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Study on Geological Genesis and Sedimentary Model of Complex Low Resistivity Reservoir in Offshore Oilfield

—A Case of NgIII Formation of X Oilfield in Bohai Sea

Wentong Zhang, Jie Tan, Feiteng Wang, Songru Mu, Bowei Liu

Bohai Oilfield Research Institute, CNOOC Ltd.-Tianjin, Tianjin, China
Email: zhangwt9@cnooc.com.cn

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Abstract

In order to study the micro genetic mechanism and main geological controlling factors of low resistivity reservoir in NgIII formation of X oilfield in Bohai sea in China, the clay mineral composition, irreducible water saturation, salinity and conductive minerals of low resistivity reservoir were studied by using the data of core, cast thin section and analysis, and compared with normal resistivity reservoir. At the same time, the control effect of sedimentary environment on low resistivity reservoir was discussed. The results show that the additional conductivity of high bound water content and high montmorillonite content in the reservoir together leads to the significant reduction of reservoir resistivity, which is the main microscopic cause of the formation of low resistance, and is mainly controlled by the sedimentary background such as paleoclimate and sedimentary cycle. During the deposition period of NgIII formation, the paleoclimate was dry and cold, and it was at the end of the water advance of the medium-term sedimentary cycle. The hydrodynamic force of the river channel was weak, the carrying capacity of the riverbed was weak, and the river channel swayed frequently, resulting in fine lithologic particle size, high shale content and complex pore structure of the reservoir, resulting in significant reduction of reservoir resistance. The research conclusion would have strong guiding significance for the development of low resistivity reservoirs in this area.

Keywords

Low Energy Braided River, Low Resistivity Reservoir, Irreducible Water Saturation, Clay Minerals, Paleoclimate, Hydrodynamic Force

1. Background

With the deepening of oil and gas exploration and development, more and more complex types of oil reservoirs have been discovered, and low resistivity reservoirs are typical of them. Low-resistance reservoir has attracted a lot of attention due to its strong concealment and complexity. At present, the research of low resistivity oil layer mainly focuses on its microgenesis and quantitative identification and evaluation of logging (Lin et al., 2019; Jin et al., 2021; Xiu et al., 2018, Zheng et al., 2018; Wang et al., 2016), but the relevant research on the macro-geological genesis and low resistivity reservoir sedimentary model controlling the formation of low resistivity oil layer is rarely involved, and the geological genetic model of low resistivity oil layer often has wide applicability, regardless of the interpretation of low resistivity oil layer in the new block. It is also of great significance to understand the deposition of low resistivity oil layers in the old block and to search for superior reservoir zones.

Low-resistance oil layers in Bohai Oilfield are mainly distributed in the middle of the Neogene Guantao Formation, which is a set of sandy braided river deposits with fine lithology and poor physical properties, known as "Guanxi Member". The stratum thickness is 15 - 20 m and is covered by stable mudstone caprocks at the top and bottom. It is widely distributed and has great potential in the region. In recent years, the CFD, QHD, PL and other oilfields located in the western Bohai Sea have successively found the existence of low resistivity oil layers in the "Guanxi Member" through the review of logging data, and the test production has confirmed that it has great development potential (Lin et al., 2019; Jin et al., 2021; Xiu et al., 2018). At the same time, the data also shows that the characteristics of the low resistivity reservoir in this section are complex, which are characterized by strong heterogeneity, poor local physical properties and high shale content, which are significantly different from the normal resistivity reservoir. At present, there is no clear understanding of the microgenesis and the main controlling factors of the deposition of the special low resistivity oil layer "Guanxi Member", so it is necessary to carry out a research. Taking the NgIII oil formation of Bohai X oilfield as an example, this paper comprehensively analyzes its microgenesis, macro-geological genesis and sedimentary model based on core, analysis, testing, logging and seismic data, so as to guide the development of low resistivity oil layers in X oilfield and provide reference for the research and development of low resistivity oil layers under similar sedimentary background.

2. Overview of Low Resistivity Reservoir

X Oilfield is located in the western sea area of the Bohai Sea, and is structurally located in the east of the eastern block of the Shaleitian uplift in the Bohai Bay Basin. It is a low-amplitude fault anticline developed on the uplift, and is a continental multi-cycle fluvial facies deposit. The main oil-bearing series are the Minghuazhen Formation and the Guantao Formation. The study shows that

NgIII oil formation is the only low resistivity oil layer in X oilfield, and the geological stratification in the region belongs to "Guanxi Member", which is developed between large and thick sandstone. According to the statistics of drilling data, the average resistivity of oil layer is 2.8 - 4.2 Ω·m, the resistivity of water layer is 2.5 - 3.8 Ω·m, and the resistivity index is 0.8 - 1.2. It is a typical low resistivity oil layer. The logging data shows that the lithology of the low resistivity section is mainly pebbly fine sandstone, the shale content is higher than that of the upper and lower layers, the total gas logging (Tg) is 10,000 - 30,000 ppm, the fluorescence display level is C~D, the gas logging is lower than that of the conventional oil layer, and the oil content is generally lower than that of the normal oil layer, but significantly higher than that of the water layer (**Figure 1**).

Controlled by the special sedimentary background, the reservoir characteristics of this layer are relatively complex. The sand ratio is only 50% - 70%, which is lower than the other thick reservoirs of the Guantao Formation (normal resistance). The lateral change of the reservoir is fast and the heterogeneity is strong. At the same time, the permeability of the reservoir is 30 - 180 mD, which is characterized by low permeability locally.

3. Microgenesis of Low Resistivity Reservoirs

The micro genesis of low resistivity oil layers is complex and diverse, generally caused by a combination of one or more factors such as reservoir lithology, physical properties, and oil bearing properties. The micro genesis is not entirely the same under different sedimentary backgrounds (Zheng et al., 2018; Wang et al., 2016; Liao et al., 2010; Schoen et al., 1999). The reason why rocks exhibit low resistivity is mainly due to the particularity of rocks and fluids, and their electrical conductivity is mainly affected by both fluid and rock skeleton. Fluid factors include high bound water saturation, high formation bound water, and high salinity of free water; The main reasons for the rock skeleton are as follows: 1) the high shale content of the reservoir and the additional conductivity of high content clay minerals; 2) The rock is rich in metal conductive minerals; 3) The

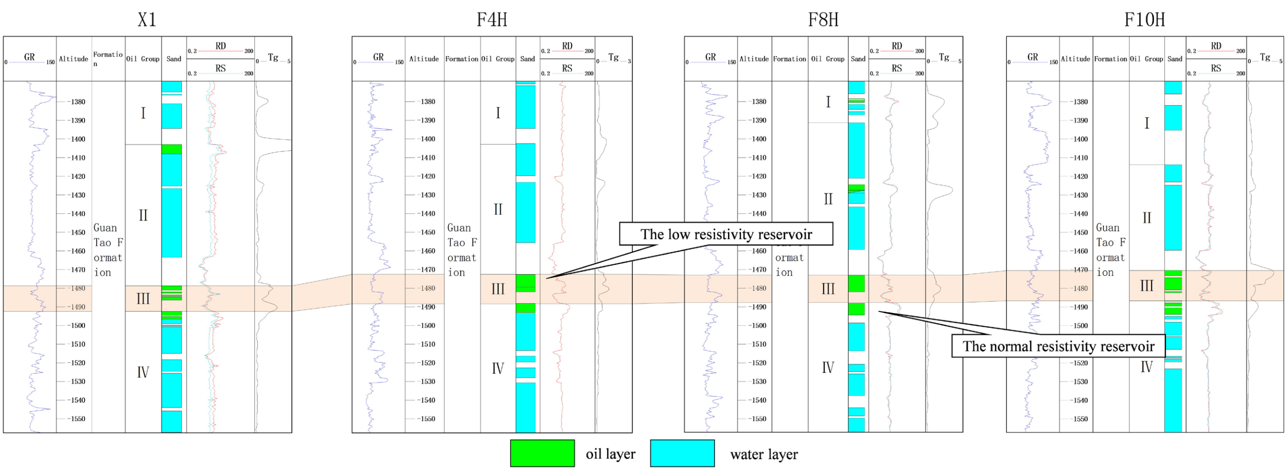


Figure 1. Logging characteristics of low resistivity reservoir in the study area.

rock has a fine particle size and a large number of micro pores, and a large amount of trapped water exists in the micro pore throat space to form a conductive network.

3.1. Irreducible Water Saturation

After the completion of oil and gas filling, due to the difference in the wettability of the fluid to the rock and the effect of capillary force, some of the non flowing membrane water still adsorbed on the surface of the rock particles or remaining in the micropores is called bound water or residual water (Figure 2), which generally contains a large amount of cation. The relatively high content of bound water in rocks can adhere to the surface of particles to form a connected conductive network, which can significantly reduce the resistivity of oil layers.

In addition to core experimental measurement, nuclear magnetic resonance logging is currently the only technical means that can directly measure the seepage volume of free fluids (oil, gas, and water) in a reservoir, and has significant advantages in evaluating low resistivity reservoirs (Hamada et al., 2003; Coates et al., 1995). This study uses two methods, logging while drilling (LWD) based on nuclear magnetic resonance technology and core experiment measurement, to determine the bound water content of low resistivity layers, and compares and verifies the two data to determine a more accurate bound water saturation.

According to core experiment measurement and nuclear magnetic resonance logging, the irreducible water saturation of NgIII oil formation (low resistivity oil layer) is mainly 39.2% - 60.1%, with an average irreducible water saturation of 47.6%. However, the bound water content of the lower NgIV oil formation (normal resistivity) is only 20.5% - 40.0%, with an average bound water saturation

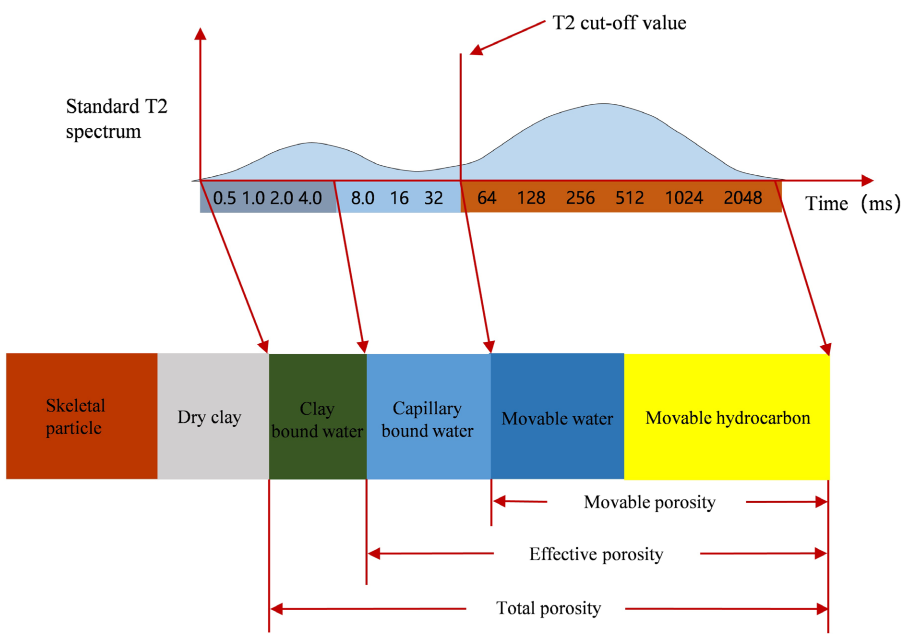


Figure 2. Relationship between T2 spectrum of nuclear magnetic resonance logging and porosity of various fluids.

of 29.6%. Compared to NgIV oil formation, NgIII oil formation low resistivity reservoirs have significantly high irreducible water saturation, with a 13% to 20% higher irreducible water saturation content, which is one of the important causes of low resistivity reservoirs.

According to the core nuclear magnetic resonance saturation experiment results, the irreducible water saturation of NgIII oil formation (low resistivity oil layer) is about 39.2% - 51.5%, and the average irreducible water saturation is 44.6%; However, the bound water content of the lower NgIV oil formation (normal resistivity) is only 20.5% - 38.7%, with an average bound water saturation of 29.6%. Compared to NgIV, NgIII low resistivity reservoirs have significantly high irreducible water saturation, with a 12% to 15% higher irreducible water saturation content, which is one of the important causes of low resistivity oil reservoirs (**Figure 3**).

3.2. Bound Water Salinity

Mineralization refers to the total content of various mineral elements in formation water, which is affected by the formation environment and clastic particle sediments. The higher the salinity of formation water, the higher the content of free metal cations, such as Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, etc. Formation water includes movable water and bound water.

According to the mineralization analysis data of the water layer of the NgIII formation, the total salinity of movable water in the formation water of the NgIII formation is 5527 - 7105 mg/L, and the total salinity of the formation water of the NgIV formation is 5918 - 7030 mg/L. The burial depth and mineralization values of the two layers are basically the same, while the NgIV ormation is a normal resistivity oil layer, with a large difference in the resistivity of the oil water layer, indicating that the salinity of free water in the formation is not the reason for the low resistivity of the NgIII formation.

To obtain an accurate bound water salinity, a core sample distillation extraction method was used. First, Centrifuge and dry the rock sample to remove movable water from the sample, then extract the salt content of the formation water, and accurately determine the cation and anion components in the filtrate using ion chromatography. The experimental results show that the mineralization degree of bound water of NgIII is 40,500 - 61,200 mg/L, with an average of 51,230 mg/L. The mineralization degree of NgIV bound water is 17,090 - 21,360 mg/L, with an average of 20,030 mg/L, only 40% of the mineralization degree of NgIII bound water (**Figure 4**).

Based on the above data analysis, compared to the NgIV oil formation, the NgIII oil formation has the "dual high" characteristics of high bound water saturation and high bound water salinity. These highly mineralized formation water forms a dense conductive network in a large number of connected micropores, which significantly reduces the resistivity of the oil and gas reservoir, and is therefore the key micro cause of low resistance in this reservoir.

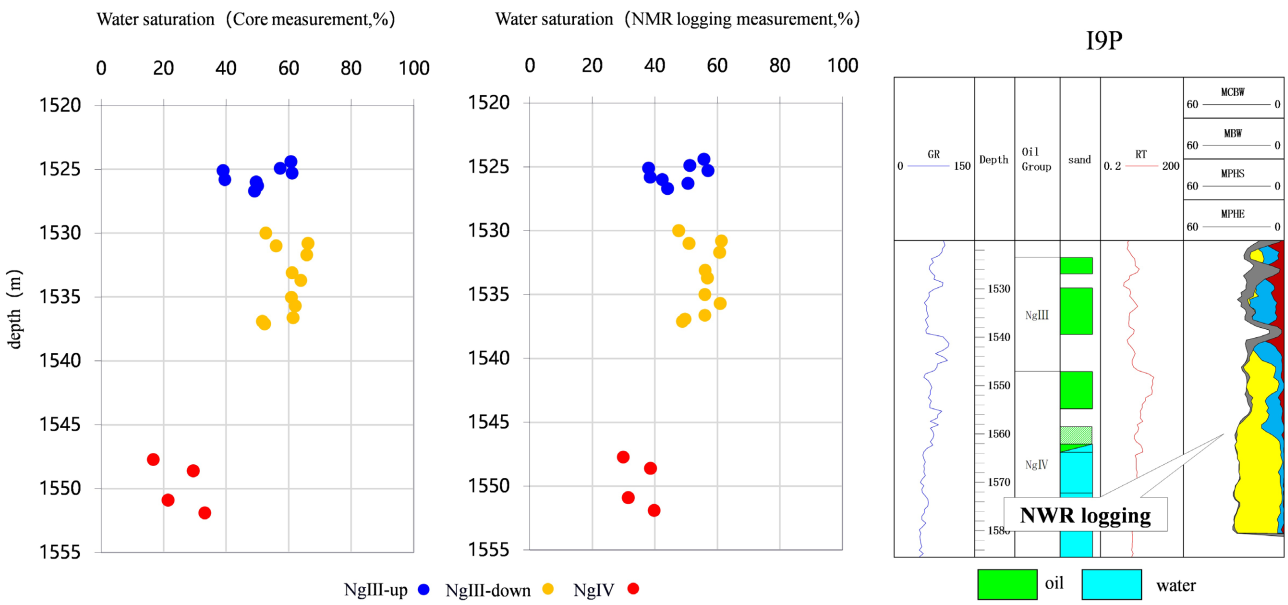


Figure 3. Irreducible water saturation in different formations.

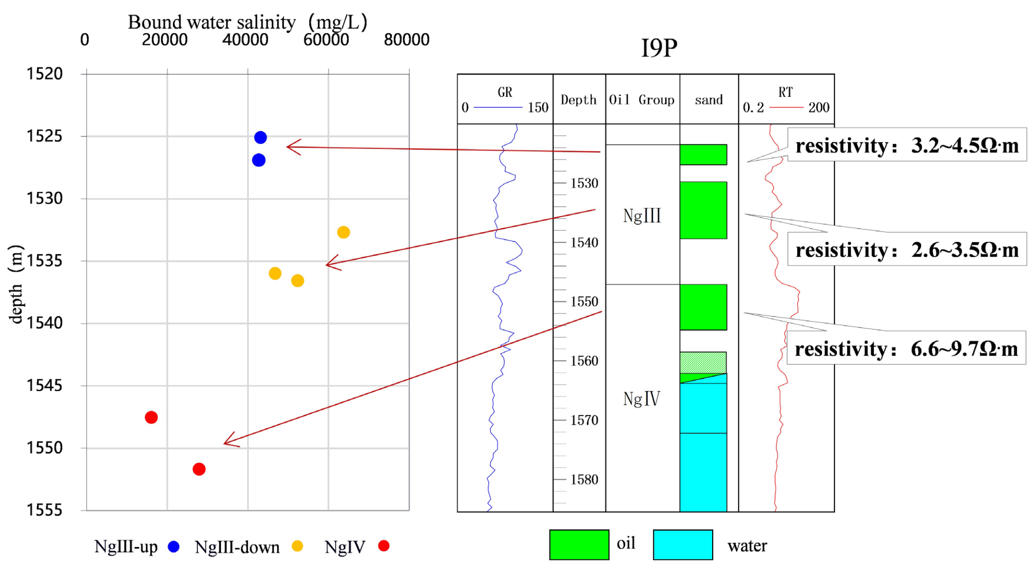


Figure 4. Relationship between bound water salinity and resistivity (logging) of samples from different formations.

3.3. Additional Conductivity of Clay Minerals

The influence of a certain content of clay minerals on the conductivity of oil reservoirs mainly manifests in the following two aspects: 1) Clay minerals have characteristics such as adsorption, expansion, and cation exchange (CEC). The larger the cation exchange capacity of clay minerals, the stronger the additional conductivity, and the lower the reservoir resistivity. Among them, montmorillonite has the strongest cation exchange ability (Table 1). 2) Minerals such as montmorillonite and illite mixed layer are prone to form "film like" and "bridge like" structures on the surface of mineral particles, further enhancing the conductivity of the reservoir.

Table 1. CEC capacity of clay minerals.

Clay mineral type	Montmorillonite	Illite	Kaolinite	Chlorite
CEC (mmol/100 g)	80 - 150	10 - 40	3 - 15	10 - 40

The scanning electron microscope and X-ray diffraction analysis data show that the clay mineral content of the NgIII oil formation is 12% to 25%, which is a medium clay mineral reservoir. The main type is the mixed layer of illite and montmorillonite, with an average mass fraction of 77%, of which illite accounts for 72%, montmorillonite accounts for 28%, followed by kaolinite, with a mass fraction of 14%, respectively (**Figure 5**). The low resistivity section of the study area is mainly composed of an illite montmorillonite layer and a montmorillonite layer, which are intermediate products of the conversion of montmorillonite to illite. Their morphology and properties are between illite and montmorillonite. Under scanning electron microscopy, they appear in the form of honeycombed thin films (**Figure 6**), with strong adsorption capacity and water absorption and expansion, resulting in low oil layer resistivity. However, the clay minerals in the lower NgIV oil group have a relatively low content of the mixed layer of the clay and the average mass fraction is only 5%. According to the clay mineral content and cation exchange content (CEC) analysis, from top to bottom, the content of the mixed layer of the clay minerals is 4%, 15%, 5%, and 1%, respectively, and the cation exchange content of the clay minerals is 10, 35, 2, and 2 (mmol/100 g), compared with the NgIV. The NgIII has a higher content of the illite montmorillonite mixed layer and a higher cation exchange content of clay minerals, resulting in lower reservoir resistivity performance. Based on the above data analysis, the additional conductivity of clay minerals is an important reason for the formation of NgIII low resistivity oil layers.

4. Macroscopic Geological Origin of Low Resistivity Oil Layers

4.1. Geologic Climate

The shallow paleoclimatic conditions directly control the hydrodynamic conditions of the river channel, affecting the size of the river and the transport of the riverbed, as well as the sedimentation rate of sedimentary rocks and the speed of rock weathering and leaching, thereby affecting reservoir characteristics such as rock particle size, shale content, and clay mineral content.

Previous researchers have conducted research on the paleoclimate in the western Bohai Sea area based on data such as paleobiological assemblages and sediment element geochemical characteristics. The climate during the NgIII sedimentary period was dry and cool, while the climate during the NgIV sedimentary period was warm and hot (Li, et al., 2019). At the same time, this paper uses the composition characteristics of authigenic clay minerals to study the paleoclimatic characteristics. According to literature research, the most important factor controlling the formation and transformation of clay minerals is paleoclimate. Under the same material source conditions, in dry and cold climatic conditions,

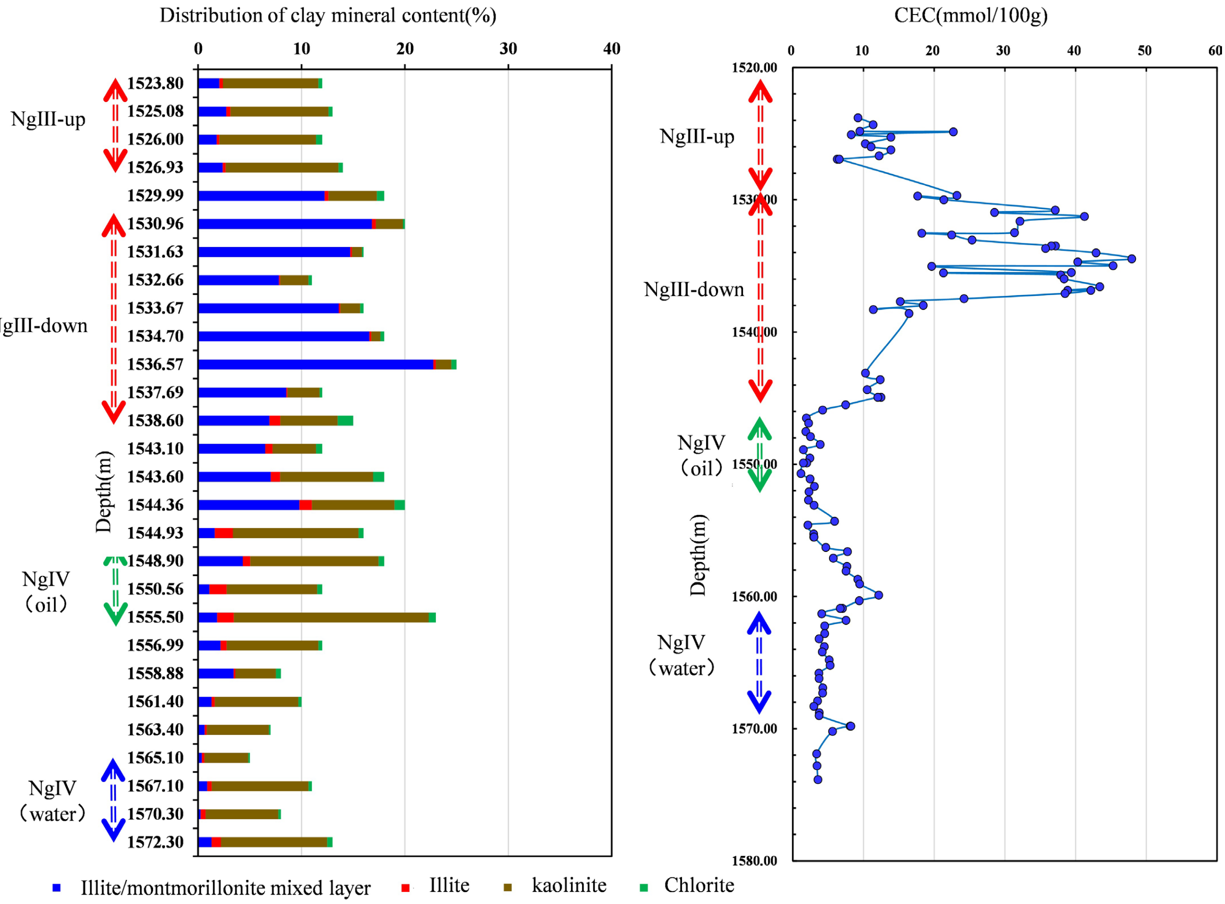


Figure 5. Distribution of clay mineral content in different stratums (Well I9P).

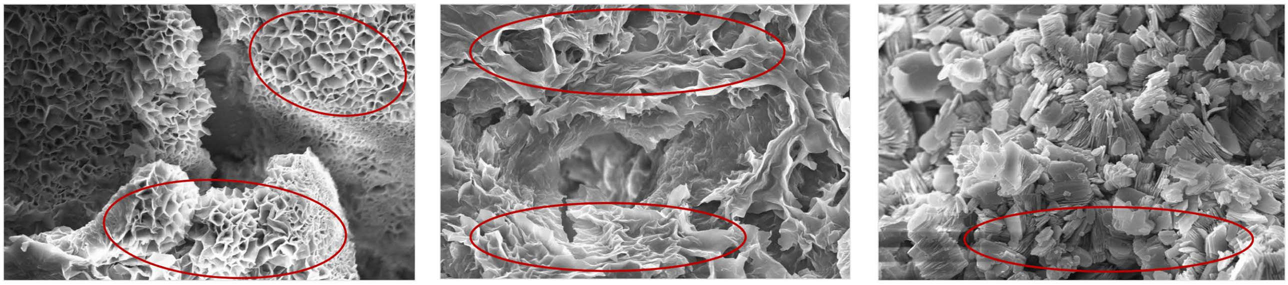


Figure 6. Clay mineral characteristics of NgIII (1500 times magnification by TEM).

it is easier to form montmorillonite and illite montmorillonite mixed layer clay minerals (Chen et al., 2003; Chen et al., 2005; Jin, 2011; Cao et al., 2017). Kaolinite is formed by intense leaching and weathering of acidic volcanic and metamorphic rocks and their weathering products in a warm and humid environment. Kaolinite generally reflects a warm and humid paleoclimate (Chen et al., 2003; Chen et al., 2005; Jin, 2011; Cao et al., 2017). Therefore, the relative content ratio of kaolinite to montmorillonite can reflect the warm and humid climate conditions in the source region. As temperature increases and precipitation increases, the stable component of kaolinite increases, while the relative content of montmorillonite decreases. The increase in the relative content ratio of kaolinite to montmorillonite indicates an increase in temperature and a warmer and wetter climate; On the contrary, it indicates a dry and cold climate.

As mentioned earlier (**Figure 5**), the clay mineral type of NgIII oil layer is mainly composed of the mixed layer of illite and montmorillonite, with the proportion of montmorillonite accounting for about 70%, while the content of kaolinite is relatively small; The clay minerals in the lower Ng IV oil layer have a relatively high content of kaolinite, with an average content of 17%, while the content of the illite montmorillonite mixed layer is relatively small. The large differences in the content of montmorillonite and kaolinite between the two layers reflect the differences in paleoclimatic conditions. The NgIII period has a dry and cold paleoclimate, while the NgIV period has a warm and humid paleoclimate, which is in good agreement with previous research results. The Guantao Formation experienced a "warm-cold-warm" climate change from bottom to top during the sedimentary period (**Figure 7**). The unique paleoclimatic conditions during the NgIII sedimentary period are an important sedimentary background that controls the low resistivity of its oil layers.

4.2. Sedimentary Cycle

The study area belongs to continental sedimentation with river lake interaction.

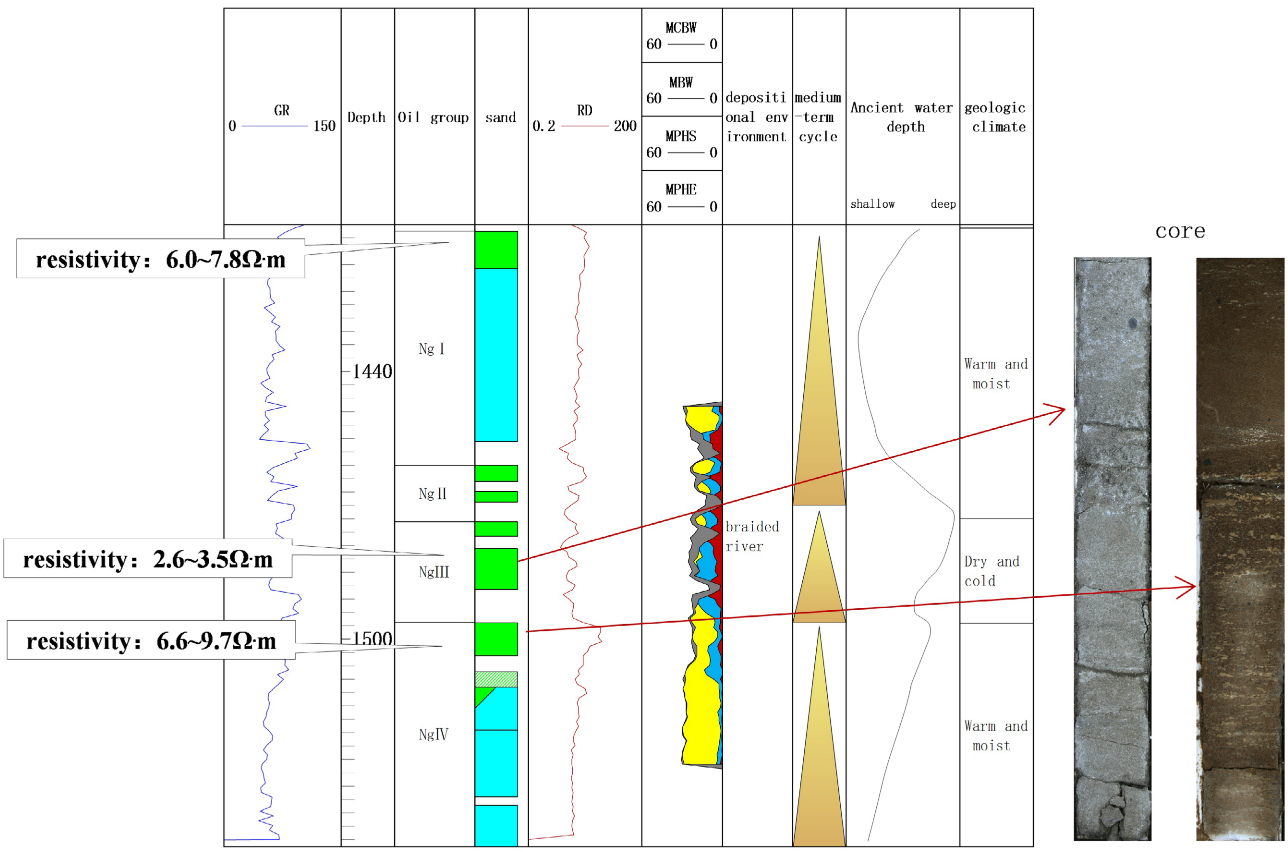
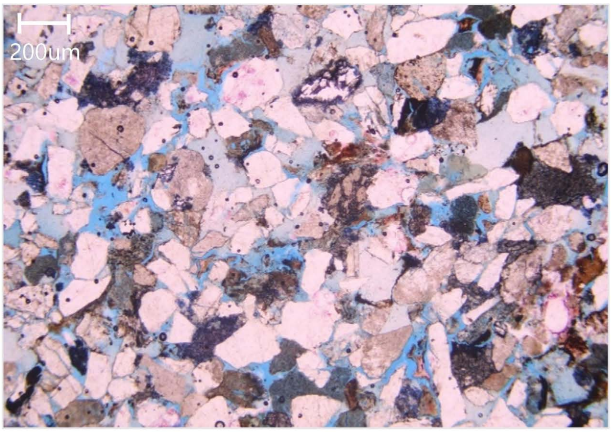


Figure 7. Division of single well sedimentary cycles in Guantao Formation in the study area (Well I9P).

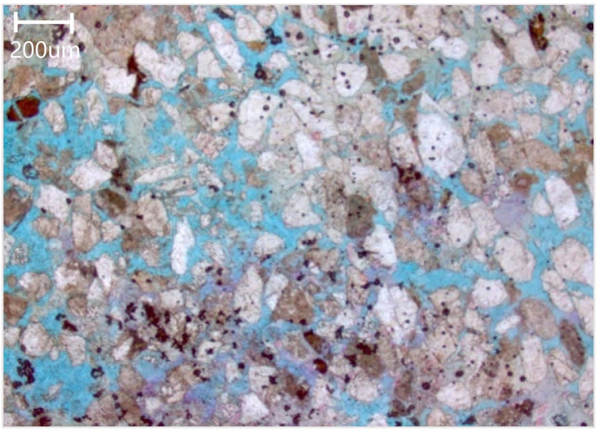
Sedimentary base level cycles control the sedimentary evolution of the stratum. With the changes in medium to short term base level cycles and paleoclimate, reservoir characteristics also change. From the perspective of sequence stratigraphy, multiple secondary sedimentary cycles developed in the Guantao Formation in the study area, indicating frequent fluctuations in the ancient water body of the lake basin. However, from the perspective of the medium-term cycle, the Guantao Formation mainly developed three ascending semi cycles, which experienced a shallow deep shallow paleowater cycle. The NgIII sedimentary period was during the lake flooding period, with the deepest water body. From the perspective of core characteristics, there are also significant differences in core color, grain size, and sedimentary structure between NgIII and NgIV, reflecting changes in their sedimentary cycles and ancient water bodies.

4.3. Geological Genetic Model of Low Resistivity Oil Layers

The formation of complex low resistivity oil layers in the NgIII is the result of the joint coupling of paleoclimatic evolution and medium-term sedimentary cycles, and none of them is indispensable. The NgIII sedimentary period is during the lake flooding period, and the sediment source supply capacity is the weakest. At the same time, the paleoclimate is dry and cold, rainfall is small, the development of river channels is shrinking, and the hydrodynamic conditions of river channels are weak, making the lithology of sedimentary sand bodies relatively fine and the content of argillaceous material relatively high. The rock pore structure is complex, with a large number of internal micropores developed, and high capillary pressure, which can significantly increase the bound water saturation and mineralization (Figure 8). At the same time, the weathering and leaching effect of the dry and cold paleoclimate weakened, providing favorable conditions for the formation and preservation of montmorillonite (or illite montmorillonite mixed layer mixed layer), resulting in a high content of montmorillonite in the reservoir, ultimately leading to a strong additional conductivity of clay in



RD=2.7Ω·m，NgIII



RD=6.1Ω·m，NgIV

Figure 8. Pore structure and characteristics of interstitial materials in thin slices of rock casting (comparison between low resistivity oil layers and normal oil layers).

the reservoir, further reducing the resistivity. Finally, high bound water and strong clay coupled with electrical conductivity jointly control the formation of the low resistivity of NgIII oil layers.

5. Application of Achievements

A complete trap is developed at 3 km to the southeast of the oil-bearing area of NgIII formation in the low resistivity layer of X Oilfield, which is an east-west anticlinal structure. There are only 2 passing wells in the block. Through reservoir comparison, this set of reservoir and NgIII oil formation of low resistivity layer in X oilfield are contemporaneous deposits, both of which belong to, and the reservoir resistivity is only 2.8 - 4.0 Ω·m, which is basically equivalent to the upper and lower water layers. The logging shows that the fluorescence display level of reservoir cuttings in this section is Grade D, with a certain oil-bearing property. However, due to the lack of logging data such as spontaneous potential, neutron, density, nuclear magnetic logging and sampling, the initial interpretation conclusion is that the top is developed with oil-bearing water layer, and the bottom is water layer.

According to the research results of geological genesis and sedimentary model of low resistivity oil layer in NgIII oil formation of X oilfield, the development of low resistivity oil layer in the study area is mainly controlled by paleoclimate and sedimentary cycle, and the development and influence of both are regional and extensive, and the new block has the same provenance as the main block of NgIII oil formation. From the analysis of genetic model, reservoir structure and other analogies, it is believed that the new block has a greater possibility of forming low resistivity oil layer. Therefore, the log interpretation conclusion is changed to suspect low resistivity reservoir. In order to verify this understanding, well C5 was perforated and produced 45 m^3 of oil per day at the initial stage. It was successfully confirmed that the NgIII oil formation in the new block is also a low resistivity oil layer (Figure 9). This achievement not only verifies the

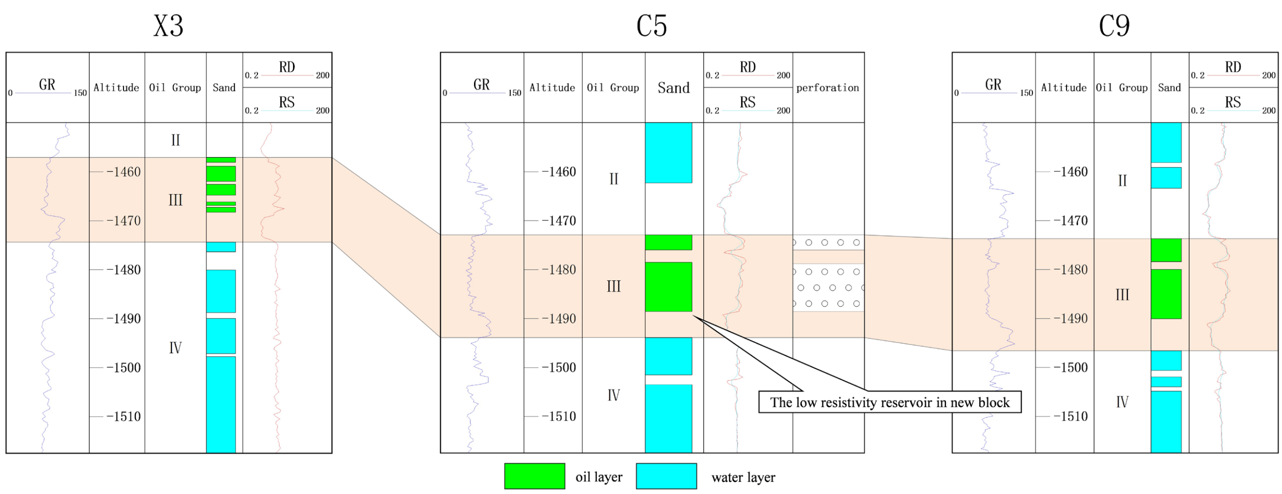


Figure 9. Recheck and verification of low resistivity oil layer of NgIII formation in the study area.

correctness of the understanding of the low resistivity geological genetic model of the Guantao Formation in the study area, but also has certain guiding significance for finding low resistivity oil layers in a larger range of the "Guanxi Member".

6. Conclusion

1) The unique macro sedimentary environment controls the reservoir characteristics of NgIII. The fine particle size and high shale content of the reservoir make the bound water saturation of NgIII higher, and the high content of montmorillonite enhances the cation exchange of the reservoir. The superposition of two influencing factors jointly leads to the formation of low resistivity oil layers.

2) The formation of NgIII low resistivity oil layer is the result of the coupling effect of two main controlling factors, namely, paleoclimate and ancient provenance. Its particularity and uniqueness indicate that low resistivity oil layer can only be formed when both main controlling factors are favorable at the same time. The paleoclimate and regional sedimentary cycle changes have a wide range of regions, which may also be the key factor for the widespread development of "Guanxi Member" low resistivity oil reservoirs in the western Bohai Sea.

3) The NgIII oil formation in the study area is a low-energy braided river deposit under weak hydrodynamic conditions. Compared with the conventional strong hydrodynamic braided river, its rocks are characterized by fine grain size and high shale content, making it easier to form low resistivity oil layers.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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