Influence of different pore structure types on the occurrence features of movable fluid in Chang-10 reservoir in Wuqi–Ansai Oilfield

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Received: 10 November 2020 / Accepted: 27 February 2021 / Published online: 12 March 2021
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Abstract

Chang-10 reservoir in Wuqi–Ansai oilfield of Ordos Basin is restricted by its strong microscopic heterogeneity, complicated microscopic pore structure and unclear oil–water movement rules. The technology of nuclear magnetic resonance (NMR) is an excellent method to quantitatively evaluate the reservoir fluid of different pore structure types, and the microscopic experiments such as cast thin slices, scanning electron microscope (SEM) and high-pressure mercury injection were also used to analyze the differences in the occurrence features of fluid of different pore structure types and their influencing factors. The experimental results show that the sandstone types of Chang-10 reservoir in Wuqi–Ansai Oilfield are mainly medium-fine arkose and lithic arkose. The pore types are mainly intergranular pore, feldspar pore, turbiditic zeolite pore and cuttings pore. The combination type of pore-throat belongs to mesopore–micropore and microlarynx–microlarynx. By mercury injection experiment analyzed the characteristic of capillary pressure curve, Chang-10 reservoir in Wuqi–Ansai Oilfield pore structures is classified into Type I, Type II, Type III and Type IV due to the different movable fluid occurrence features. The occurrence features of movable fluid are obviously controlled by the pore-throat, and the orders of control effect from strong to weak are from Type I, Type II, Type III to IV. The saturation of movable fluid gradually becomes low when the pore-throat radius decreases.

Keywords Wuqi–Ansai Oilfield · Chang-10 reservoir · Different pore structure types · NMR · Occurrence features of movable fluid

Introduction

In Ordos Basin, Wuqi–Ansai Oilfield is in the central and eastern part of the northern Shaanxi slope. It belongs to Yan'an City of Shaanxi Province in administration, which spans Ansai County and Zhidan County of Yan'an City with an area of 3474.2 km². The Triassic Yanchang formation and Jurassic Yanan Formation are the most important exploration and development strata. The Chang-10 reservoir is a newly discovered oil and gas development system in recent years. It is found that the study area Chang-10 reservoir has great exploration and development potential through actual construction and production in recent years (Huang et al. 2016; Li et al. 2018, 2019).

Both at home and abroad, many experimental methods have been used to study microscopic pore structure, including mercury intrusion porosimetry (MIP) (Toda and Toyoda 1972), constant-rate-controlled mercury porosimetry (CMP) (Yao and Liu 2012), low-pressure nitrogen adsorption (LP-N₂A) (Li 2020), low-pressure carbon dioxide adsorption (LP-CO₂A) (Li et al. 2020), synchrotron small-angle X-ray scattering (SAXS) (Qi et al. 2002), small-angle neutron scattering (SANS) (Okolo et al. 2015), low-field NMR spectral analysis (LFNMR) (Yao and Liu 2012), micro-X-ray computed tomography (μCT) (Karacan and Okandan 2000), optical microscopy (Li et al. 2015), scanning electron microscopy (SEM) (Li et al. 2015), atomic force microscopy (AFM) (Dun et al. 2014) and so on. However, previous studies did not combine the pore-throat parameters obtained from the constant-rate mercury injection experiment with the percentage of movable fluid in NMR curve, so the effects of different pore structure factors on the occurrence of movable fluid cannot be intuitively seen. NMR technology, as a typical reservoir evaluation technology, has been widely

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utilized in the field of petroleum development (Kenyon et al. 1995; Yao et al. 2010; Gao and Li 2015). Wang et al. (2001) believed that the percentage of movable fluid is the key to evaluate the potential for development of low-permeability reservoirs. Yang et al. (2007) analyzed the relationships among movable fluid and permeability and efficiency of oil displacement and believed that the percentage of movable fluid could be used to better predict the development effectiveness of low-permeability reservoirs. Wang et al. (2008) believed that the porosity of the movable fluid could better reflect the reservoir capacity and fluid occurrence features. The morphology and size of pore-throat at different scales can be observed directly by scanning electron microscope, and the types, distribution and existence state of pore, throat and clay minerals can be analyzed. The casting thin section experiment can be used to count the throat and pore number, throat and pore matching relations in the thin section, and directly observe the face rate of the sample, as well as the clast component, etc. Combined with oil and gas field data, current production degree can be evaluated (Li et al. 2015). High-pressure mercury injection technology uses high injection pressure and can obtain data quickly and directly. According to the features of capillary pressure curve, experiment parameters such as pore and throat scale, separation coefficient, skew, maximum pore-throat radius and mercury removal efficiency can be calculated, and the pore structure of the reservoir can be characterized qualitatively and semi-quantitatively, and the oil recovery rate can be estimated by combining with the field data (Li et al. 2015). Constant-rate mercury technology can distinguish throat and pore, directly obtain the distribution characteristics, shape and size of throat and pore, and show the mercury inlet curve of pore and throat and quantitatively evaluate the characteristics of micropore and throat (Wang et al. 2001; Nguyen et al. 2006; Fitch et al. 2015; Gao et al. 2016; Yang et al. 2016; Li et al. 2017; Sima et al. 2017; Zhang et al. 2018).

At present, study on the microscopic characteristics of the reservoir is weak, systematic study of it is few, which restricts the further development of the reservoir system. Study on occurrence features and influencing factors of movable fluid in different pore structure types of reservoir is relatively weak. In this study, the Chang-10 reservoir in Wuqi–Ansai Oilfield is taken as the study object, and the core samples in study area are tested and analyzed by multiple tests including cast thin slices observation, X-ray diffraction experiment, scanning electron microscope (SEM), NMR, high-pressure mercury injection, etc., to compare and analyze the effects of different pore structure types on the occurrence features of movable fluid. Furthermore, analyzing the occurrence and distribution characteristics and seepage law of the movable fluid in tight sandstone reservoirs, then the main factors affecting the occurrence and seepage characteristics of the movable fluid are revealed.

Geological setting and experimental section

Geological background and samples

Ansai County is a significant oil-producing area in Yi-Shan slope, covering an area of about 3000 square kilometers. Wuqi–Ansai Oilfield is a typical extra-low permeability oilfield with typical characteristics of low permeability, but it has a production of 100 million tons and is a miracle in the history of oil development. The main oil-bearing rock series in Wuqi–Ansai Oilfield is the Yanchang Formation of Triassic, which includes vast oil and gas resources and well-developed reservoirs. Chang-10 in Wuqi–Ansai Oilfield is a representative low-porosity and low-permeability reservoir, with a thickness of about 300 m. Rock core observation experiment data of Chang-10 reservoir in Wuqi–Ansai Oilfield show that the main lithology of Chang-10 reservoir sandstone in Wuqi–Ansai area is a set of gray and gray-green sandstone. According to the classification scheme of standard sandstone of China National Petroleum Corporation (CNPC), the content of Chang-10 sandstone is relatively high component with arkose, and the rock types are mainly arkose and lithic arkose. The cementation type is pore cementation, and the contact mode of rock particles is mostly linear contact, and part is point-line contact.

Microscopic pore structure experimental

Cast thin slices

Rock cast thin section identification is a traditional laboratory method, which can combine with mercury injection to compare and analyze pore structure and characteristics of rock samples. The rock thin section preparation (SY/T 5913-2004) was consulted to make the cast thin slices, and the sample was polished with a size of approximately $10 \times 10 \times 0.03$ mm. With thin section examination of rock (SY/T 5368-2000), it would be viewed with the Olympus BXFM-S optical microscope under room temperature. Through the analysis of cast, thin slices experiment and image can obtain the content of clay minerals content filling and physical property data.

The test of rock cast thin section needs to go through several important aspects, such as the specification of cast thin section, identification and image analysis. The pore cast thin section of rock is a kind of thin section that studies the distribution of pore size in petrology. The principle of thin section of casting production technology is to inject the infusion fluids matched with curing agent (triethanolamine) and oil-soluble dyes (red, blue) epoxy resin into the

pores of the rock, by using the vacuum method. Under a certain temperature and pressure, the infusion fluids are oxidized and solidified within the pore network, forming the same casting as the pore network. And then carefully grind the rock filled with infusion fluids into sheets with thickness of 0.03 mm and observed the pore, throat and their mutual connection with two-dimensional spatial structure under polarized light microscope. In this study, 50 cast thin slices were selected for observation and statistics.

Scanning electron microscopy (SEM)

SEM has been widely and maturely used to study and evaluate oil and gas field, especially in the study of pore structure distribution characteristics, microscopic pore origin, authigenic mineral composition and distribution. The core sample was firstly cut with a size of $10 \times 10 \times 5$ mm. Due to the non-conductive of the sandstone sample, it would be covered with a film of gold. Then, the sample would be view with the Lecia/Cambridge LEO 435 VP under room temperature. The general rules for measurement of length in microscale by SEM (GB/T 16594-2008) were taken a reference to complete the SEM measurements. And through studying the characteristics of pore and throat, the matching relation, and measuring the size of pore-throat finally determine the pore types (Gao et al. 2019). In this study, 50 scanning electron microscope samples were selected for observation and statistics.

High-pressure mercury injection technology

Mercury injection test is one of the most important methods to determine capillary pressure curve in rock. The direct result of the high-pressure mercury injection experiment is relation diagram of pressure and mercury injection volume (Eslami et al. 2013; Huang et al. 2016; Liu et al. 2018). According to pore size distribution and porosity of solid materials by mercury porosimetry and gas adsorption. Part 1: Mercury porosimetry (GB/T 21650.1-2008), the core sample was handled with a diameter of 25 mm, the length of the sample ranges from 20 to 35 mm. The main experimental apparatus is AutoPore IV 9505 automatic mercury injection apparatus, with the maximum experimental pressure of 228 MPa. The specific test conditions were as follows: test temperature 25.4 °C test humidity 38% RH, surface tension 0.48 N/m, wetting contact angle 140°, and high-pressure mercury injection experiment analysis were carried out on 15 samples. Usually, the capillary pressure and mercury injection saturation are plotted in the semi-logarithmic coordinate to obtain the capillary pressure curve of the core under mercury injection. The capillary pressure

curve distribution characteristics can qualitatively reflect the separation and skew of pores.

X-ray diffraction experiment

X-ray diffraction measurement was launched with a Bruker AXS D8 Advance X-ray diffractometer (Germany) using monochromatic Cu radiation (40 kV, 40 mA) with a scanning speed of $1^\circ/\text{min}$ and a step length of 0.1° over an angular 2θ of 2° – 80° , and the total amount of clay minerals in sedimentary rocks and common non-clay minerals X-ray diffraction method for quantitative analysis (SY/T 6210-1996) was taken as a reference.

When X-ray hits the surface of the object to be measured, the electron shells of the matter atoms collide elastic with X-ray photons, and the secondary X-ray spherical waves are emitted into space. Bragg scattering occurs when the secondary X-ray is of the same wavelength as the primary ones. Because the electron clouds of each atom can produce spherical Bragg scattering, the scattered X-ray can interfere with each other, causing spherical waves in some scattering directions to strengthen and others to cancel each other out, resulting in diffraction. The sample to be measured is placed on the platform. When the instrument starts to work, the X-ray tube on the left emits X-ray to illuminate the sample surface, and the detector on the right receives the diffraction wave reflected from the object and transmits it to the computer, finally forming the diffraction spectrum. XRD is a mature means to characterize and explore the types and evolution rules of clay minerals. Its most basic and extensive application is to conduct qualitative analysis of different types of soil clay minerals in a region, explore the differences in crystallography of different types of soil and analyze the evolution rules among them. In this study, 15 samples were analyzed.

Principle of NMR

NMR is a technology to study pore structures of rocks by means of measuring the amplitude and relaxation rate of NMR relaxation signals of hydrogen nuclei in pore fluids and establishing T_2 spectrum based on the magnetic properties of hydrogen nuclei and their interaction with external magnetic fields (Chen et al. 2006; Talabi et al. 2009; Megawati et al. 2012; Gao et al. 2015). This technique can accurately and rapidly determine the parameters of reservoir fluids. The occurrence state of fluid in pores of tight sandstone can be categorized into movable fluid and irreducible fluid. NMR T_2 spectrum analysis was performed on 8 core samples from study area (Yao and Liu 2012; Xiao et al. 2017). The specification for measurement of rock NMR parameter in laboratory is SY/T 6490-2014, the core sample (with a diameter of 25 mm, and the length ranges from 30

to 50 mm) was prepared, and the NMR was measured with the Geospec2/53 NMR spectrometer.

NMR method is mainly based on the energy level transition of hydrogen atoms in water under constant and pulsed magnetic field (Yao et al. 2010; Yao and Liu 2012). When the pulsed magnetic field is withdrawn, the atoms in the sample will gradually return to the original state, and the delay time of atoms returning to the initial state from the state after the transition is called relaxation time. Relaxation time is divided into longitudinal relaxation time T_1 and transverse relaxation time T_2 . Among them, T_1 test takes a long time, so T_2 is generally selected for study. T_2 can be expressed as:

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2D}} + \frac{1}{T_{2S}} \quad (1)$$

In the equation above, T_{2B} stands for volume relaxation time, T_{2D} stands for diffusion relaxation time, T_{2S} stands for the surface relaxation time. Among them, the volume relaxation time T_{2B} is greater than the surface relaxation time T_{2S} , generally 2 s greater, so it can be ignored. When the magnetic field gradient is low and the echo interval is short, the T_{2D} term of diffusion relaxation time can be ignored. Therefore, Eq. (1) can be simplified as:

$$\frac{1}{T_2} = \frac{1}{T_{2S}} \quad (2)$$

The surface relaxation time T_{2S} can be expressed as:

$$\frac{1}{T_{2S}} = \rho \frac{S}{V} \quad (3)$$

In the equation, ρ stands for surface relaxation coefficient, $\mu\text{m}/\text{ms}$; V stands for the pore volume, cm^3 ; S stands for the pore area, cm^2 . Therefore, Eq. (1) can be expressed as:

$$\frac{1}{T_2} = \rho \frac{S}{V} \quad (4)$$

Results and discussion

Rock characteristics of reservoirs

Rock core characteristics observation data show that Chang-10 reservoir sandstone in Wuqi–Ansai Oilfield is mainly composed of gray and gray-green sandstone. According to the classification scheme of standard sandstone of CNPC, the content of Chang-10 sandstone is relatively high component with arkose, and the rock types are mainly lithic arkose and arkose (Fig. 1).

The interstitial material of sandstone consists of two parts mainly: matrix and cement. Matrixes are fine sediments whose particle size is less than 0.03 mm, which are distributed among the clastic particles and deposited

Fig.1 Sandstone characters and types of Chang-10 reservoir in Wuqi–Ansai Oilfield

together with the clastic particles in a mechanical manner (suspended load). Cement is a variety of authigenic minerals that are deposited from colloids or true solutions by chemical precipitation during the deposition and diagenesis stages of clastic rocks and filled between clastic particles. According to the identification and analysis of rock thin sections, there are many cementation types in study area, mainly chlorite, turbidite, iron calcite, calcite, siliceous and hydromica. Chang-10 is rich in laumontite and chlorite, but not kaolinite (Fig. 2).

Chlorite cementation is widely distributed in Chang-10 sandstone in study area, mainly in the form of chlorite

film, with an average content of 4.2% (Fig. 2). The chlorite film was brown and dark brown, surrounded by clastic particles. Under SEM, the chlorite film was seen to grow like fish scales and leaves (Fig. 3d). There are intergranular pores at the cementation point of chlorite film, which often become pore lining. Chlorite film is missing at the close contact point of clastic particles. Microscopically, illite (illite-montmorillonite mixture) is primarily distributed in the pore wall and throat wall in the form of silk hair and network. It often grows with the intergranular pore-throat filled with spontaneous microcrystalline quartz, which reduces the reservoir permeability (Fig. 3e). The content

Fig.2 Interstitial type of Chang-10 reservoir in Wuqi–Ansai Oilfield

Fig.3 Photographs of SEM of Chang-10 reservoir in Wuqi–Ansai Oilfield. **a** Feldspar partially dissolves; **b** partial dissolution of turbidite occurs; **c** micropore; **d** chlorite filling throat; **e** montmorillonite is honeycombed; **f**. book-shaped kaolinite fills the pores)

of silica in Chang-10 sandstone in study area is relatively high, with an average content up to 2%. There are mainly two forms of observation under the mirror: one is the secondary enlargement of quartz; another is that they fill in the intergranular pores in the form of microcrystalline quartz. These two siliceous cements are quite common in Chang-10 sandstone (Fig. 3c). The content of turbidite cement in Chang-10 sandstone in study area was high, with an average content of 5.7%. Through the microscopic observation of the thin section, the laumontite and ferrocalcite often filled the pores with porphyritic distribution and metasomatic detritus (Fig. 3b). The average content of carbonate cement in Chang-10 sandstone is 1.2%, mainly ferrocalcite and calcite, but few ankerites (Fig. 3).

The distribution characteristics of different pore structure types

Through high-pressure mercury injection experiment data of 15 pieces of sample and comparison of characteristics of the curve of capillary pressure, pore structures in Chang-10 reservoir of Wuqi–Ansai Oilfield are classified into Type I, Type II, Type III and Type IV (Table 1, Fig. 4).

Type I of pore structure has tilted the curve of capillary pressure distribution characteristics, with the mesopore and thin throat combination. The displacement pressure was 0.0465 MPa, and the median pressure was 0.8221 MPa. Type I of pore structure of porosity was 13.47%, the permeability of $18.2715 \times 10^{-3} \mu\text{m}^2$,

Fig. 4 Classification diagram of capillary pressure curve of Chang-10 reservoir in Wuqi–Ansai Oilfield

the sample pore volume was 12.006 cm^3 , the separation coefficient was 2.7515, and the coefficient of variation was 0.3418. The mean coefficient is 8.0506, the skew coefficient is 1.7477, the maximum pore-throat radius is 15.7938 nm, and the median radius was 0.8941 nm. The maximum mercury intake saturation was 86.4394%, the unsaturated mercury saturation was 13.5606%, the residual mercury saturation was 65.4064%, and the mercury removal efficiency was 24.3326%. Type I of pore structure has the largest volume of large pore and throat. The reservoir of this type possesses the best storage performance and seepage ability. The lithologic features are mainly coarse and medium-grained arkose. The intergranular pores were more developed, the dissolution pores recovered a great many intergranular pores, and the pore connectivity was fine (Table 1, Fig. 4).

Type II of pore structure has a platform in capillary pressure curve, with the mesopore and micro-fine throat combination. Expulsion pressure is a bit higher than the Type I of pore structure, 0.7163 MPa, the median pressure is 9.9576 MPa. Type II of pore structure of permeability was $0.3438 \times 10^{-3} \mu\text{m}^2$, the porosity was 11.04%, and the sample volume was 11.642 cm^3 , the sorting coefficient was 2.2413, the variation coefficient was 0.2039, and the mean coefficient was 10.9905. The skew coefficient was 1.5486, the maximum pore-throat radius was 1.026 nm, and the median radius was 0.0738 nm. The maximum mercury inflow saturation was 87.6529%, the unsaturated mercury saturation was 12.3471%, the residual mercury saturation was 44.2448%, and the mercury outflow efficiency was 49.5228% (Table 1, Fig. 4). The volume of large pore-throat in type II is less than Type I of pore structure, and the ratio of pore and throat radius is smaller. This type of reservoir has better storage performance and seepage ability. The rock type is mainly turbiditic zeolite-medium-grained arkose sandstone, and the

Table 1 Different pore structure types parameters of mercury penetration of Chang-10 reservoir in Wuqi–Ansai Oilfield

Classification of parameter	I	II	III	IV
Porosity/%	13.47	11.04	10	10.01
Permeability/ $10^{-3} \mu\text{m}^2$	18.2715	0.3438	0.2028	0.1819
The volume of the sample/ cm^3	12.006	11.642	12.742	12.903
The threshold pressure/MPa	0.0465	0.7163	0.7188	1.1659
The median pressure/MPa	0.8221	9.9576	2.7119	10.6737
Sorting coefficient	2.7515	2.2413	2.3251	2.3947
Coefficient of variation	0.3418	0.2039	0.2216	0.2241
Coefficient of the mean	8.0506	10.9905	10.4933	10.6851
The coefficients of crooked	1.7477	1.5486	2.136	1.5889
Maximum throat radius/ μm	15.7938	1.026	1.0226	0.6304
The median radius/ μm	0.8941	0.0738	0.271	0.0689
Maximum mercury saturation/%	86.4394	87.6529	88.9176	83.7294
Unsaturated mercury saturation/%	13.5606	12.3471	11.0824	16.2706
Residual mercury saturation/%	65.4064	44.2448	66.2395	43.9393
Exit the efficiency/%	24.3326	49.5228	25.5047	47.5223

dissolution pores revive a great many intergranular pores, which makes the pore connectivity better.

Type III of pore structure has slightly slanted capillary pressure curve distribution characteristics, and a medium pore and throat sorting distribution characteristics, with the small pore and microthroat combination. The displacement pressure was 0.7188 MPa, and the median pressure was 2.7119 MPa. Type III of pore structure of porosity was 10%, the permeability of $0.2028 \times 10^{-3} \mu\text{m}^2$, the sample volume was 12.742 cm^3 , the separation coefficient was 2.3251, the variation coefficient was 0.2116, and the mean coefficient was 10.4933. The skew coefficient was 2.136, the maximum pore-throat radius was 1.0226 μm , and the median radius was 0.271 μm . The maximum mercury inflow saturation was 88.9176%, the unsaturated mercury saturation was 11.0824%, the residual mercury saturation was 66.2395%, and the mercury outflow efficiency was 25.5047% (Table 1, Fig. 4). The volume of large pore-throat in type III is less than Type II, and pore-throat radius ratio is larger. This type of reservoir has an average storage performance and seepage ability. The lithologic features are mainly medium-fine-grained arkose and turbidite or calcite medium-fine-grained arkose. Laumontite was distributed in lamellar and crystalline porphyritic pattern, filled with pores and slightly dissolved, resulting in uneven pore distribution. Calcite fills the pores in the form of fine crystals, which results in the disappearance of some intergranular pores. Chlorite film thickness is not uniform, which is thicker where laumontite exists and vice versa. These conditions enlargement of quartz forms of mosaic structure with poor pore connectivity.

Type IV of pore structure has capillary pressure curve leaning to the top right corner. The large pore-throat occupies very little volume. Most of the pore-throats are unable to participate in seepage, and the pore-throats have a narrow distribution range, belonging to the area of microthroat. Type IV class belongs to a dense reservoir pore structure of reservoir. The displacement pressure is higher than other types, which is 1.1659 MPa, and the median pressure is 10.6737 MPa. Type IV of pore structure of porosity was 10.01%, the permeability of $0.1819 \times 10^{-3} \mu\text{m}^2$. The sample volume was 12.903 cm^3 , the separation coefficient was 2.3947, and the variation coefficient was 0.2241. The mean coefficient was 10.6851, the skew coefficient was 1.5889, the maximum pore-throat radius was 0.6304 μm , and the median radius was 0.0689 μm . The maximum mercury intake saturation was 83.7394%, the unsaturated mercury saturation was 16.2706%, the residual mercury saturation was 43.9393%, and the mercury removal efficiency was 47.5223% (Table 1, Fig. 4). Type IV of pore structure has the largest volume of small pore-throat. This type of reservoir has the worst storage performance and seepage ability. The lithologic features are mainly turbidite zeolite and calcite fine-grained arkose sandstone. Type IV of pore structure of reservoir because

of laumontite or calcite filling pore, large area leads to intergranular pore reservoir basic disappearance, dissolution is also very weak.

NMR T_2 spectrum distribution of different pore structure types

Select the four types of pore structures in 8 pieces of core sample from Wuqi–Ansai Oilfield Chang-10 reservoir and take experiment in NMR. As shown in Fig. 5, the frequency distribution of NMR T_2 spectrum of different pore structure types can be seen. The T_2 spectrum is mainly bimodal, the Type I and Type III pore structure show left lower and right higher peaks and Type II and Type IV show left higher and right lower peaks, showing that reservoir pore and throat of Type I and Type II pore structure have fine connectivity, pore-throat radius is larger (Table 2, Fig. 5).

The pore structure of the sandstone samples all feature as bimodal (Fig. 5), but the characteristics of various types are different. Type I shows that the micropore volume is larger than that of the macropore (Fig. 5a). While Type II and Type IV show the contrary characteristics. Although Type II and Type IV show almost the similar characteristics, it can be found that the total pore volume of Type II is larger than that of Type IV (Fig. 5b, c). When it comes to Type III, the micropore volume is almost equal to that of macropore (Fig. 5d).

Better pore structure type comes larger the pore radius and throat radius, better reservoir capacity and seepage capacity and higher movable fluid saturation. Therefore, the pore-throat characteristics are obviously different in different pore structure types, and the difference determines the relative content of movable fluid in pores and throat.

Analysis of main control factors influencing the saturation of movable fluids

Reservoir physical properties

Porosity and permeability are the basic properties parameters to evaluate the reservoir quality. Commonly, higher porosity and permeability of the reservoir features more movable fluids in the reservoir. Figure 6 shows that movable fluid saturation parameters and porosity of NMR experiment samples have a positive correlations and its correlation coefficient R^2 is 0.393, besides, movable fluid saturation and permeability have a better positive correlations and its correlation coefficient R^2 is 0.428 (Fig. 6). The distribution range of movable fluid saturation is wide in study area, and the saturation of movable fluid does not necessarily go up along with the increase in porosity and permeability. Higher permeability comes smaller movable fluid saturation. However, in most of the samples,

Fig.5 Frequency distribution of NMR T_2 spectra of Chang-10 reservoir in Wuqi-Ansai Oilfield

Table 2 NMR test results of Wuqi-Ansai Oilfield

Sample No	Depth/m	Porosity/%	Permeability/ $10^{-3} \mu\text{m}^2$	T_2 cutoff value/ms	Bound water saturation/%	Movable fluid saturation/%
B46	2109.50	3.46	0.085	6.136	42.229	57.771
B53	2035.75	3.79	0.098	2.656	30.083	69.917
B58	2123.83	3.28	0.020	4.642	81.418	18.582
B19	2083.85	5.18	0.045	1.748	50.462	49.538
B35	2074.80	9.84	0.254	0.757	27.767	72.233
B50	2210.70	9.09	0.367	0.757	24.692	75.308
B52	1973.50	7.65	0.639	0.757	19.844	80.156
B59	2263.60	10.60	16.511	1.520	18.409	81.591

the higher the permeability, the higher the saturation of movable fluid. The saturation of movable fluid is closely associated with the distribution of porosity which are connected. The reservoir physical property can not reflect the

occurrence features of the movable fluid completely. The influence of the occurrence features of movable fluid is not under the control of a single reservoir parameter.

Fig.6 Correlation between reservoir physical property and the saturation of movable fluid in different pore structure types

Pore radius and throat radius

Pore radius and throat radius always mean the higher porosity and permeability of the reservoir, the higher pore radius and throat radius could allow the seepage of fluids more easily. The average pore radius of the Chang-10 reservoir samples in Wuqi–Ansai Oilfield showed little difference, mainly ranging from 104.84 to 173.27 μm . Pore radius and movable fluid saturation are positively correlated relationship, and its coefficient R^2 is 0.4358 (Fig. 7). The distribution of pore radius is not uniform. The smaller the pore radius is, the worse the reservoir capacity is and the less the movable fluid occurs. The throat radius is primarily distributed between 0.095 and 2.59 μm . As shown in Fig. 7, the saturation of movable fluid is positively correlated with the throat radius, and its correlation coefficient R^2 is 0.6332, showing a good correlation. The better the correlation between the saturation of movable fluid and throat radius, the better the throat radius is, indicating that the radius of throat is the most significant factor that affects the occurrence of the movable fluid, which can more intuitively and factually represent the reservoir space and seepage capacity.

The ratio of pore-throat radius and sorting coefficient

The ratio of pore and throat radius can be tested by high-pressure mercury injection experiment. The ratio of pore-throat could finally determine the permeability of the reservoir, which contributes to the seepage of fluids. The sorting coefficient is another parameter that mainly determined by the distribution of the particles in the reservoir, which is related to the permeability of the reservoir. This parameter reflects the degree of connection between pore and throat. Figure 8 shows that there is a negative correlation between the saturation of movable fluid and the ratio of pore-throat radius, and the negative correlation coefficient R^2 is 0.431, that is to say, larger the ratio of pore and throat radius comes worse connectivity of the pore and throat, and lower movable fluid saturation. The ratio of pore and throat radius determines the percolation capacity of the effective pore fluid. Larger the ratio of pore and throat radius comes more uniform distribution of the pore-throat. The effective throat number of connected pores is reduced, the fluid is easy to get stuck when passing through, and the saturation of movable fluid is reduced. Smaller the radius of pore and throat comes more and larger pore-throat causing fluid easier to flow, and make the saturation of the movable fluid higher. However, as the ratio of pore and throat radius decreases, small pores

Fig.7 Correlation between the saturation of movable fluid and pore-throat radius

Fig.8 Correlation between the saturation of movable fluid and the ratio of pore-throat radius, sorting coefficient

are more likely to be surrounded by throat, resulting in lower saturation of the movable fluid. Therefore, the ratio of pore and throat radius is the main factor affecting the occurrence of movable fluid.

The occurrence of movable fluid saturation is affected by the ratio of pore-throat radius and the size of pore-throat radius. Besides, it is also closely related to the sorting coefficient. Figure 8 shows that the saturation of movable fluid of 8 NMR samples of Chang-10 reservoir in Wuqi–Ansai Oilfield increases with the increase in separation coefficient, showing a positive correlation, and its correlation R^2 is 0.4628. The larger the separation coefficient is, the larger the seepage coefficient of the structure will be, and the wider the throat distribution interval will be. The better the pore structure of the low-permeability reservoir rock, the more uniform the distribution of pore-throat, the more the number of large throat, the stronger the flow capacity, and the higher the saturation of the movable fluid.

Mercury saturation of pore and throat

Pore mercury saturation and throat mercury saturation are mainly determined by the permeability of the reservoir. The higher permeability, the higher pore mercury saturation and throat mercury saturation will be, which

will determine the seepage of the fluid in the reservoir. Four different types of reservoir pore structure of sorting coefficient, throat radius, pore radius and the saturation of movable fluid present positive correlation. Larger pore and throat radius comes more and larger pores and throat, and larger volume of the pore and throat, causing the better pore-throat connectivity, and make the saturation of the movable fluid higher. Pore volume and throat volume can be reflected by the mercury saturation of pore and throat. As Fig. 9 shows, the correlation coefficient R^2 between the saturation of movable fluid and pore mercury saturation is 0.2181, with a general positive correlation. The correlation coefficient R^2 between the saturation of movable fluid and throat mercury saturation is 0.3381, showing the correlation between throat mercury saturation and the saturation of movable fluid is better than pore. Higher pore mercury saturation makes higher the saturation of movable fluid. Including Type III and Type IV of reservoir pore structure effective throat less quantity, small volume, small radius, pore connectivity is poor, poor physical property, make the most of the oil and gas enrichment in the pores and small throat, recovery efficiency is low, low content of movable fluid. In Type I and Type II reservoir pore structure, the effective throats are larger in radius and quantity and have fine pore connectivity and high content of movable fluid.

Fig.9 Correlation between the saturation of movable fluid and pore-throat mercury saturation

Therefore, the effect of effective throat mercury saturation on the movable fluid saturation of reservoirs with different pore structure types is greater than that of effective pore mercury saturation.

According to above conclusion, it is shown that micropore structure has great effects on the occurrence features of the saturation of movable, in which throat radius of reservoir and sorting coefficient are the main factors. In the next place, the ratio of pore-throat radius, pore-throat mercury saturation and pore radius of reservoir also have obvious effect on the saturation of movable fluid.

Conclusions

Through high-pressure mercury injection experiment of 15 pieces of sample data, a comprehensive analysis and comparison of Wuqi–Ansai Oilfield Chang-10 reservoir pore structure are classified into I, II, III, IV four types, and the occurrence features of movable fluid of different pore structure types are different. Type I and Type II pore structure of reservoir have fine connectivity in pore and throat, and larger radius in pore-throat. Type III and Type IV pore structure of reservoir are poor in pore connectivity and have small pore radius and the distribution was uneven and has strong heterogeneity, poor physical property.

Based on analyzing experimental result of sorting coefficient, physical property, radius, the ratio of pore and throat radius, mercury saturation of pore, mercury saturation of throat, study shows that the correlation between physical property and movable fluid saturation is good, the correlation between permeability and the movable fluid saturation is better than porosity. Microscopic pore structure characteristics are the important factors that affect the occurrence features of movable fluid saturation, the ratio of pore and throat radius and throat radius are the major factors influencing the saturation of movable fluid. Throat radius and the saturation of movable fluid show a better positive correlation, which can represent the reservoir space and seepage capacity more intuitively and truly. The ratio of pore and throat radius, movable fluid saturation show a negative correlation, the sorting coefficient has obvious influence on moveable fluid saturation.

Author Contributions Corresponding author is TL, all co-authors name order is YG, PL, TL. YG contributed to writing—original draft. PL was involved in software, supervision. TL contributed to investigation.

Funding This work was supported by the Natural Science Basic Research Plan in Shaanxi Province of China (Program No. 2019JQ-527), and Scientific Research Program Funded by Shaanxi Provincial Education Department (Program No. 20JS116).

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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