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

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Abstract

Log interpretation and evaluation of tight sandstone reservoir in Chang 8 Member of Longdong West area, Ordos Basin, China, are facing great challenges due to the co-development of normal oil pay and resistivity low-contrast oil pay. To better guide the exploration and development of oil resources in this area, the reservoir characteristics and control mechanism of resistivity low-contrast oil pay were studied. Firstly, the reservoirs were divided into resistivity low-contrast oil pay (RLP) and normal oil pay (NP) based on the relative value of the apparent resistivity increase rate. Then, the difference of reservoir characteristics between RLP and NP is analyzed by comparing a series of experimental data and real logging data in those two reservoir types. Finally, the control mechanism of RLP was studied from reservoir micro-factors and regional macro-factors, respectively. It is found that the chlorite and illite are the most abundant clay minerals in RLP and NP, respectively. Compared with NP reservoir, the average porosity of RLP is better, but the pore space is mainly composed of micropores, which lead to smaller average pore throat radius and poor pore structure. The high irreducible water saturation and high formation water salinity reduced the reservoir resistivity from micro-aspect. Besides, the difference of hydrocarbon expulsion capacity of source rock and the regional difference of formation water salinity controlled the distribution of RLP and NP. Comprehensive consideration of the reservoir micro-factors and regional macro-factors is important to carry out effective logging interpretation and evaluation.

Keywords Tight sandstone · Resistivity low-contrast oil pay · Reservoir characteristic · Control mechanism · Longdong west area

Introduction

Resistivity low-contrast oil pay, as an important oil resources with strong concealment, has received much interest in recent years due to their high oil production and wide

distribution around the world (Zemanek 1989; Worthington 2000; Onyinye 2010). The resistivity low-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 log interpretation and evaluation of resistivity low-contrast oil pay has existed for many years because of its complicated genesis and conductive mechanism (Etnyre and Mullarkey 1996; Kumar et al. 2009). Up till now, there are more than ten known factors that lead to resistivity low-contrast oil pay reservoirs, such as shoulder bed effects, irreducible water, conductive minerals, clay types and their

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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 these influential factors into two categories, including internal factors related to reservoir properties and external factors affected by external conditions. Generally, the resistivity low-contrast oil pay is usually caused by the combining influence of several factors, and the main influence factors are often controlled by the geological characteristics of the reservoir, so that there is not a unified standard for understanding the genesis of resistivity low-contrast oil pay 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 resistivity low-contrast oil pay 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 resistivity low-contrast oil pay 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 resistivity low-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 resistivity low-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 resistivity low-contrast oil pay reservoir.

The 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 due to its good hydrocarbon storage condition (Fig. 1). However, with the deepening of oil exploration and development, more and more resistivity low-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 resistivity low-contrast oil pay, which aim to provide a valuable reference for the future exploration and development of resistivity low-contrast oil pays in this area.

Data and research method

Considering that the resistivity low-contrast oil pay and normal oil pay are developed together in this region, so we first separated the reservoir into resistivity low-contrast oil pay (RLP) and normal oil pay (NP) 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 (R_0) of the same or adjacent well sections. According to the previous understanding of the definition of RLP 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 RLP, and the oil pay reservoir with ARI greater than 3 as NP. Then, the reservoir rock composition, porosity and permeability, pore structure and logging response characteristics were analyzed by comparing the experimental data and real logging data collected from these two reservoir types. Finally, the control mechanism of RLP 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.

Results and discussion

Reservoir characteristics analysis

Rock composition

Figure 3 shows the ternary diagrams of the reservoir rock composition in RLP and NP reservoir based on the XRD whole-rock analysis result. It can be seen that the reservoir rock composition of RLP and NP is basically the same, and the rock lithology is mainly lithic arkoses and feldspathic litharenites. The content of interstitial materials in the rock pores is high, and the components are mainly authigenic clay minerals. According to 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 RLP (ave. 50.1%), and illite is the most abundant clay mineral in NP (ave. 39.7%). But the content of illite–smectite mixed layer with strong cation exchange capacity is not high, less than 15% of the total amount of clay minerals (Fig. 4a). Based on the experimental data of clay cation exchange capacity of 8 cores from RLP and 6 cores from NP, the relationship between clay cation exchange capacity of reservoir and log resistivity is established (Fig. 4b). It can be seen that the clay cation exchange capacity of RLP in our study area is less than 2 mmol/100 g, and the effect of clay cation exchange capacity on reservoir resistivity is not significant.

Porosity and permeability

Figure 5 shows the distribution frequency histogram based on the overburden porosity and permeability measurement

Fig. 1 Location of the research area and target horizon

results of 35 cores from RLP and 40 cores from NP. It can be seen that the porosity of RLP is mainly distributed between 8 and 12%, with an average of 10.43%. And the permeability is mainly distributed between 0.001 and 0.3mD, with an average of 0.2mD. The porosity of NP reservoir is mainly distributed between 4 and 10%, with an average of 7.01%. And the permeability is mainly distributed between 0.001 and 0.3mD, with an average of 0.16mD. According to the cross-plot of porosity and permeability, the porosity and permeability meet a good power index relationship, and the curve slope of the fitting relationship between porosity and permeability of RLP reservoir is lower than that of NP reservoir (Fig. 6). That is to say, although the average porosity and permeability of RLP reservoir are better than that of NP reservoir, the permeability of RLP reservoir will be lower than that of NP reservoir under the same porosity.

Pore structure characteristics

Figure 7 shows the intrusive mercury curve obtained from the core mercury injection experiment of RLP and NP. 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 macro-pores to micropores. 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 macro-pores. Figure 8 shows the distribution characteristics of NMR T_2 spectrum in RLP and NP. In general, the pore size is related to the distribution range of T_2 spectrum, macro-pores component corresponds to the longer T_2 relaxation time, and the micropores component corresponds to the

Fig. 2 Flowchart for the research

Fig. 3 Ternary diagram of rock composition: **a** RLP reservoir (61 core samples) and **b** NP reservoir (128 core samples). Notes: Q: quartz; F: feldspar; R: rock fragments

shorter T_2 relaxation time. The sum of T_2 spectrum amplitude reflects the porosity of the core. The pore structure parameters calculated by MICP and NMR experiments are shown in Table 1. It can be seen that the NMR porosity of RLP is higher than that of NP (ave. 10.4% and ave. 7.05%, respectively), the T_2 geometric average value (T_{2gm}) and the average pore throat radius (R_{ave}) of RLP are smaller, and the displacement pressure (P_d) is larger. Besides, the

maximum mercury saturation (S_{Hg}) of RLP reservoir is higher than that of NP reservoir (89.02% and 77.75%, respectively). These indicate that although the porosity of RLP is higher, the pore space is mainly composed of micropores, which lead to the smaller average pore throat radius and poor pore structure. When the oil filling pressure is high enough, high oil saturation can be formed in RLP reservoir.

Fig. 4 **a** The distribution of different interstitial materials in RLP and NP from XRD clay fraction mineralogy analysis; **b** the relationship between the clay cation exchange capacity and reservoir resistivity

Fig. 5 The characteristics of reservoir porosity and permeability: **a** the porosity distribution histogram and **b** the permeability distribution histogram

Fig. 6 The relationship between porosity and permeability

Logging response characteristics

Logging response is 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 is drawn in Fig. 9. It can be seen that with the increase in reservoir density, the reservoir resistivity increases gradually. And it is difficult to identify the RLP 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 RLP formations and 20 NP formations and their adjacent wells. It can be seen that the difference of relative shale content (ΔGR) between RLP reservoir and NP reservoir is small, which indicates that the influence of reservoir shale content on resistivity is not obvious. However, the relative amplitude of spontaneous potential (ΔSP) of RLP reservoir is higher than NP reservoir, and with the improvement of oil-bearing, the value of ΔSP decreases gradually, which reflects that the water property is likely to be an important reason for the change of electrical property.

On the basis of the above analysis of reservoir characteristics, the control mechanism of RLP was studied and summarized into two aspects: One is micro-reservoir factors,

Fig. 7 The characteristics of mercury injection curve of **a** RLP reservoir and **b** NP reservoir

Fig. 8 The distribution characteristics of NMR T_2 spectrum of **a** RLP reservoir and **b** NP reservoir

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

Type	NMR POR(%)		NMR T_{2gm} (ms)		P_d (MPa)		R_{ave} (μ m)		S_{Hg} (%)	
	Range	Ave	Range	Ave	Range	Ave	Range	Ave	Range	Ave
RLP	8.4–15.6	10.4	1.3–5.8	4.78	0.31–2.55	1.12	0.02–0.7	0.19	77–98.5	89.02
NP	4.95–9.6	7.05	1.9–8.9	6.99	0.63–1.26	0.82	0.07–0.7	0.27	69.8–91.7	77.75

Fig. 9 The cross-plot of density (DEN) and resistivity (RT) of different fluid types

including the influence of irreducible water saturation and formation water salinity on formation resistivity; the other is regional macro-factors, including the influence of hydrocarbon expulsion capacity of source rock and the regional difference of formation water salinity on the distribution of RLP.

Control mechanism of RLP reservoir

Micro-factors: irreducible water saturation

According to the scanning electron microscope (SEM) analysis results, the main clay minerals of chlorite and illite mainly fill the pores in the form of thin film and filamentous, which is easy to adsorb and form bound water (Fig. 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 RLP reservoir and 12 cores from NP reservoir, it is found that the S_{wi} of RLP is generally higher than that of NP. The irreducible water saturation of RLP is mainly distributed in 40–70%, with an average value of 64.2%, while the irreducible water saturation of NP is mainly distributed between 30 and 50%, with an average value of 45.7% (Fig. 11a). The relationship between apparent resistivity increase rate (ARI) and irreducible water saturation is plotted in Fig. 11b. It can be seen that with the increase in 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 indicates that high irreducible water saturation reduced the resistivity contrast between water layer and oil layer.

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 RLP layer and NP layer, the formation water salinity varies greatly and the salt is mainly calcium chloride (Table 3). The formation water salinity in the NP is

Table 2 Logging response characteristics of different fluid types

Types	Fluid types	DEN(g/cm ³)		Δ GR		Δ SP(mV)		RT(Ω -m)	
		Range	Ave	Range	Ave	Range	Ave	Range	Ave
RLP	Oil layer	2.37–2.52	2.38	0.1–0.34	0.24	0.5–0.94	0.70	6.44–22.5	11.65
	Oil–water layer	2.39–2.49	2.42	0.2–0.45	0.33	0.4–0.82	0.72	7.03–20.42	15.32
	Water layer	2.34–2.45	2.37	0.25–0.33	0.26	0.6–0.95	0.83	5.01–10.78	7.04
NP	Oil layer	2.44–2.52	2.47	0.09–0.45	0.26	0.4–0.85	0.66	23.03–92	57.68
	Oil–water layer	2.45–2.53	2.43	0.23–0.37	0.30	0.4–0.8	0.67	19.5–44.2	29.38
	Water layer	2.37–2.43	2.39	0.15–0.37	0.25	0.6–0.83	0.74	8.7–10.13	8.44

Fig. 10 SEM observation: **a** chlorite mainly fills the pores in the form of thin film, and **b** illite mainly fills the pores in the form of filamentous. (CF: chlorite film; FI: filamentous illite)

Fig. 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)

distributed between 18,760 and 51,000 mg/L with an average value of 32,712.91 mg/L. The formation water salinity in the RLP is mainly distributed between 45,950 and 88,010 mg/L with an average value of 63,462.5 mg/L, and the formation water salinity in the RLP is almost twice than that of the NP. Figure 12 shows the relationship between formation water salinity and formation resistivity. It can be seen that with the increase in formation water salinity, 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 leads to the RLP reservoir.

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 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

Fig. 12 The relationship between formation resistivity and formation water salinity

profiles from low resistivity constant area to high resistivity area are drawn in Fig. 13a, in which the first track of each well is depth, second track is the overlapping of acoustic and resistivity log curves to reflect source rock and the filling

Table 3 Formation water salinity statistics results

Types	Wells	K ⁺ + Na ⁺ (mg/L)	Mg ²⁺ (mg/L)	Ca ²⁺ (mg/L)	Cl ⁻ (mg/L)	SO ₄ ²⁻ (mg/L)	CO ₃ ²⁻ (mg/L)	Type	Salinity (mg/L)	Average (mg/L)
NP	B2	10,942	1236	4074	25,762	2325	340	CaCl ₂	44,680	32,712.91
	M50	6690	64	422	10,583	505	496	CaCl ₂	18,760	
	M93	9285	627	3447	22,017	0	380	CaCl ₂	35,760	
	Z234	8349	488	1574	16,685	196	424	CaCl ₂	27,716	
	M159	14,708	287	3500	28,638	1360	95	CaCl ₂	48,590	
	B20	7971	517	1419	13,502	3401	499	CaCl ₂	27,310	
	L146	4379	120	2970	12,026	237	262	CaCl ₂	27,716	
	X259	7214	150	496	11,376	238	1525	CaCl ₂	21,000	
	B53	3234	316	6774	1747	500	85	CaCl ₂	28,380	
	Y435	5516	181	5069	17,671	211	250	CaCl ₂	28,930	
	Z336	17,652	292	1463	28,909	2161	244	CaCl ₂	51,000	
RLP	H11	12,693	6016	9505	37,493	22,046	257	CaCl ₂	88,010	63,462.5
	M92	21,185	1464	6204	44,681	4131	286	CaCl ₂	77,950	
	Z386	18,299	1868	3762	39,463	819	409	CaCl ₂	64,620	
	M132	24,599	724	5169	46,193	3573	580	CaCl ₂	80,840	
	H12	15,350	1628	1789	27,780	5003	171	CaCl ₂	51,720	
	B4	16,642	706	2539	30,850	1775	71	CaCl ₂	52,580	
	M116	9649	1722	8702	32,630	3401	250	CaCl ₂	56,350	
	Z251	11,753	503	7786	32,062	1588	207	CaCl ₂	53,900	
	Z138	31,637	193	1381	51,122	0	466	CaCl ₂	85,310	
	Z412	16,368	1245	3762	34,680	819	394	CaCl ₂	57,270	
	Z113	12,020	391	4901	27,560	949	124	CaCl ₂	45,950	
	M141	12,301	844	4175	26,366	3097	265	CaCl ₂	47,050	

color is black-gray, third track is geological stratification, 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 low resistivity reservoir area is small, and the distance between source rock and reservoir is long. Figure 13b shows 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 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 13c 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

Fig. 13 The influence of hydrocarbon expulsion capacity of source rock on reservoir resistivity: **a** The cross-well profiles from RLP reservoir to NP reservoir, **b** the location of cross-well profiles and **c** the

relationship between formation resistivity and the hydrocarbon expulsion ability factor of source rock

of RLP reservoirs also controlled the difference of hydrocarbon expulsion ability of source rock.

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 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 is shown in Fig. 14a. The plane distribution map of formation water salinity was plotted based on the formation water salinity analysis data (Fig. 14b). By comparing Fig. 14a and Fig. 14b, it can be seen that 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 corresponding relationship between formation resistivity and formation water salinity shows that the distribution

of RLP and NP reservoirs is also controlled by the regional difference of formation water salinity.

Discussion

According to the analysis of reservoir characteristics, the reservoir main difference between RLP and NP lies in the main types of clay minerals and pore structure. The thin-film chlorite and filamentous illite are the most abundant clay minerals in RLP reservoirs and NP reservoirs, respectively. Although the pore structure of RLP is poorer and the micropores are more developed in RLP reservoir than NP reservoir, the average porosity and permeability are better. Previous researches have shown that the clay mineral is an important factor to affect reservoir physical properties (Durand et al. 2001; samakinde et al. 2016; Yousef et al. 2018). 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

Fig. 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

Fig. 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

cementation (Chen et al. 2011; Stephan and Stuart, 2016; Higgs et al. 2017). In Fig. 15a, b, we plot the relationship between chlorite and illite and core porosity and permeability. It can be seen that the reservoir porosity and permeability are positively correlated with chlorite content, but negatively correlated with illite content. Therefore, it is considered that good reservoir porosity and permeability of RLP reservoir in our study area are related to the filling of a large number of thin-film chlorite in the pores.

In addition, good porosity but high content of micropores in RLP reservoir indicates that when the filling pressure of crude oil is sufficient enough, the oil-bearing reservoir with high oil saturation can be formed. However, the hydrocarbon expulsion ability of source rock in RLP reservoir is weak and pore spaces are mainly occupied by irreducible water, which makes the oil layer indicating a low oil saturation and low resistivity logging response. In addition, the difference of formation water salinity not only indicates the distribution characteristics of the RLP and NP from the macro-aspect, but also reduces the contrast of resistivity on the micro-aspect. The formation and distribution of RLP in our study area are controlled by the micro-factors and macro-factors together.

Conclusions and suggestions

- (1) There are differences in main clay mineral types and pore structure between RLP reservoirs and NP reservoirs. Chlorite and illite are the most abundant clay minerals in RLP reservoirs and NP reservoirs, respectively. Although the porosity of RLP is better than NP, the pore space is mainly composed of micropores.
- (2) The high content of micropores in RLP reservoir makes the irreducible water saturation high, together with the high formation water salinity reduced the reservoir resistivity from reservoir micro-aspect.
- (3) The difference of hydrocarbon expulsion capacity of source rock as well as the regional difference of forma-

tion water salinity is the macro-factors influencing the distribution of RLP and NP.

- (4) It is suggested to comprehensively consider the micro-factors and macro-factors during the exploration and development of oil resources in our study area.

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