

Genesis Mechanism and Identification Methods of Low-Resistivity Oil Layers in Shahejie Formation of Bohai C Oilfield

Jianmin Zhang

Bohai Oilfield Research Institute, Tianjin Branch of CNOOC Ltd., Tianjin, China
Email: 75657043@qq.com

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Abstract

The genesis mechanism of low-resistivity oil formation in the medium-deep Shahejie Formation of Bohai C Oilfield is unclear, and there is a lack of effective methods for identifying low-resistivity oil layers. This article conducts a comprehensive analysis based on core sample experiments, and research shows that the formation of low-resistivity oil layers in the oilfield is mainly caused by the superposition of three factors: 1) microcapillary development, high irreducible water; 2) additional conductive effect of clay; 3) deep invasion of high salinity mud filtrate. The low-resistivity oil layer in this oilfield is mainly characterized by high mud content and strong additional conductivity of clay, and the complex pore throat structure leads to high irreducible water saturation, and the impact of saline mud intrusion, resulted in low-resistivity oil layers. The oilfield is mainly a lightweight oil layer with hydrophilic wettability, studying the response characteristics of oil and water layers through core nuclear magnetic resonance experiments, effectively identifying low-resistivity oil layers based on the correlation between resistivity and physical properties.

Keywords

Low-Resistivity Oil Layer, Genesis Mechanism, Medium-Deep Formation, Irreducible Water Saturation, Additional Conductivity of Clay, NMR Logging

1. Introduction

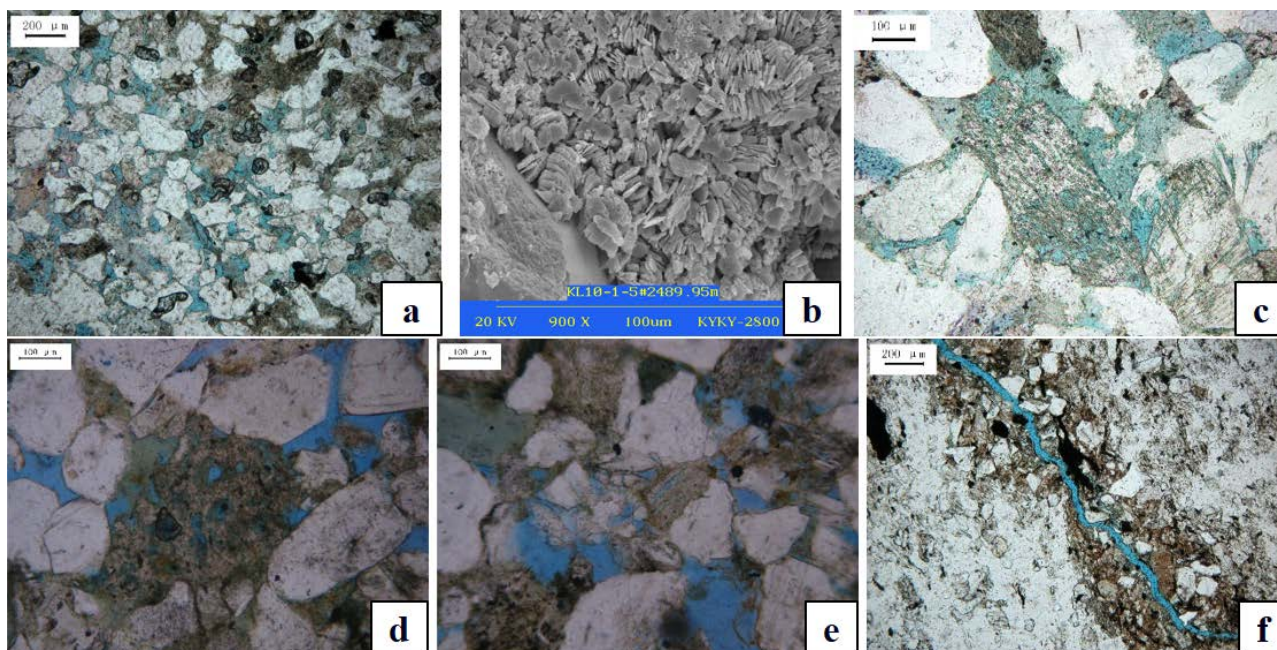
With the gradual deepening of Bohai Oilfield development, researchers have found a large number of low-resistivity oil layers in oil fields (Lv et al., 2006). Some low resistivity oil layers have higher production rates, and effectively identifying

and utilizing low-resistivity oil layers has become one of the important guarantees for increasing oil reserves and production in oilfields. Low-resistivity oil layers, due to their low electrical resistivity, are often misunderstood as oil-water layers, oil-bearing water layers, or even water layers. At present, there is relatively more research on the low resistance oil layers of the shallow Minghuazhen Formation and Guantao Formation in the Bohai Oilfield (Wang et al., 2019; Liang et al., 2022; Wang et al., 2023; Lu et al., 2022; Liu et al., 2023). However, due to the strong effects of rock compaction, cementation, and dissolution in the middle and deep layers, the pore structure of the reservoir is more complex, there is relatively little research on low-resistivity oil reservoirs in the medium-deep formation (Wang et al., 2016). The main method for identifying mid to deep low resistance oil layers is through gas logging combined with testing and production data for comprehensive judgment, and the identification method for low resistance oil layers still needs further expansion. In recent years, the large-scale promotion and application of nuclear magnetic resonance logging (Zhang et al., 2014; Lu et al., 2023), play an important role in identifying low-resistivity oil layers. This article takes the Shahejie Formation oil layer in Bohai C Oilfield as an example. Research on the genesis mechanism and identification methods of low-resistivity oil reservoirs achieves good application results, and can provide a reference for the identification of low-resistivity oil layers in other similar oilfields.

2. Geological Setting

The particle size range of the Shahejie Formation in Bohai C Oilfield is mainly composed of medium to fine sandstones; The lithology is mainly composed of lithic feldspar sandstone, In the rock debris component, the average quartz content is 37.6%, the average content of feldspar is 40.1%, the rock filling material is mainly composed of muddy mixed base, next is Changing texture, the average impurity content is 11.4%, the average cement content is 7.0%, mainly composed of calcite cementation, accompanied by clay cementation, Occasionally seen siliceous cementation. The sorting of debris particles is moderate, and rounding is mainly secondary to secondary edges, the bonding method is mainly porous bonding, the main contact methods are line, point line, and line point contact. The clay minerals are mainly illite and illite-smectite mixed layer, accompanied by a small amount of kaolinite and chlorite. The results of thin section and scanning electron microscopy analysis indicate that the pore geometry is complex and diverse. The reservoir storage space of the Shahejie Formation is primarily composed of primary intergranular pores, secondary pores mainly include dissolution granular pores and dissolution intergranular pores, occasional microcracks are observed (Figure 1). Pores are mainly distributed between 5.5% and 30.0%, with an average of 22.6%; The permeability is mainly distributed between 1 mD and 1000 mD, with an average value of 192.8 mD; The physical properties of the Shahejie Formation reservoir are mainly characterized by medium porosity and medium permeability. The Shahejie Formation reservoir is buried at a depth of

2100 to 2800 meters.



(a) Well 5, 2508.60 m, casting thin section, particle point-line contact, primary intergranular pores development; (b) Well 5, 2489.95 m, scanning electron microscope, Inter-crystal micropores of kaolinite; (c) Well 5, 2489.35 m, casting thin section, feldspar particles corrosion occur along cleavage fractures; (d) Well B16, 2911.92 m, casting thin section, debris particles dissolved into honeycomb; (e) Well B16, 2911.92 m, casting thin section, corrosion occurs at the edge of particles; (f) Well 5, 2509.51 m, casting thin section, sandy mudstone, The width of microcracks is about 0.06 mm.

Figure 1. Storage space type of the Shahejie Formation reservoir in Bohai C Oilfield.

3. Analysis of the Genesis Mechanism of Low-Resistivity Oil Layers

There are significant differences in lithology and physical properties of the Shahejie Formation reservoir in Bohai C Oilfield, resulting in significant changes in the resistivity values of the Shahejie Formation reservoir in the oilfield, there is development from low resistance oil layers of $3 \Omega \cdot m$ to high resistance oil layers above $50 \Omega \cdot m$, according to the sampling confirmation of cable formation testing, the minimum resistivity of the oil production layer is $3.1 \Omega \cdot m$. By collecting data on formation testing, sampling, oil testing, and existing interpretation results from collected wells, analysis of the Shahejie Formation Reservoir in Bohai C Oilfield. Analysis shows that there are no problems in identifying vertical oil and water layers in a single well, but based on the comprehensive reservoir information of the entire oilfield, it can be found that the resistivity is within the range of $3.0 \Omega \cdot m - 5.0 \Omega \cdot m$, and there are oil layers, oil-water layers, oil-bearing water layers, and water layers. Analysis suggests that the genesis mechanism of the low resistance oil layer in the oilfield is mainly composed of three factors superimposed: 1) Microcapillary development with high bound water content; 2) Additional conductive effect of clay; 3) Deep invasion of high salinity mud filtrate.

3.1. The Influence of Irreducible Water Saturation

The widespread development of low resistance oil layers caused by high bound water saturation requires further analysis and research. This article defines irreducible water from a dynamic perspective, which refers to water that cannot flow in reservoir pores under a certain production pressure difference. Reservoir irreducible water often consists of three parts: 1) Thin film water retention on the surface of rock particles due to wettability; 2) Capillary trapped water in capillary pores; 3) Clay particles adsorb water.

The lower the porosity and permeability of a reservoir, the higher the irreducible water saturation of the reservoir. Under the same porosity or permeability conditions, the irreducible water saturation still has a certain distribution range. By analyzing 147 rock samples from the Shahejie Formation, when the porosity is 20%, the average irreducible water saturation is 50%, and the highest can reach 65%; When the porosity is 25%, the average irreducible water saturation is 32%, and the highest can reach 55%; When the porosity is 30%, the average irreducible water saturation is 23%, and the highest can reach 45% (Figure 2). In high porosity conditions, the reservoir may still contain relatively high bound water, resulting in low reservoir resistance.

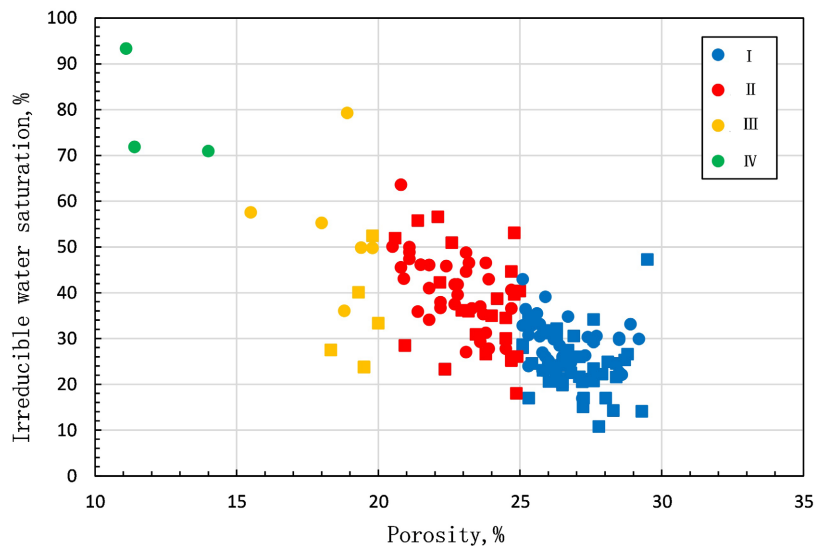


Figure 2. Cross plot of porosity and irreducible water saturation in C Oilfield.

3.2 Additional Conductive Effect of Clay

Muddy sandstone formations all contain a certain amount of clay, and the surface of clay particles usually carries negative charges. According to the principle of electrical neutrality, an equal amount of cations will inevitably adsorb on the surface of clay minerals to achieve equilibrium. In general, the cations adsorbed by the negative charge on the surface of clay particles cannot move, but this adsorption is not very tight. Under the action of an electric field, the adsorbed cations can exchange positions with other hydrated ions in the rock solution, causing con-

ductivity. This conductivity characteristic generated by the cation exchange of clay minerals is called the additional conductivity of clay minerals.

Researches indicate that the clay minerals of disordered illite-smectite mixed layer have strong cation exchange capacity. Clay minerals in the region are mainly illite and illite-smectite mixed layer, accompanied by a small amount of kaolinite and chlorite (**Figure 3**), the mixed layer ratio of illite-smectite mixed layer is 8:2.

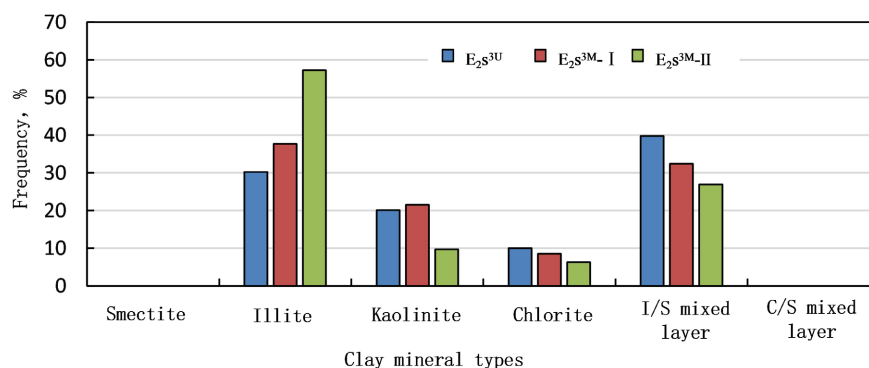


Figure 3. Histogram of clay mineral content statistics of the Shahejie Formation reservoir in C Oilfield.

Table 1. Experimental results data table of cation exchange capacity in C oilfield.

Number	Well	Horizon	Depth(m)	Lithology	Cation Exchange Capacity (mmol/100 g)	Porosity (%)	Rock Density (g/cm ³)	Qv (mmol/ml)
1	C-2	$E_2S_3^m$	2553.28	Sandstone	1.053	27.8	1.89	0.072
2	C-2	$E_2S_3^m$	2557.20	Sandstone	11.354	10.2	2.36	2.627
3	C-2	$E_2S_3^m$	2554.73	Sandstone	2.647	21	2.07	0.261
4	C-3	$E_2S_3^u$	2566.36	Sandstone	1.383	27.3	1.93	0.098
5	C-3	$E_2S_3^u$	2569.41	Sandstone	12.893	12	2.37	2.546
6	C-3	$E_2S_3^u$	2572.76	Sandstone	5.314	16	2.26	0.751

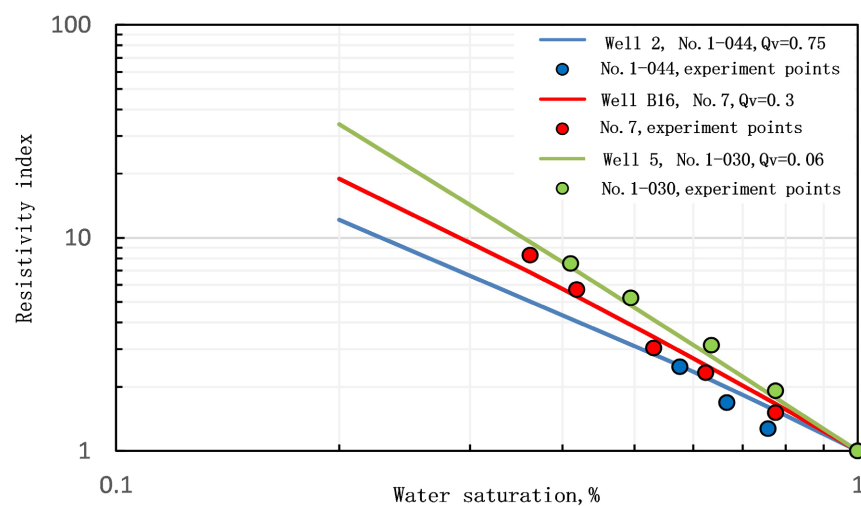


Figure 4. Comparison chart of core rock electrical experiment curves.

According to the experimental data of cation exchange capacity (**Table 1**), establish a statistical model between cation exchange capacity Q_v value and natural gamma logging relative values.

The change in cation exchange capacity is an important reason for the slope change of the rock electrical experiment curve. The larger the cation exchange capacity Q_v value, the smaller the rate of increase in resistivity (**Figure 4**), resulting in low oil reservoir resistance. The additional conductive effect of the clay in this target layer will to some extent further reduce the resistivity of oil bearing reservoirs.

3.3. Mud Intrusion

The invasion of drilling fluid into oil bearing reservoirs changes the fluid saturation, water mineralization, and corresponding resistivity profiles in the intrusion zone around the wellbore, making it difficult to measure the true resistivity of the oil bearing reservoir through electrical logging. For the target layer of the oilfield, the invasion of drilling fluid is one of the reasons for the formation of low resistance oil layers, which makes it difficult to identify and evaluate oil and water layers through logging, especially the impact of saline drilling fluid on electrical logging is more severe.

The Bohai C Oilfield is drilled with saline mud, and the logging series is complex. For cable logging, the intrusion of saline mud can further reduce the reservoir resistivity. Statistics were conducted on the ratio of resistivity curves before and after invasion correction in the target reservoir of 8 wells in the oilfield. The correction amount for water layers was relatively small, and the correction coefficient was generally around 1.11; The correction amount of the oil layer is relatively large, and the correction coefficient is generally around 1.23. Although the intrusion of saline mud reduces the overall resistivity of the reservoir, its impact on the oil layer is greater.

4. Identification Methods for Low-Resistivity Oil Layers

NMR logging can provide information on the number of fluids, fluid characteristics, and fluid containing pore size in rock pores, which conventional logging instruments cannot provide. The response characteristics of NMR logging are of great significance for identifying low-resistivity oil layers.

To characterize the NMR response characteristics of different rock samples under different fluid states, 5 rock cores were selected, numbered 8, 10, and 11 (well B16); A8 (Well 2); B4 (Well 3). Use a semi permeable partition and replace it with a mixture of oil, while measuring its capillary pressure and resistivity curve. When the displacement reaches the irreducible water state, measure the NMR T_2 spectrum of the core. The capillary pressure curves of 5 samples are shown in **Figure 5**, and the NMR T_2 spectrum are shown in **Figure 6**.

Observing the experimental results, **Figure 5** shows that as the pore structure deteriorates, the capillary pressure curves of 8, A8, 11, and B4 gradually rise, and

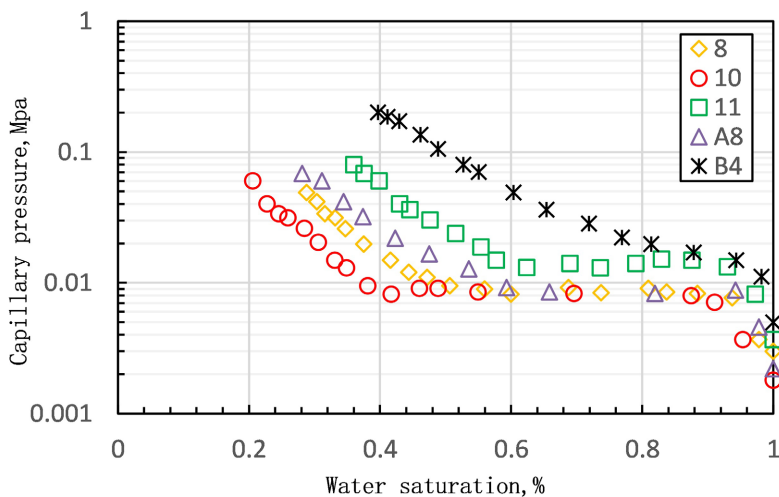


Figure 5. Crossplot of water saturation and displacement pressure of test samples.

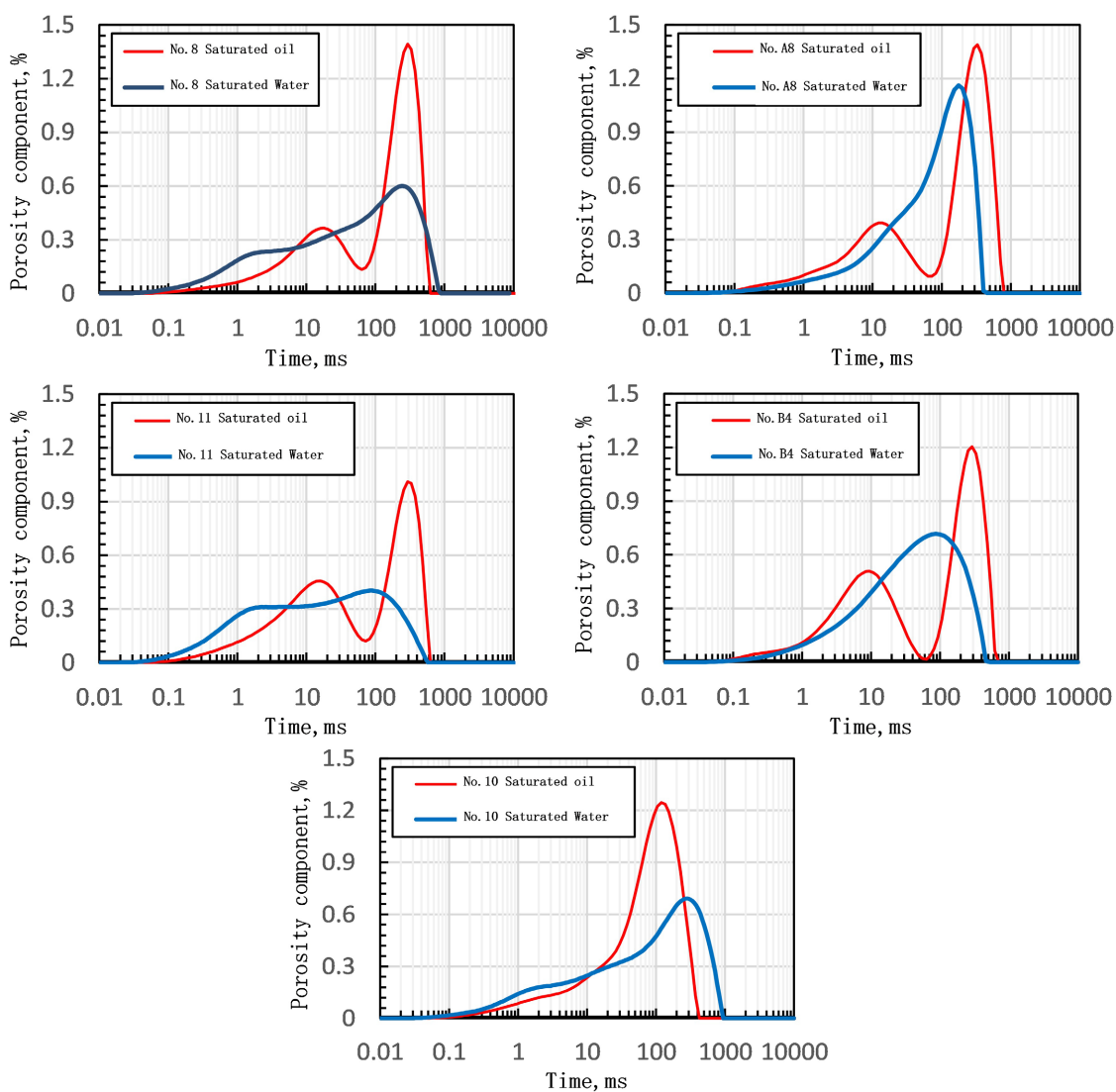


Figure 6. NMR T_2 spectrum of test samples in water and oil saturated states.

the saturation of bound water increases. These four samples have hydrophilic wettability, and the surface of the reservoir pores is enveloped by a water film. Oil exists in the center of the pores, reflecting a volume relaxation characteristic. The relaxation time is mainly determined by the viscosity of the crude oil. Due to the longer lateral relaxation time of light oil compared to the water layer, the second peak of the T_2 spectrum shifts to the right. The NMR T_2 spectrum of several samples in a saturated oil state shows a bimodal pattern. As the oil saturation changes, the oil signal in the T_2 spectrum will maintain a relatively fixed peak, and the amplitude will increase with the increase of oil saturation; The water signal, which reflects the pore structure in a saturated water state, will shift to the left and its amplitude will decrease. As the pore structure of the core deteriorates and the irreducible water saturation increases, the amplitude of the first peak in the T_2 spectrum gradually increases.

Sample 10 shows a single peak in a saturated oil state, and the peak shifts to the left at around 100 ms. The results of the joint testing experiment show that the sample has fine particles and a relatively small proportion of macropores; The proportion of small and medium-sized pores is relatively high, and the sorting is excellent with good connectivity, resulting in a good pore structure and low irreducible water saturation of the sample. The large pores are hydrophilic, but do not block the conductive network. The small and medium-sized pores are hydrophilic, and the conductive network is well preserved, so their overall conductivity is not affected by this mixed wetting. Due to the lipophilicity of macropores, oil films exist in macropores. When oil molecules come into direct contact with the surface of particles, they exhibit surface relaxation, and the T_2 relaxation mechanism is more complex; The position and width of oil components on the T_2 spectrum distribution depend on the viscosity of the oil and the wettability of the rock sample. For mixed wetting phase rocks, due to the wide and overlapping distribution of oil and water components on the T_2 spectrum (Prammer et al., 1995; Kleinberg & Vinegar, 1996; Morris et al., 1997), It is even more difficult to distinguish between oil and water, so it is necessary to combine multiple data for comprehensive discrimination.

5. Identification and Application of Low-Resistivity Oil Layers

In the oil layer 2605.8 - 2606.4 m of E_2s^{3M} -II oil group in Well 1, the interpreted layer number is 187, as shown in **Figure 7**, this layer is located at the top of an oil-water system, with a high resistivity oil layer developed in the lower part. The lower 192 layers have good physical properties, low-resistivity water saturation, and high resistivity. But their physical properties are poor, the porosity of the oil layer is 20%, the permeability is 20 mD, and the resistivity is 4.7 Ω -m. The relatively low porosity and low permeability result in a higher irreducible water saturation of the layer, which can reach 55%. In addition, the invasion of saline mud in this layer ultimately led to a further decrease in the resistivity of the layer, reaching the actual response value of the deep lateral resistivity curve.

The reservoir of the Shahejie Formation in the oilfield is mainly hydrophilic and

wettable, so the measured T_2 spectrum of the oil layer is mainly volume relaxation, with a formation oil density of 0.77 g/cm^3 , leaning towards light oil. The oil layer shows a peak indicating oil and gas at 300 ms on the NMR T_2 spectrum, and an oil and gas signal after 1000 ms. The T_2 spectrum shows a “tailing phenomenon”.

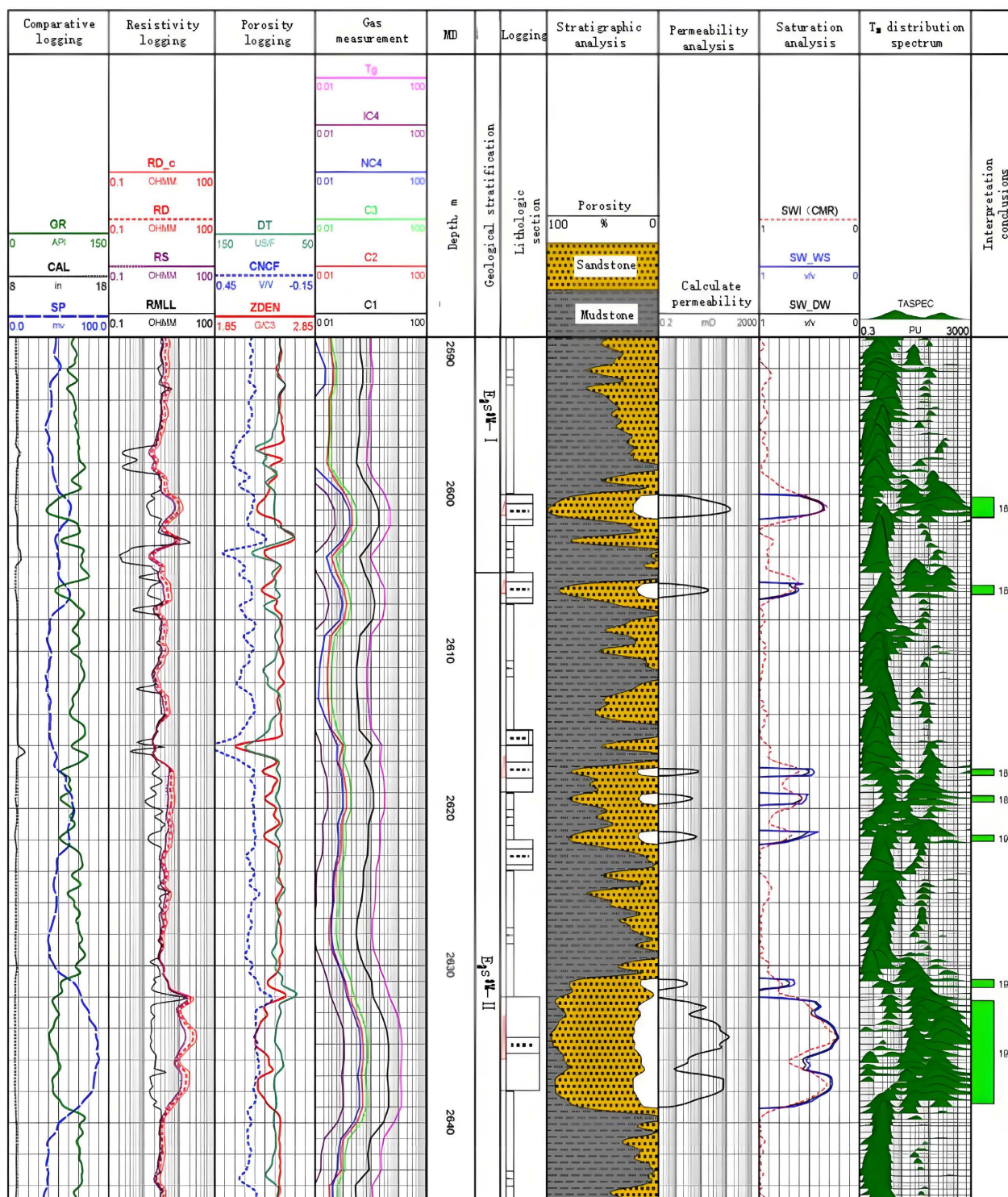


Figure 7. Logging curve image of E₂S³M-II oil layer in Well 1 of C Oilfield.

6. Conclusion

1) The formation of low-resistivity oil layers in Bohai C Oilfield is mainly caused by the superposition of three factors: One is the development of micro capillaries and high irreducible water saturation; The second is the additional conductive effect of clay; The third is the deep invasion of high salinity mud filtrate.

2) For light oil reservoirs with hydrophilic wettability, the spectral peak indicating oil and gas on the NMR T_2 spectrum shifts to the right, and the low-resistivity oil layers have high saturation of irreducible water, indicating a larger amplitude of the left spectral peak indicating irreducible water. Therefore, the bimodal distribution is more pronounced, and a “tailing phenomenon” can be observed; the resistivity of low-resistivity oil layers increases with the increase of porosity, while the resistivity of water layers decreases with the increase of porosity. Through comprehensive research, low-resistivity oil layers and water layers can be distinguished.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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