Characteristics and control mechanism of low resistivity contrast oil pays in Chang 8 tight sandstone reservoir of Longdong West area, Ordos Basin

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Abstract

The log interpretation and evaluation of Chang 8 tight sandstone reservoir in Longdong West area, Ordos Basin, is facing great challenges due to the existence of low resistivity contrast oil pays. To better guide the exploration of oil resources in this area, the characteristics and control mechanism of low resistivity contrast oil pays were studied in this research. Firstly, according to the relative value of apparent resistivity increase rate of the target formation, the reservoir was divided into two types: low resistivity contrast oil pay (LRCP) and high resistivity oil pay (HRP). Then, the reservoir characteristics were studied by comparing and analyzing the experimental data, formation water data and logging data collected from the two reservoir types. On this basis, the control mechanism of LRCP was studied and summarized into reservoir
micro factors and regional macro factors, respectively. It is found that the reservoir rock composition between LRCP and HRP is basically the same. Compared with HRP reservoir, the average porosity and permeability of LRCP reservoir are relatively better, but the pore structure is relatively poorer because of the high content of micro pores. When the filling pressure of crude oil is sufficient enough, the high oil saturation can be formed in LRCP reservoir. The high irreducible water saturation and high formation water salinity are the main micro factors reduced the reservoir resistivity. Besides, the difference of hydrocarbon expulsion capacity of source rock and the regional difference of formation water salinity are the macro factors influenced the distribution of LRCP and HRP from vertical and horizontal of the region. The formation of LRCP is controlled by the comprehensive influence of reservoir micro factors and regional macro factors. And the comprehensive consideration of the influence of micro factors and macro factors on LRCP is suggested during the log interpretation and evaluation.

**Keywords:** Tight sandstone; Low resistivity contrast oil pay; Reservoir Characteristic; Control mechanism; Longdong West area.

1. **Introduction**

Low resistivity contrast oil pay, as an important oil resources with strong concealment, have received much interest in recent years due to their high oil production and wide distribution around the world(Zemanek, 1989; Worthington, 2000; Onyinye, 2010; Feng et al., 2017a). The low resistivity contrast oil pay is defined as an oil zone which has small resistivity difference to the water layer, and it can be summarized into two aspects: (1) The absolute value of resistivity in oil layers is low, which can be lower
than that of adjacent water layers. (2) The resistivity increase rate of the oil layer is generally between 1.0 and 3.0 (Xie et al., 2002; Ouyang et al., 2009; Zhang et al., 2018). This phenomenon makes it difficult to distinguish oil pays from water layers by using resistivity logging response (Chu and Steckhan, 2011; Xiao et al., 2012).

The problem for the logging interpretation and evaluation of low resistivity contrast oil pays has existed for many years because of its complicated genesis and conductive mechanism (Etnyre and Mullarkey, 1996; Kumar et al., 2009). Up to now, there are more than ten factors were found can lead to low-resistivity oil pay reservoir, such as shoulder bed effects, irreducible water, conductive minerals, clay types and their contents, pore structure, wettability, formation water salinity, and drilling mud invasion (Yang et al., 2008; Claverie et al., 2010; Qin et al., 2013; William et al., 2016).

Yan et al (2018) classified those influence factors into two categories, including internal factors related to reservoir properties and external factors affected by external conditions. Generally, the low resistivity contrast oil pay is usually caused by the combination influence of several factors, and the influence factor is often different in different areas or different reservoir types, which leads to that there is not a unified standard for understanding the genesis of low contrast oil reservoirs in different oilfields and research institutes (Hamada and Al-Awad, 2000; Montaron, 2007; Kibria and Hossain, 2012; Feng et al., 2017b). However, there is a law to follow for the low resistivity contrast oil pays in a certain area or a certain type of specific reservoir (Yan et al., 2010; Mao, 2016). On the basis of reservoir characteristics analysis, studying the main influence factors of low resistivity oil pays from multiple aspects is the key to
carry out effective log interpretation and evaluation (Mao et al., 2007; Ayham et al., 2016; Pratama et al., 2017). Kusuma et al. (2016) proposed an effective method to identify low resistivity contrast oil pay zones during the re-evaluation of old wells in the “S” field by integrated analysis of the main factors causing the low resistivity zones. Arbab et al (2017) established a reliable water saturation model based on the pore structure characteristics of low resistivity contrast oil pay in carbonate reservoir of Buwaib Formation in the Persian Gulf. Bai et al. (2019) proposed a comprehensive fluid identification method for fluid typing in the Huanxian area of the Ordos Basin in China by analyzing the regional distribution characteristics of low resistivity contrast oil pay reservoir.

In these years, tight sandstone reservoir in Longdong West area, Ordos Basin, China, is exploring and developing. The target bed of this study is Chang 8 tight sandstone reservoir, which is located below the Chang 7 oil shale and it is the main production horizon of oil and gas in this area because its good hydrocarbon storage condition(Figure 1). However, with the deepening of oil exploration and development, more and more low resistivity contrast oil pays were found, which brings great difficulties to the log interpretation and evaluation of reservoir. Therefore, we present a research to study the reservoir characteristics and control mechanism of low resistivity contrast oil pays, which aim to provide a valuable reference for the future exploration and development of low resistivity contrast oil pays in this area.
Figure 1. Location of the research area and target horizon.

2. Data and Research method

Considering that the low resistivity contrast oil pay and high resistivity oil pay are developed together in this region, so we first separated the reservoir into low resistivity contrast oil pay (LRCP) and high resistivity oil pay (HRP) based on the relative value of the apparent resistivity increase rate (ARI), which is calculated by dividing the log data of formation resistivity (RT) by the pure water layer (R₀) of the same or adjacent well sections. According to the previous understanding of the definition of LRCP reservoir (Xie et al., 2002; Ouyang et al., 2009; Zhang et al., 2018), we take the oil pay reservoir with ARI less than 3 as LRCP, and the oil pay reservoir with ARI greater than 3 as HRP in this research. Then, the reservoir rock composition, porosity and permeability, pore structure and logging response characteristics were analyzed by
comparing the experimental data, formation water analysis data and real logging data collected from this two reservoir types. Finally, the control mechanism of LRCP was studied from the micro factors and macro factors respectively. Among them, the micro factors include the reservoir irreducible water saturation and formation water salinity. And the macro factors include the hydrocarbon expulsion capacity of source rock and the regional difference of formation water salinity. Figure 2 shows the flowchart of the whole research method.

Figure 2. Flowchart for the research

3. Results and Discussion

1) Reservoir characteristics analysis

(1) Rock composition

Figure 3 is the ternary diagrams of the reservoir rock composition in LRCP and HRP reservoir based on the XRD whole-rock analysis result. It can be seen that the reservoir lithology is mainly lithic arkoses and feldspathic litharenites. The mineral
composition of the rock is mainly feldspar (ave. 30.49%) and quartz (ave. 29.6%), followed by various rock fragments (ave. 27.06%). According to the microscopic observation and statistical results of sandstone thin sections, the rock interstitial materials are mainly composed of authigenic clay minerals, followed by ferrocalcite and siliceous (Fig. 4a). The XRD clay fraction mineralogy analysis results show that the main types of authigenic clay minerals are chlorite and illite, among which the chlorite is the most abundant in LRCP (ave. 50.1%), and illite is the most abundant clay mineral in HRP (ave. 39.7%). But the content of illite-smectite mixed layer with strong ion exchange capacity is not high, even less than 15% in LRCP reservoir, which indicate that the ionic conductivity of reservoir caused by clay is not strong.

Figure 3. Ternary diagram of rock composition: (a) LRCP reservoir (61 core samples) and (b) NRP reservoir (128 core samples). Notes: Q: quartz; F: feldspar; R: rock fragments.
(a) The distribution of different interstitial materials in LRCP and HRP from thin section observation experiment and (b) clay minerals from XRD experiment.

(2) Porosity and permeability

Porosity and permeability, as main physical properties of reservoir, play an important role in the migration and storage of hydrocarbon (Grude et al., 2015). Figure 5 is the distribution frequency histogram based on the overburden porosity and permeability measurement results of 35 cores from LRCP reservoir and 40 cores from HRP reservoir. It shows that the porosity of LRCP is mainly distributed between 8% and 12%, with an average of 10.43%. And the permeability is mainly distributed between 0.001mD and 0.3mD, with an average of 0.2mD. The porosity of HRP reservoir is mainly distributed between 4% and 10%, with an average of 7.01%. And the permeability is mainly distributed between 0.001mD and 0.3mD, with an average of 0.16mD. According to the cross plot of porosity and permeability (Figure 6), the porosity and permeability meet a good power index relationship, and the curve slope of the fitting relationship between porosity and permeability of LRCP reservoir (Slope=0.3323) is lower than that of HRP reservoir (Slope=0.771). That is to say,
although the average porosity and permeability of LRCP reservoir is better than that of HRP reservoir, the permeability of LRCP reservoir will be lower than that of HRP reservoir under the same porosity.

Figure 5. The distribution frequency histogram of porosity and permeability: (a) is the porosity distribution histogram, and (b) is the permeability distribution histogram.

Figure 6. The relationship between porosity and permeability

(3) Pore structure characteristics

Pore structure is an important factor affecting reservoir quality and petrophysical property of tight reservoir (Lai et al., 2018; Wang et al., 2018). The mercury injection capillary pressure (MICP) and nuclear magnetic resonance (NMR) experiment were
used to analyze the reservoir pore structure. Figure 7 shows the intrusive mercury curve based on MICP experiment. The mercury injection curve can be divided into three stages from its shape characteristic: initial mercury injection stage, intermediate platform stage and final rising stage, which correspond to the mercury intrusion process from macropore to micropore (Yang and Wei, 2004). The pressure corresponding to the initial stage of mercury injection is called displacement pressure ($P_d$). The smaller the displacement pressure is, the more easily mercury enters the macropores (Ma and Zhang, 2017). Figure 8 is the distribution characteristics of NMR $T_2$ spectrum in LRCP reservoir and HRP reservoir, respectively. The pore size is related to the distribution range of $T_2$ spectrum. In general, the first peak of the $T_2$ spectrum represents the volume of the micropores and the last peak represents the macropores, and the sum of $T_2$ spectrum amplitude reflects the porosity of the core (Liu et al., 2009). The pore structure parameters calculated from MICP and NMR experiments are shown in Table 1. It can be seen that the NMR porosity (POR) of LRCP is higher than that of HRP reservoir (ave.10.4% and ave.7.05%, respectively), but the $T_2$ geometric average value ($T_{2gm}$) of LRCP is slightly smaller (ave.4.78um and ave.6.99um, respectively), which indicate that the pore structure in LRCP reservoir is relatively poor. Based on the pore structure parameters calculated from MICP experiment, the average pore radius ($R_{ave}$) of LRCP reservoir is smaller than that of HRP reservoir (0.19um and 0.27um, respectively), and the displacement pressure ($P_d$) is larger (1.12mpa and 0.82mpa respectively), which indicates that the pore space of LRCP reservoir is mainly composed of micro pores with small pore radius, and it is difficult for mercury to enter
into micro pores. Besides, the maximum mercury saturation ($S_{Hg}$) of LRCP reservoir is higher than that of HRP reservoir (89.02% and 77.75%, respectively), which indicates that when the oil filling pressure is high enough, the oil saturation of LRCP reservoir is higher than that of HRP reservoir.

Figure 7. The characteristics of the intrusive mercury curve of (a) LRCP reservoir and (b) HRP reservoir.

Figure 8. The distribution characteristics of NMR T2 spectrum of (a) LRCP reservoir and (b) HRP reservoir.

Table 1. The pore structure parameters calculated from MICP and NMR experiments

<table>
<thead>
<tr>
<th>Type</th>
<th>NMR POR(%)</th>
<th>NMR T2gm(ms)</th>
<th>Pe(MPa)</th>
<th>Rave(um)</th>
<th>S_{Hg}(%)</th>
</tr>
</thead>
</table>
(4) Logging response characteristics

Logging response are the comprehensive reflection of physical properties and oil-bearing properties of reservoir rocks, and it is the most direct and effective data to understand reservoir characteristics (Tan, 2020). According to the logging response and formation testing results of reservoir, the cross-plot of density and resistivity of different fluid types was drawn in Figure 9. It can be seen that the density value of LRCPs and water layers is relatively low, and with the increase of reservoir density, the reservoir resistivity increases gradually. And it is difficult to identify the LRCP layer from water layer by the difference of density and resistivity. Table 2 shows the logging response characteristics of different fluid types by analyzing the logging response of 13 LRCP reservoirs and 20 HRP reservoirs and their adjacent wells. It can be seen that the difference of relative shale content (ΔGR) between LRCP reservoir and HRP reservoir is small, which indicates that the shale content is not the main reason to lead to the LRCP. However, the relative amplitude of spontaneous potential (ΔSP) of LRCP reservoir is higher than HRP reservoir, and with the improvement of oil-bearing, the value of ΔSP decreases gradually. Based on the logging response characteristics, there is a certain relationship between the reservoir physical property, electrical property, formation water property and oil-bearing property. The physical property affect the oil-bearing property and electrical property, together with the difference of formation water property jointly complicated the logging response of different pore fluids.
Figure 9. The cross plot of density (DEN) and resistivity (RT) of different fluid types by oil-testing and logging data.

Table 2. Logging response characteristics of different fluid types

<table>
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<th>Types</th>
<th>Fluid types</th>
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<th>ΔSP (mV)</th>
<th>RT (Ω·m)</th>
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<td>Ave.</td>
<td>Range</td>
<td>Ave.</td>
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According to the above analysis results of reservoir characteristics, the average porosity and permeability of LRCP reservoir are relatively better than those of HRP reservoir, but the micro pores are more developed, and the pore structure is relatively poorer. When the filling pressure of crude oil is sufficient enough, the high oil saturation can be formed in LRCP reservoir. In addition, the difference of formation water property is also a key factor affecting reservoir resistivity based on the logging response. On the basis of these understandings, the control mechanism of LRCP was studied and summarized into two aspects: one is the influence of micro factors related to the
reservoir irreducible water saturation and formation water salinity on formation resistivity; the other is the influence of macro factors related to hydrocarbon expulsion capacity of source rocks and regional difference of formation water salinity on the distribution of LRCP.

2) Study of the control mechanism of LRCP

(1) Micro factors: irreducible water saturation

According to the scanning electron microscope (SEM) analysis results, the main clay minerals of chlorite and illite are mainly fill the pores in the form of thin film and filamentous, which is easy to adsorb and form bound water (Figure 10). Meanwhile, the micropores are filled with bound water, which easily leads to high irreducible water saturation ($S_{wi}$). Based on the calculation and statistics results of nuclear magnetic resonance $S_{wi}$ of 14 cores from LRCP reservoir and 12 cores from HRP reservoir, it is found that the $S_{wi}$ of LRCP reservoir is generally higher than that of HRP reservoir. The irreducible water saturation of LRCP reservoir is mainly distributed in 40% ~ 70%, with an average value of 64.2%, while the irreducible water saturation of HRP reservoir is mainly distributed between 30% ~ 50%, with an average value of 45.7% (Figure 11a).

In order to study the effect of irreducible water saturation on formation resistivity, the relationship between the apparent resistivity increase rate (ARI) and irreducible water saturation was plotted in Figure 11(b). It can be seen that with the increase of irreducible water saturation the formation resistivity increase rate decreases gradually. When the irreducible water saturation increases to nearly 45%, the API is less than 3, which indicate that the additional conductivity caused by irreducible water is an
important factor to reduce the resistivity contrast between water layer and oil layer.

Figure 10. SEM observation shows: (a) the chlorite mainly fill the pores in the form of thin film, and (b) illite mainly fill the pores in the form of filamentous.

Figure 11. Distribution of irreducible water saturation and the relationship between the irreducible water saturation and apparent resistivity increase rate, including: (a) Irreducible water saturation distribution, and (b) Relationship between the irreducible water saturation and the apparent resistivity increase rate (ARI).

(2) Micro factors: formation water salinity

As the main conductive medium in pore space of rock, the salinity of formation water also affects the reservoir resistivity logging response. According to the statistical results of formation water analysis data of production well adjacent to LRCP layer and HRP layer, the formation water salinity varies greatly and the salt is mainly calcium.
chloride (Table 3). The formation water salinity in the HRP reservoir is distributed between 18760 and 51000 mg/L with an average value of 32712.91mg/L. The formation water salinity in the LRCP reservoir is mainly distributed between 45950 and 88010 mg/L with an average value of 63462.5mg/L, and the formation water salinity in the LRCP reservoir is almost twice than that of the HRP reservoir. Figure 12 shows the relationship between the formation water salinity and formation resistivity. It can be seen that with the formation water salinity increases, the value of formation resistivity decreases. When the formation water salinity is greater than 45 g/L, the resistivity difference between oil-water layer and water layer is not obvious, which indicates that high salinity of formation water is an important factor to reduce the reservoir resistivity and lead to the LRCP reservoir.

### Table 3. Formation water salinity statistics results

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<th>Ca²⁺ (mg/L)</th>
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<th>SO₄²⁻ (mg/L)</th>
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Figure 12. The relationship between formation resistivity and formation water salinity

(3) Macro factors: hydrocarbon expulsion capacity of source rock

Source rocks with larger effective thickness and closer to the reservoir usually have strong hydrocarbon expulsion ability, which makes it easy to displace crude oil into the small pores and form high oil saturation, vice versa (Yao et al., 2015; Shi et al., 2016). The hydrocarbon of Chang 8 reservoir mainly comes from the upper Chang 7 oil shale rock. The cross-well profiles from low resistivity contrast area to high resistivity area was drawn in Figure 13(a), in which the first track of each well is depth, the second track is the overlapping of acostic and resistivity log curves to reflect source rock and the filling color is black-gray, the third track is geological stratification, the fourth track is logging interpretation conclusion and the fifth track is natural gamma and permeability. It can be seen that the effective thickness of source rock in the low resistivity reservoir area is small, and the distance between source rock and reservoir is long. Figure 13(b) is the plane distribution of formation resistivity in the Huanxian area, which is located in the northwest of our study area, and the red line represents the location of the cross wells. In order to characterize the hydrocarbon
expulsion capacity of source rock, we measured the distance between source rock and reservoir \((D)\), and the effective thickness of source rock \((H)\) based on the cross-well profiles. Then the hydrocarbon expulsion capacity factor \(H/D\) was calculated by dividing \(H\) by \(D\) to reflect the hydrocarbon expulsion capacity of source rocks. The larger the \(H/D\) value, the stronger the oil filling capacity of source rocks to reservoir.

Figure 13(c) shows the relationship between calculated \(H/D\) and reservoir resistivity. It can be seen that with the increase of \(H/D\), the reservoir resistivity increases gradually, which indicates that the development of LRCP reservoirs is related to the difference of hydrocarbon expulsion ability of source rock. The weak hydrocarbon expulsion ability of source rock in LRCP reservoir leads to low oil saturation, and the pore space is mainly occupied by irreducible water, which makes the oil layer show a low resistivity logging response.

![Diagrams showing the relationship between distance from source rock and resistivity](image)

**Low resistivity contrast area**

**High resistivity area**

Distance from source rock
Figure 13. The influence of hydrocarbon expulsion capacity of source rock on reservoir resistivity: (a) The cross-well profiles from LRCP reservoir to HRP reservoir, (b) the location of cross-well profiles, and (c) the relationship between formation resistivity and the hydrocarbon expulsion ability factor of source rock.

(4) Macro factors: Regional difference of formation water salinity

The plane distribution characteristics of formation resistivity and formation water salinity were compared to study the influence of regional difference of formation water salinity on the reservoir resistivity. The average values of resistivity log in the test interval were used to represent the reservoir resistivity and a plane distribution map of formation resistivity was shown in Figure 14(a). The plane distribution map of formation water salinity was plotted based on the formation water salinity analysis data(Figure 14b). By comparing Figure 14(a) and Figure 14(b), there is a good corresponding relationship between formation resistivity and formation water salinity in the regional. In the west of Huanxian area, the formation water salinity is high and the formation resistivity is low. While in the east of Huanxian area, the formation
water salinity is low and the formation resistivity is high. This indicates that the formation water salinity has regional difference, which affects the formation resistivity logging response. Besides, this corresponding relationship between formation resistivity and formation water salinity also indicates the distribution of LRCP reservoirs.
Figure 14. Plane distribution maps of (a) formation resistivity and (b) formation water salinity, in which the red solid dots are the location of the wells.

3) Discussion

(1) Influence of clay minerals on reservoir porosity and permeability

The effect of clay minerals on reservoir physical properties and resistivity is a very important topic (Durand et al., 2001; Samakinde et al., 2016; Yousef et al., 2018). Based on the above analysis, the overburden porosity and permeability of LRCP reservoir are better than HRP reservoir in our study area. Besides, the thin film chlorite and filamentous illite are the most abundant clay minerals in LRCP reservoirs and HRP reservoirs, respectively (Figure 4b). In general, the clay minerals filling in the pores will reduce the porosity and permeability and the pore structure becomes worse.
However, if the rock matrix grains are coated by chlorite films, the intergranular porosity will be well protected due to its preventing function for quartz cementation (Chen et al., 2011; Stephan and Stuart, 2016; Higgs et al., 2017). Figure 15 shows the variation characteristics of porosity and permeability with the increase of clay mineral content. It shows that the reservoir porosity and permeability are positively correlated with chlorite content, but negatively correlated with illite content. Therefore, it is considered that the good reservoir porosity and permeability of LRCP reservoir in our study area is related to the filling of a large number of thin-film chlorite in the pores.

Figure 15. (a) Cross-plot of core porosity and the content of illite and chlorite, and (b) Cross-plot of core permeability and the content of illite and chlorite.

(2) Comprehensive influence of reservoir macro and micro factors on resistivity

In the macro vertical direction, the hydrocarbon expulsion ability of source rock in LRCP reservoir is weak, which leads to the reservoir oil saturation is low. At the same time, the regional difference of formation water salinity affects the conductivity of reservoir. Both of them controlled the distribution of LRCP reservoir from macro aspect. In the micro aspect, the porosity of LRCP reservoir is good, but it is mainly
micro pores, which leads to high irreducible water saturation. In addition, the formation water salinity of LRCP reservoir is high, which further reduces the resistivity logging response of the reservoir. The development of LRCP reservoir in our study area is controlled by the comprehensive influence of reservoir micro factors and macro factors. Therefore, the micro-factors and macro-factors should be considered comprehensively during the log interpretation and evaluation.

4. Conclusions and suggestions

(1) Compared with the HRP reservoir, the average porosity and permeability of LRCP reservoir are relatively better, but the micro pores are more developed, and the pore structure is relatively poorer. And when the filling pressure of crude oil is sufficient enough, the high oil saturation can be formed in LRCP reservoir.

(2) The high irreducible water saturation and high formation water salinity reduce the reservoir resistivity from reservoir micro aspect. In addition, the difference of hydrocarbon expulsion capacity of source rock, as well as the regional difference of formation water salinity are the macro factors influenced the distribution of LRCP and HRP from the regional.

(3) The development of LRCP reservoir is controlled by the comprehensive influence of reservoir micro factors and regional macro factors. Comprehensive consideration of the reservoir micro factors and regional macro factors is the key to guide the exploration and development of oil resource in our study area.

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