

Identification Parameters	Argillaceous interlayers	Physical Property interlayers
Natural Gamma (API)	> 100	85-125
Deep Lateral Resistivity (Ω·m)	＜9	5-20
Permeability ($10^{-3}\mu m^2$)	≤10	10-300
Porosity (%)	＜20	20-30
Density (g/cm^2)	>2.17	2.1-2.17

4.3 Effectiveness of interlayers Identification

There are relatively few core-drilled wells in the study area. Through comparative analysis of well-log identification results and core observation data, the identification accuracy of the number of interlayers reaches approximately 89%. Based on these interlayers interpretation criteria, the interpretation of interlayers for all 89 development wells in the study area was completed. A total of 1340 argillaceous interlayers segments and 637 physical property interlayers segments were interpreted, with a total of 1977 interlayers identified.

5. DISTRIBUTION CHARACTERISTICS OF INTERLAYERS

5.1 Sandbody Configuration Characteristics

Based on core-calibrated logging, the establishment of interlayers identification criteria, and the identification of well-based interlayers in the study area, inter-well interlayers were predicted by integrating sedimentary microfacies and relative elevation positions within the layer. This enabled the characterization of interlayers distribution across Oil Groups II and III in the entire study area. The study area is dominated by fifth-grade to third-grade interlayers (Figures 3a, 3b). Mudstone interlayers between oil groups are classified as fifth-grade interlayers; mudstone interbeds between sub-layer sandstones are fourth-grade interlayers; and physical property interlayers within sandbodies are third-grade interlayers.

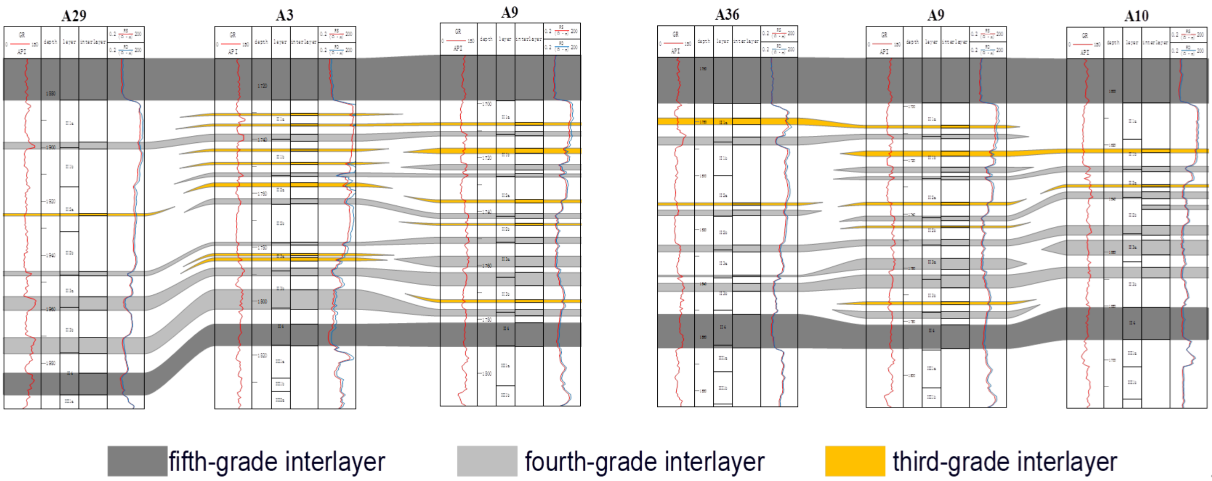


Figure 3a: fifth-grade to third-grade interlayers profile of the main section of the source and vertical source

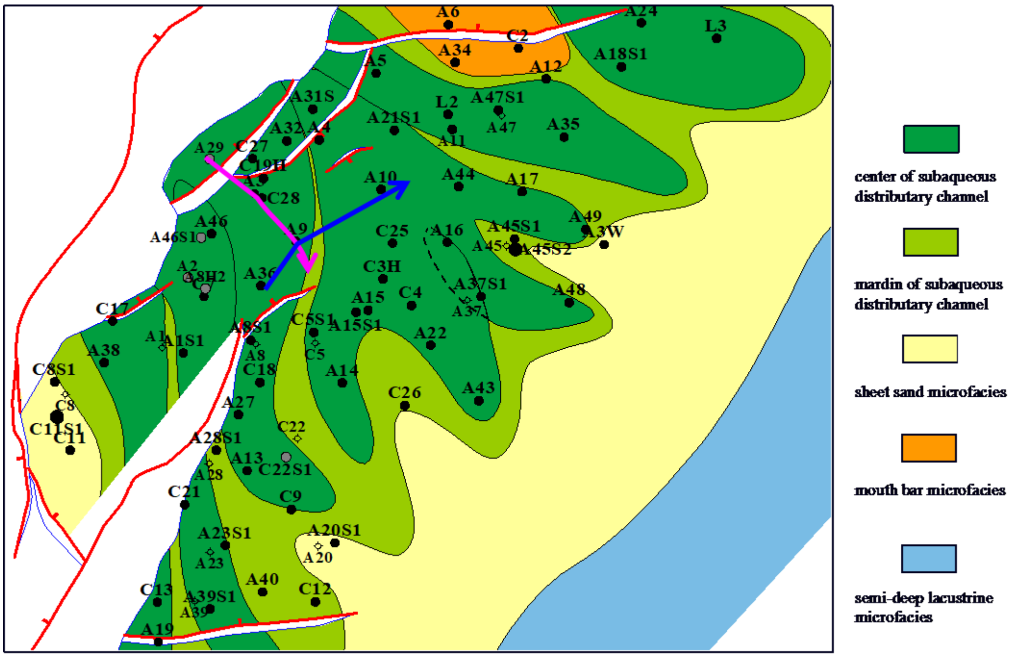


Figure 3b: Location Map of Various Profiles

5.2 Distribution Characteristics of Interlayers in Single Wells

Based on the vertical revelation of interlayers in single core-drilled and development wells, it was observed that interlayers between oil groups are thick, those between sub-layers are relatively thick, and there is significant variation in the thickness of interlayers within each sub-layer. The development of interlayers is closely related to sedimentary microfacies. A small number of physical property interlayers develop within the main channel bodies and main bar bodies, while they are rare within the constant bar bodies and bar margins, where argillaceous interlayers dominate.

5.3 Distribution Patterns of Interlayers

The sediment sources of Oil Groups II and III in the L Oilfield are from the northwest direction. Based on the analysis of interlayers in single wells, typical profiles perpendicular and parallel to the sediment source direction were selected to further investigate the distribution characteristics of interlayers across the entire oilfield (Figure 4).

Vertically, the development of interlayers is related to sandbody development and sedimentary microfacies. Near the sediment source area (i.e., the subaqueous distributary channel area), where sediment supply is abundant and hydrodynamic conditions are strong with high scouring capacity, argillaceous or silty materials are less likely to deposit and preserve. Thus, interlayers are sparsely distributed and relatively isolated, developing only between the superimposed intervals of two-stage channels. In areas far from the sediment source (i.e., bar areas and sheet sand areas), hydrodynamic conditions change rapidly, leading to a significant increase in the distribution of interlayers and their thickness.

The vertical distribution of interlayers is closely related to the vertical evolutionary laws of sedimentation. In areas with strong transgression, argillaceous interlayers develop most prominently, with well-developed intra-layer argillaceous interbeds. During the regression-transgression transition, the thickness of argillaceous interlayers decreases, while their drilling encounter rate increases (Figure 4).

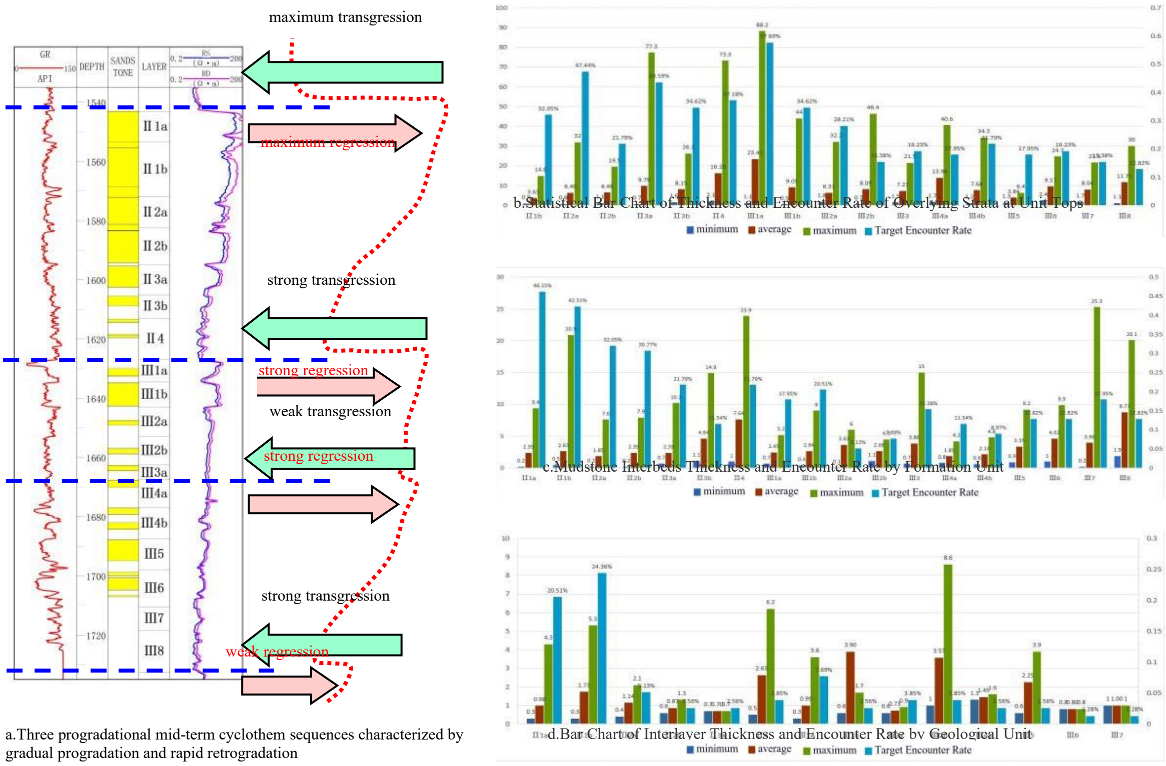
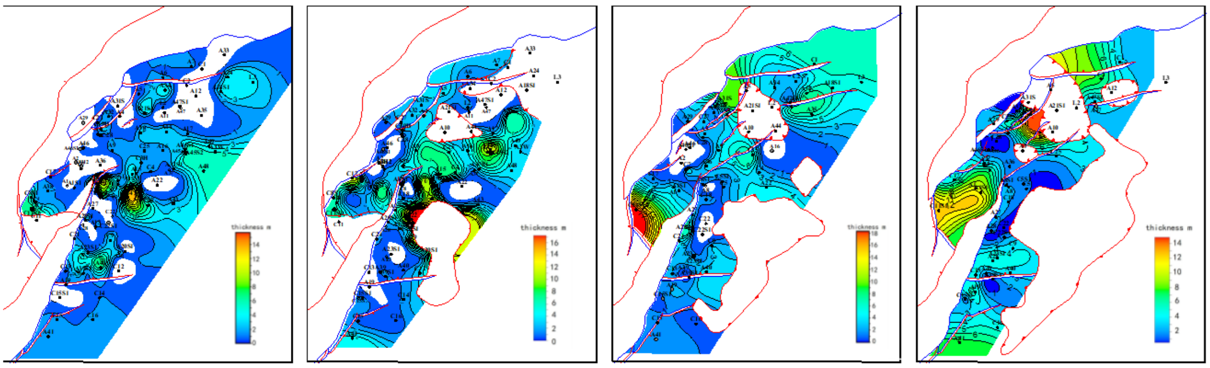


Figure 4: Relationship Between the Vertical Distribution of interlayers and Sedimentary Vertical Evolution

Planarly, influenced by sedimentary stages and scales, there are significant differences in the distribution of interlayers across the entire oilfield. The mudstone interlayers between oil groups exhibit relatively stable distribution, good continuity, and large thickness. The interlayer types between sub-layers are dominated by mudstone, with relatively large thickness and relatively stable distribution (Figure 5). The interlayers within each sub-layer include both argillaceous and gravel physical property interlayers, showing significant differences in thickness, limited distribution, and poor continuity (Figure 6).



a. II 1b- II 2a interlayer b. II 2b- II 3a interlayer c.III1b-III2a interlayer d.III2b-III3a interlayer

Figure 5: Thickness Distribution Map of Typical Argillaceous interlayers Between Sub-Layers Below D2

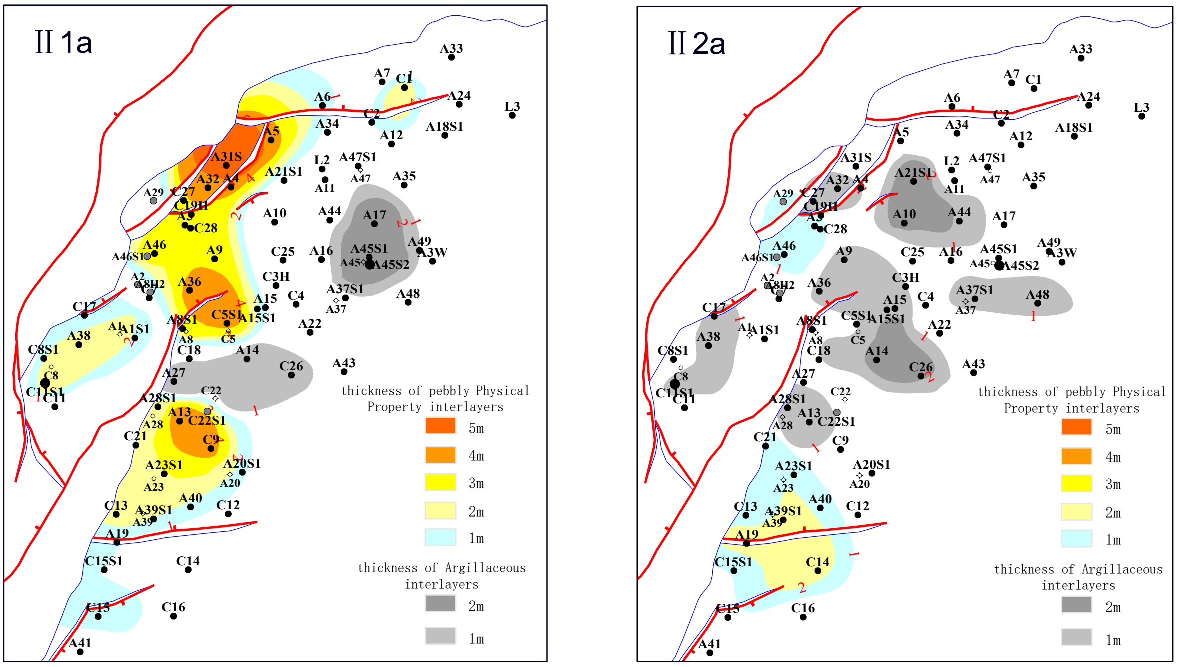


Figure 6: Thickness Distribution Map of Typical interlayers Within Sub-Layer Below D2

6. INFLUENCE OF INTERLAYERS ON REMAINING OIL

In thick reservoirs, the blocking effect of interlayers leads to the formation of remaining oil types such as "top-shielded by interlayers" and "sandwiched between upper and lower barriers." When continuous and stable lithological or physical property interlayers develop within a single layer, remaining oil accumulates in areas with relatively poor physical properties adjacent to the lower part of the interlayers or between interlayers. The presence of interlayers results in multi-stage water flooding in oil wells.

Different types of interlayers have varying capacities to block bottom water. Generally, continuous interlayers have the strongest blocking capacity for bottom water, followed by transitional interlayers, while random interlayers have the weakest blocking capacity. The distribution patterns of remaining oil shielded by interlayers are as follows: First, below the interlayers, due to their shielding effect, the exploitation degree is poor, retaining a portion of remaining oil; second, the upper part of interlayers near the reservoir is often also an area of remaining oil enrichment. The lower part of the reservoir, due to bottom water coning, experiences rapid water cut increase in oil wells, whereas the upper part, shielded by interlayers, enriches remaining oil.

In the L Oilfield, the distribution of remaining oil in thick reservoirs is significantly influenced by interlayers. interlayers block fluid flow, causing remaining oil to accumulate above or below them. After targeted exploitation of these interlayers, remaining oil becomes jointly controlled by interlayers and development wells. Effective exploitation of such remaining oil requires targeted perforation.

Taking the C4 well group as an example: The upper thick reservoir of Well Group 1a-b has good horizontal connectivity with no interlayer isolation. Injected water migrates downward under gravity, enriching remaining oil at the top of the thick reservoir. Between Sub-layer 2a-b and A37, there is a thin and poor-quality interlayer. Injected water is obstructed here, and the vertical shielding by the upper interlayer further concentrates remaining oil in this interval (Figure 7).

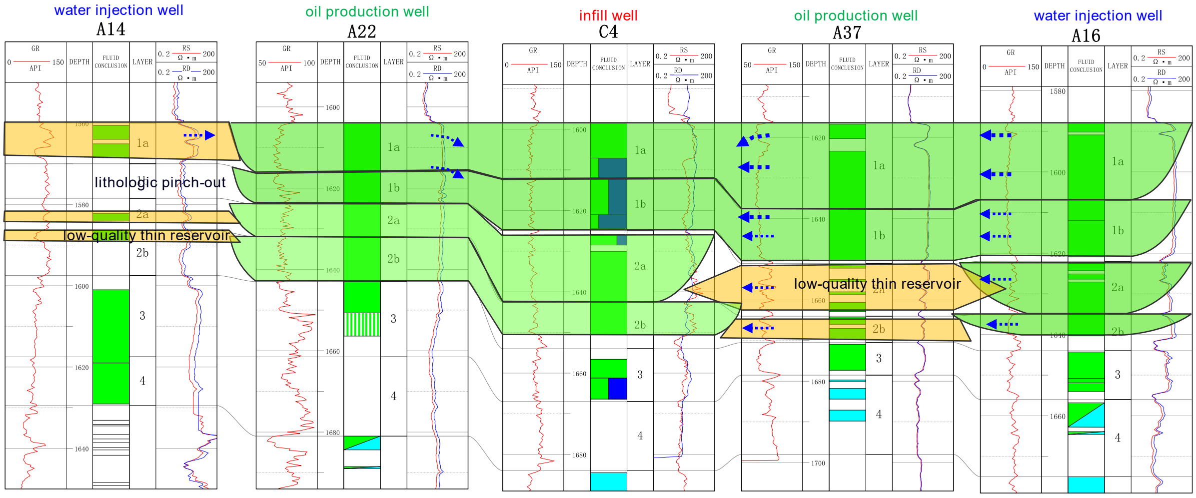


Figure 7: Composite Well Profile of Wells A14, A22, C4, A37, and A16

7. CONCLUSION

1) The interlayers in thick reservoirs of the L Oilfield are categorized into three types: argillaceous interlayers, physical property interlayers, and calcareous interlayers. Among these, argillaceous and physical property interlayers are dominant, with their genesis primarily attributed to sedimentary processes, while diagenetic origins are less common.

2) Based on the positioning, description, and detailed research of core wells, a quantitative identification criterion for interlayers was established using the core-calibrated logging method. This enabled the interpretation of interlayers for 87 wells, achieving quantitative characterization of physical property interlayers.

3) The distribution characteristics of interlayers in single wells, planar areas, and vertical profiles of main reservoir layers were summarized. It was proposed that the vertical distribution of interlayers is closely linked to the vertical evolutionary laws of sedimentation: argillaceous interlayers develop most prominently in areas with strong transgression, argillaceous interbeds are well-developed within the layer, and during the regression-transgression transition, the thickness of argillaceous interbeds decreases while their drilling encounter rate increases.

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