

Characteristics of Connected Pores and Evaluation of Shale Oil Mobility in the Qianjiang Formation, Qianjiang Sag, Jiangnan Basin, China

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ABSTRACT: The connectivity of shale pores and the occurrence of movable oil in shales have long been the focus of research. In this study, samples from wells BX7 and BYY2 in the Eq3⁴-10 cyclothem of Qianjiang Formation in the Qianjiang depression, were analyzed. A double mercury injection method was used to distinguish between invalid and effective connected pores. The pore characteristics for occurrence of retained hydrocarbons and movable shale oil were identified by comparing pore changes in low temperature nitrogen adsorption and high pressure mercury injection experiments before and after extraction and the change in the mercury injection amounts in the pores between two separate mercury injections. The results show that less than 50% of the total connected pores in the Eq3⁴-10 cyclothem samples are effective. The development of effective connected pores affects the mobility of shale oil but varies with different lithofacies. The main factor limiting shale oil mobility in Well BX7 is the presence of pores with throat sizes less than 15 nm. In Well BYY2, residual mercury in injection testing of lamellar dolomitic mudstone facies was mainly concentrated in pores with throats of 10–200 nm, and in bulk argillaceous dolomite facies, it was mainly concentrated at 60–300 nm. The throats of hydrocarbon-retaining pores can be 5 nm or even smaller, but pores with movable shale oil in the well were found to have throat sizes greater than 40 nm. Excluding the influence of differences in wettability, the movability of shale oil is mainly affected by differences in lithofacies, the degree of pore deformation caused by diagenesis, the complexity of pore structures, and the connectivity of pore throats. Dissolution and reprecipitation of halite also inhibit the mobility of shale oil.

KEY WORDS: Qianjiang depression, double mercury injection, effective connected pores, retained hydrocarbons, movable hydrocarbons, hydrocarbons.

0 INTRODUCTION

Shale oil and gas resources have enormous potential, which, have become an essential area for increasing oil and gas reserves and production with constant improvements in recovery technology. However, the current recovery rate of shale oil and gas resources is low. The main reason is that shale oil and gas are usually stored in micro/nano pores with complex structures (Liu H M et al., 2019). To be exploited, hydrocarbon molecules need to be able to migrate into fracture networks through inter-

connections in the micro/nano matrix pore network. Matrix pore connectivity in shale reservoirs therefore directly affects the ability of oil and gas molecules to flow and migrate, thus effectively controlling production. Pore connectivity in shale is an important research topic, but, characterization is difficult and progress is slow given the extremely low porosity and permeability of shale matrix.

The most commonly used methods for pore connectivity analysis are focused ion beam scanning electron microscopy (FIB-SEM), low-temperature nitrogen adsorption (LTNA), high-pressure mercury intrusion (HPMI), small-angle neutron scattering, spontaneous fluid imbibition, fluid-tracer migration, nano-CT scanning, and nuclear magnetic resonance scanning (NMR) (Fan et al., 2025; Zhang et al., 2024; Liu Z J et al., 2019; Song et al., 2019; Hu et al., 2018a; Wu et al., 2018). FIB-SEM and nano-CT are used to scan and reconstruct shale sam-

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ples in three dimensions. Differences in gray scale are used to analyze pores, pore throats, and mineral compositions so the characteristics and connectivity of pores in shale samples can be evaluated (Fan et al., 2025; Wu et al., 2018; Kelly et al., 2016). HPMI reveals porosity and pore size distribution according to mercury injection amounts and the pressure required for mercury injection. Pores that can be injected with mercury are regarded as connected pores (Zhang et al., 2018). Some studies have estimated pore structure tortuosity in shale matrix—which reflects pore connectivity—from mercury injection curves obtained under different pressure conditions (Gao et al., 2013). Small-angle neutron scattering is used to investigate pore connectivity by comparing results from pore structure tests and fluid injection tests (such as nitrogen adsorption and high-pressure mercury injection) to determine the ratio of open to closed pores (Sun et al., 2017; Wu et al., 2018). Spontaneous fluid imbibition and fluid-tracer migration rely on differences in wettability and the capillary forces of different fluids in the pores. Wettable fluids replace non-wettable fluids spontaneously (imbibition), and the imbibition slope or tracer distribution of fluid entering the pores reveals the connectivity characteristics (Yang et al., 2019; Hu et al., 2018b, 2015; Vega et al., 2014). NMR uses T_2 peak spectra and movable fluid cutoff values (T_2 cutoff value) to determine pore connectivity (Liu Z J et al., 2019).

All these methods have disadvantages. For example, LTNA can only be used for pores of 2–50 nm (Jiang et al., 2016). HPMI may simply destroy samples when it is used for small pores. FIB-SEM and nano-CT three-dimensional image analysis intuitively reflects pore connectivity, but they can only be used on pore networks with throat diameters larger than 10 nm since they are limited by image resolution (Zhao et al., 2017; Kelly et al., 2016). The accuracy of small angle scattering depends on the specific model applied, the sample size, and other factors, so it is inherently inconsistent (Yang Z M et al., 2017; Yang R et al., 2017b; Bahadur et al., 2015). NMR has too many variables, such as selection of echo interval, centrifugal strength, wettability, etc. Accordingly, a combination of methods is often used in studying connected pores (Jiang et al., 2016; Wang G C et al., 2015; Wang Y et al., 2015). However, none of these methods is capable of distinguishing naturally flowing connected pores in shales.

Unlike shale gas, not all connected pores are effective for permitting shale oil flow in a production environment. In some connected pores, shale oil flows only with difficulty under natural conditions. For example, injecting mercury into micro/nano pores requires extremely high pressure. When the pressure is reduced, the mercury has difficulty exiting the pores. When shale oil flows with similar difficulty under development conditions, the connected pores are regarded as ineffective, or ‘invalid’. Many studies have analyzed connected pores in shale, but few have focused on connected pores containing movable shale oil. This study takes typical samples of dif-

ferent lithofacies from the Eq3⁴-10 rhythmic coring section in two exploration wells in the Qianjiang depression to qualitatively and quantitatively analyze the pore structures using Field emission scanning electron microscopy experiment (FE-SEM), LTNA, and HPMI. The accommodation space for shale oil can be assessed by comparing pore space before and after extraction. A double mercury injection method was used to identify effective connected pores for shale oil production and the main controlling factors for movable shale oil accommodation space were determined, which will be of great benefit for shale oil production.

1 SAMPLES AND EXPERIMENTS

1.1 Samples

The samples were selected from Eq3⁴-10 rhythmic core samples from wells BYY2 and BX7 in the Qianjiang Formation, in the Qianjiang sag, Jiangnan Basin. Due to differences in the sedimentary environments at the various sampling locations (Figure 1), the development and types of pores in the two sets of samples are significantly different (Li et al., 2020) (Figure 2), which is typical of shales in the Qianjiang depression. The Qianjiang sag is in a saline lacustrine environment, so salt rock is an important element in the mineral composition (Wang et al., 2016). In order to avoid affecting the results by salt minerals, the samples selected for this study contained little or no salt rock. To determine the factors influencing the effectiveness of connected pores, the samples were divided into lithofacies based on contents of terrigenous clasts, calcite, and dolomite (Sun et al., 2019). The sampling depth in Well BX7 was between 3 040 and 3 060 m, where the lithofacies is mainly light-dark gray bulk dolomitic mudstone facies, carbonaceous mudstone facies, and mudstone facies, with S_1 ranging from 2.06 to 5.87 mg/g (average 4.31 mg/g). The sampling depth in Well BYY2 was 2 810–2 830 m, where the lithofacies is mainly brown lamellar or thin lamellar argillaceous dolomite facies, argillaceous limestone facies, dolomitic mudstone facies and bulk argillaceous dolomite facies (Figure 2), with S_1 values ranging from 4.24 to 9.85 mg/g (average 7.27 mg/g). Due to the strong heterogeneity of continental shale, cores with no cracks and uniform color were generally selected for sampling. Large samples were taken along the direction of parallel bedding, and each was evenly divided into four parts. One part was pulverized to 1–2 mm powder for LTNA before and after extraction. The other three parts were cut into 1 cm cubes for HPMI before and after extraction and double HPMI after extraction. Before the experiments, the samples were screened using XRD to ensure that the mineral compositions were as similar as possible. In addition, in order to minimize the influence of differences in fluids and wettability between pores (Yang et al., 2017), all the samples to be used in the double mercury injection experiments were extracted and dried at 100 °C. In order to distinguish connected pores with naturally flowing shale oil, the pore distributions under LTNA and HPMI were compared before

and after extraction, to reveal the spatial distribution of shale oil.

1.2 Experimental Methods

1.2.1 LTNA

A Quantachrome AutoSORb-IQ3 specific surface area and pore size analyzer was used to conduct nitrogen adsorption experiments on the shale samples. The test samples were crushed to 60–80 mesh (particle size 0.18–0.25 mm). Samples of about 1g were selected and inserted into the degassing station of the instrument. They were degassed at 105 °C for 8 hours to remove moisture and volatile substances. The samples were then placed in the adsorption station, with pure nitrogen (> 99.99%) as the adsorbent. The adsorption tests were carried out at liquid nitrogen temperature (77.3 K). The relative pressure range of the adsorption process was 0.005–0.995, with 62 pressure points set. The relative pressure range of the desorption process was 0.995–0.100, with 24 pressure points set. The measured pore size range was 0.9 to 270 nm. The nitrogen adsorption and desorption capacities of the samples were measured under various equilibrium steam pressures. The BJH model was then used to calculate the pore size distributions and pore volumes of the samples.

1.2.2 HPMI

The samples were tested using a Micromeritics Auto-pore IV 9500 automatic mercury injection apparatus, which has a test pressure range of 0 to 60 000 psi (equivalent to 414 MPa). In this process, mercury entering shale pores under pressure forces non-wetting phase fluid to displace wetting phase fluid. When the pressure applied by the instrument is greater than the capillary pressure in the pore-throat, mercury enters the pore. The volume of mercury entering the pore under different pressure conditions can therefore be obtained. Based on the fact that all pores in porous media are cylindrical, Washburn (1921) proposed the following relationship between capillary pressure and pore-throat radius.

$$\Delta p = \frac{2\sigma \cos \theta}{r} \quad (1)$$

where, ΔP represents capillary pressure, σ represents surface tension of mercury (485 dynes/cm); θ represents the contact angle between mercury and porous media (130°); R represents the pore throat radius (cm) with a test diameter range of 3 nm–36 μ m. The process was as follows: the shale samples were prepared into 1 cm cubes and then moisture and volatile substances removed by baking in an oven at 100 °C for 48 h. The sam-

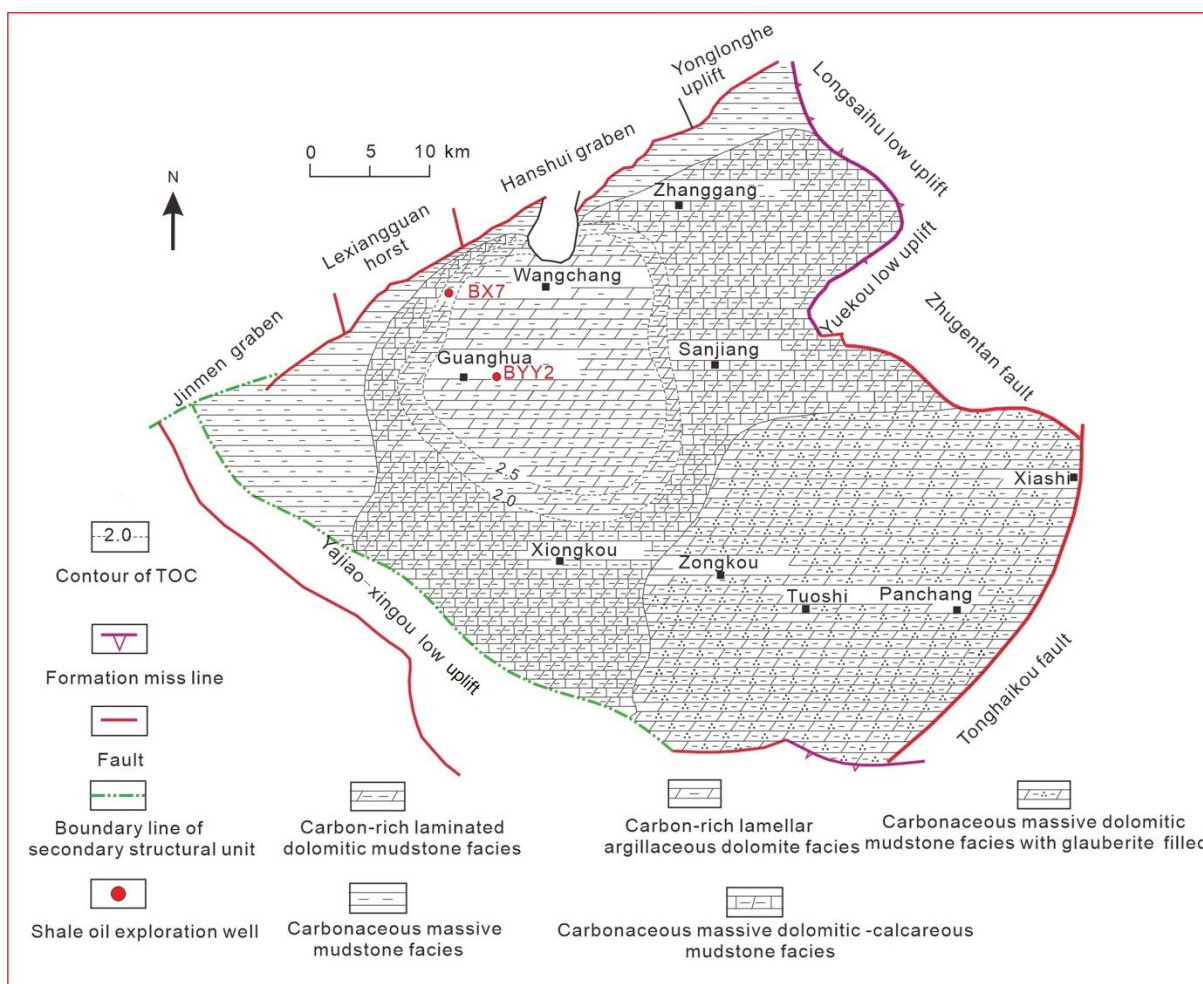


Figure 1. Sedimentary facies and sampling locations in the Qianjiang depression (Li et al., 2020).

ples were then placed individually in the sample chamber of the instrument for measurement. Pressure was applied in two stages: low pressure (5 to 30 psi) and high pressure (30 to 60 000 psi).

1.2.3 FE-SEM

FE-SEM is the main method for observing the two-dimensional structural characteristics of nano-micron scale shale pores. An SU8010 field emission scanning electron microscope was used in this study. The principle of scanning electron microscopy is that the electron gun targets at a focused high-energy electron beam on the surface of the sample, exciting molecules which emit secondary electrons, backscattered electrons, and X-rays. This information is received and amplified by a signal detection system to obtain images of the surface and data on the composition of the sample. The size of the electron beam spot and the electron beam can be adjusted using a coil and objective grating to alter the magnification and depth of field of the observed image. The samples for this study were polished with an argon ion beam to produce a flat surface. The apparatus was equipped with an energy-dispersive spectrometer (EDS), which allowed the mineral compositions of the samples to be determined.

1.2.4 Soxhlet extraction

Cable extraction was used to obtain samples for nitrogen adsorption and high-pressure mercury injection experiments, which were conducted in parallel. Pore volumes before and after extraction were compared to determine the accommodation space for retained hydrocarbons. To ensure that residual hydrocarbons trapped in the pores could be extracted cleanly, the samples were extracted using a ternary solvent (acetone : chloroform : methanol = 19 : 16 : 15) in a Soxhlet apparatus at 70–90 °C for 72 h. The extracted samples were dried at 100 °C in a vacuum oven until the weight changed by less than ± 0.001 g.

1.2.5 Double mercury injection experiment

The effectiveness of connected pores was determined using a double mercury injection method. The principle is that the pressure of the mercury injection forces a quantity of mercury into smaller pores. When the pressure decreases, the mercury in some pores cannot easily escape, resulting in a large difference between the amounts of mercury injected and ejected. In this paper, these pores where shale oil cannot flow freely under natural conditions are defined as invalid connected pores; Invalid connected pores are filled and ‘blocked’ by the first mercury intrusion, which means that all pores that are entered by mercury during the second injection can be regarded as effective connected pores.

2 RESULTS

2.1 Pore Types

FE-SEM images of the Eq3⁴-10 rhythmic shale samples show that there are differences in pore types be-

tween the two wells. The samples from Well BX7 contained more intermixed intergranular pores, composed of quartz, clay, and carbonate minerals (Figures 3a and 3b), and clay mineral interlayer pores (Figures 3b, 3c, 3d). The maximum pore diameter of the interlayer pores is 500 nm (Figures 3b, 3d). Due to compaction, the pores between the clay mineral layers are mostly elongated (Figures 3c, 3d). Quartz grains are usually mixed with the clay minerals, which could help to protect the interlayer pores from overburden pressure (Dong et al., 2024) (Figures 3a, 3d). Many dissolved pores were found in carbonate particles (Figures 3a, 3e). Because connectivity of these pores with the external environment is poor under SEM, it is speculated that most of them are invalid. The samples from Well BYY2 contained relatively more dolomite intercrystalline pores (Figures 3f, 3g) and intermixed intergranular pores (Figure 3h), together with a small number of clay mineral interlayer pores (Figure 3g). The porous dolomite beds were found to contain both euhedral and sub-rounded (Figure 3f) bacterially-induced dolomite crystals. Intercrystalline pores were found in the dolomite, many on a micron scale. This is probably because, in a reducing environment, sulfate-reducing bacteria acted as a dolomite nucleation carrier and the internal organic matter decomposed to form intercrystalline pores (Shen, 2013; Mastandrea et al., 2006; García Del Cura et al., 2001).

2.2 Pore Structure

Figure 4 shows that the nitrogen adsorption capacity of the samples from Well BX7 increased slowly when the relative pressure was low (relative pressure represented as P/P_0 , where P represents the pressure of the adsorption gas and P_0 represents the saturated vapor pressure). However, when the relative pressure exceeded 0.8, the adsorption capacity increased rapidly and saturation occurred under saturated vapor pressure. The desorption and adsorption curves formed a large hysteresis loop similar to H₂ type according to the IUPAC classification, indicating that the pores are complex and have ‘ink-bottle’ shapes (Brunauer et al., 1938).

2.3 Pore Size Distribution

FE-SEM results indicate a wide pore size distribution range among shale pores in the study area, so a single method will not yield satisfactory results in a full-scale analysis (Wang et al., 2019). This study therefore combines LTNA and HPMI to study pore size distribution in the Qianjiang Formation shale. The LTNA results (Figures 5, 6) show that the Well BX7 samples are high in pores with diameters less than 20 nm, and also in pores with diameters 20–100 nm. Pore development in mudstone facies (BX7-15) is better than in carbonaceous mudstone (BX7-6) or dolomitic mudstone facies (BX7-1, BX7-2, BX7-18). HPMI results (Figures 5, 6) show that pore throat sizes in the Well BX7 samples are mostly less than 50 nm, with the peak distribution around 5–10 nm. There were only a small number of micron-scale

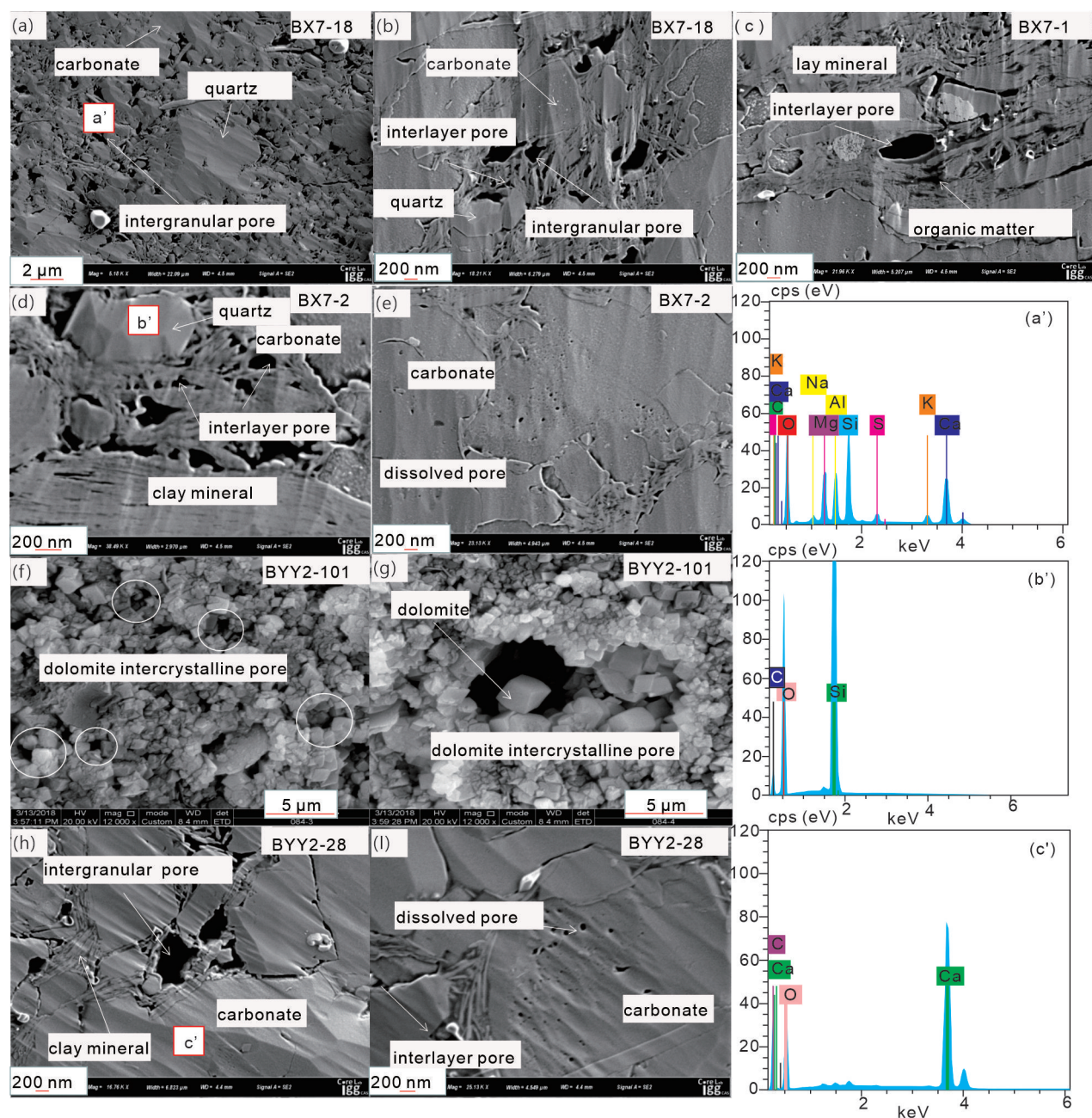


Figure 3. FE-SEM image of shale samples of the Eq3⁴-10 cyclothem in Well BX7 and Well BYY2.

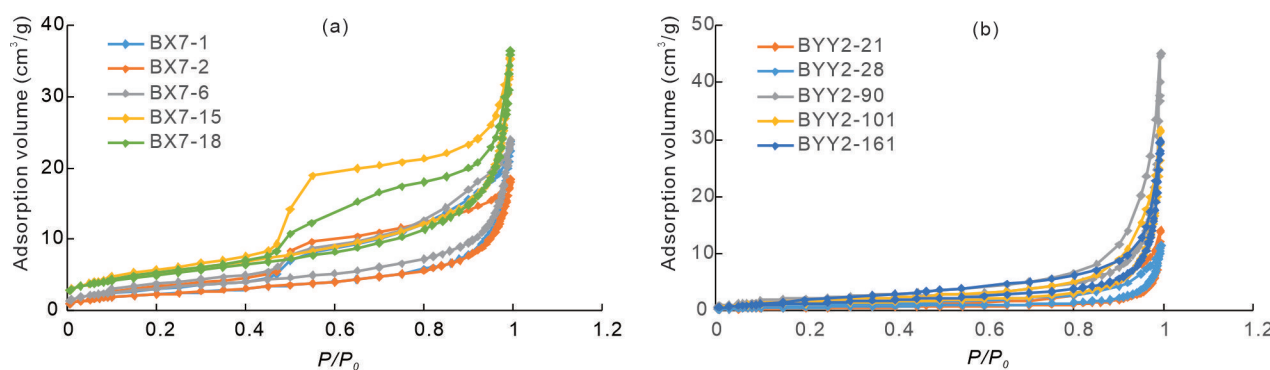


Figure 4. N₂ Isothermal adsorption curves of raw shale from the Eq3⁴-10 cyclothem in the Qianjiang Formation.

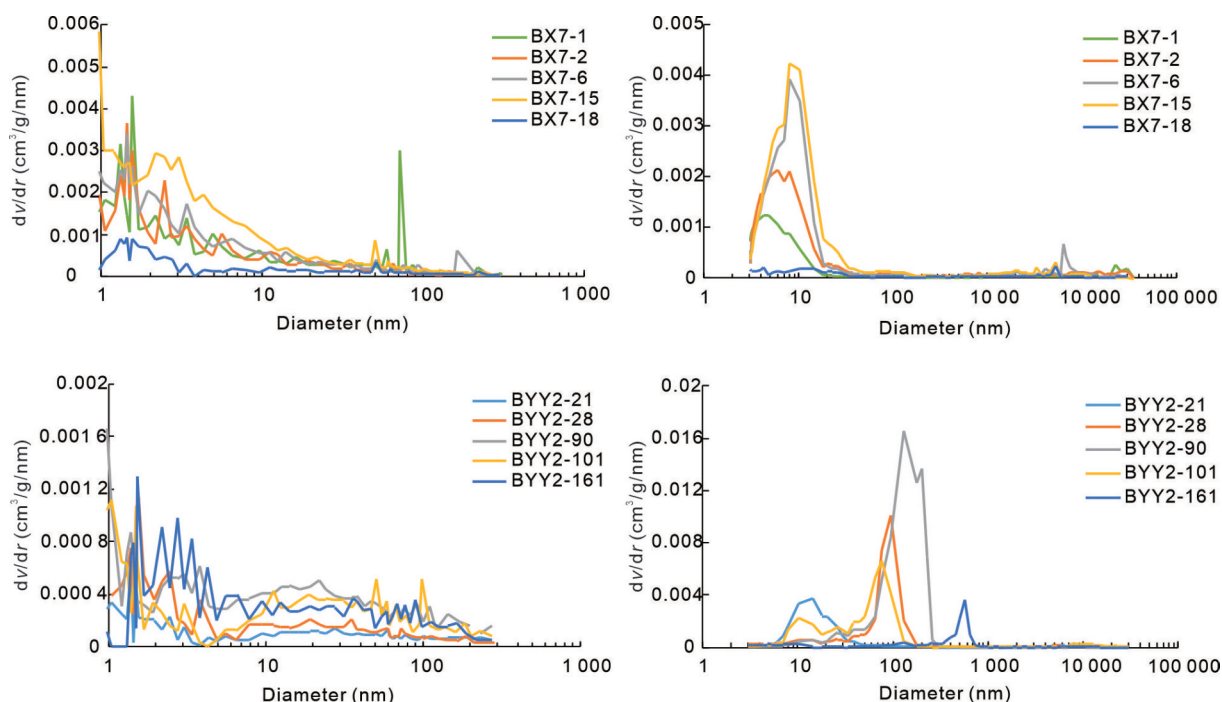


Figure 5. Pore size distribution in the Eq3⁴-10 rhythmic shale samples from the Qianjiang Formation.

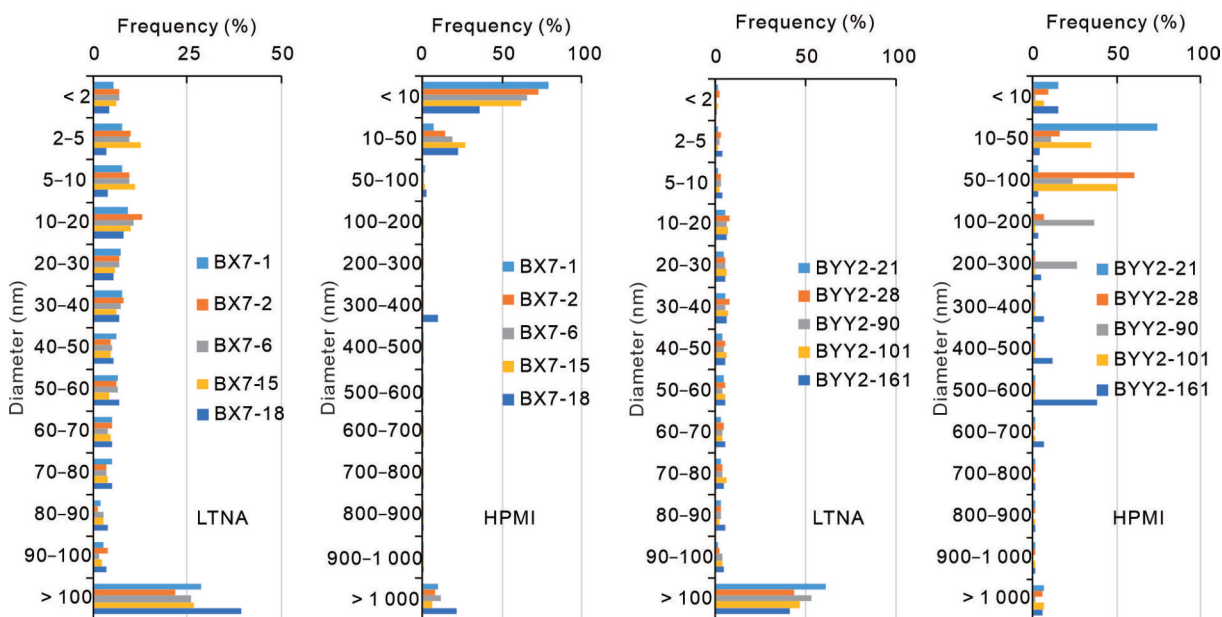


Figure 6. Pore size distribution histogram of Eq3⁴-10 rhythmic shale samples from the Qianjiang Formation.

pores. Similar to the LTNA results, pore development in mudstone facies is better than in carbonaceous mudstone or argillaceous dolomite facies. LTNA results from the Well BYY2 samples (Figures 5, 6) show that, when the pore diameter is less than 4 nm, the specific pore volume decreases with increase of the pore diameter. When the pore diameter is larger than 4 nm, the specific pore volume increases with increase of the pore diameter, peaking at about 20 nm, after which the specific pore volume decreases with increase of the pore diameter. In

general, the pore sizes in the samples were less than 100 nm, mainly 10–100 nm. The lithofacies with the greatest pore development is dolomitic mudstone facies (BYY2-90, BYY2-101), followed by argillaceous dolomite facies (BYY2-28, BYY2-161), and argillaceous limestone facies (BYY2-21). HPMT results show variations in pore-throat distributions between the samples. The pore-throat distribution of argillaceous limestone facies (BYY2-21) was about 10–50 nm and of dolomitic mudstone facies (BYY2-101) about 10–200 nm. There is a difference in

pore throat development between lamellar and bulk argillaceous dolomite facies, with the pore-throat distribution of lamellar argillaceous dolomite facies (BYY2-28) ranging from 50 to 200 nm and that of bulk argillaceous dolomite facies (BYY2-161) from 200 to 600 nm.

2.4 Characteristics of Effective Connected Pores

In this paper, the effectiveness of connected pores was determined using a double mercury injection method (see 2.25 *supra*). Figure 7 shows the characteristics of mercury intrusion and withdrawal following double mercury injections of samples from Wells BX7 and BYY2. Figure 7a shows that, when the mercury injection pressure was less than 10 000 Pa, the amount of mercury injected into the BX7 sample increased slowly with increase in pressure. When the mercury injection pressure exceeded 10 000 Pa, the mercury injection amount increased rapidly. However, when maximum pressure was reached, mercury saturation did not occur, indicating a high breakthrough pressure, which suggests that pore-throat diameters in the BX7 sample are small. These small pores may have remained unfilled, preventing saturation. An alternative explanation is that some pores were destroyed by the high pressure during the injection process. However, no obvious micro-cracks were found in the samples after injection, which suggests that non-filling of very small pores is the likely explanation. When the injection pressure was reduced, almost no mercury was ejected from the BX7 samples, indicating that most of the connected pores in Well BX7 are invalid. During the second mercury injection, the volume of mercury injected into the BX7 sample decreased significantly. Reaching maximum pressure, mercury saturation still did not occur, and some of

the mercury again remained in the pores as the pressure was reduced. This confirmed that some invalid pores had remained unfilled during the first mercury injection, and that there were few effective connected pores.

Figure 7b shows the results of double mercury injection in Well BYY2. When the injection pressure was less than 800 Pa, the amount of mercury injected into the sample increased slightly. When the injection pressure exceeded 800 Pa, the mercury amount increased significantly. When the injection pressure reached 5 000 Pa, the mercury volume stopped increasing and entered an equilibrium state. During mercury withdrawal, the volume of mercury ejected increased rapidly at first and then reached equilibrium, with the total amount of ejected mercury being about 50% of the injected mercury. The injection curve of the second mercury injection was similar to that of the first, except for the decrease in mercury volume. During withdrawal, the volume of mercury ejected was almost equal to the injection volume. The connected pores entered by mercury during the second injection can therefore be regarded as effective connected pores.

3 DISCUSSION

3.1 Accommodation Space for Retained Hydrocarbons

LTNA is often used to analyze the pore structures of porous materials, because the form of hysteresis ring formed by discordance between the adsorption and desorption curves accurately represents the pore structure. Shale has a complex pore structure, so gas adsorption is widely used to study pore structures in shale. In this paper, the nitrogen adsorption results were analyzed according to the IUPAC classification. The pores were divid-

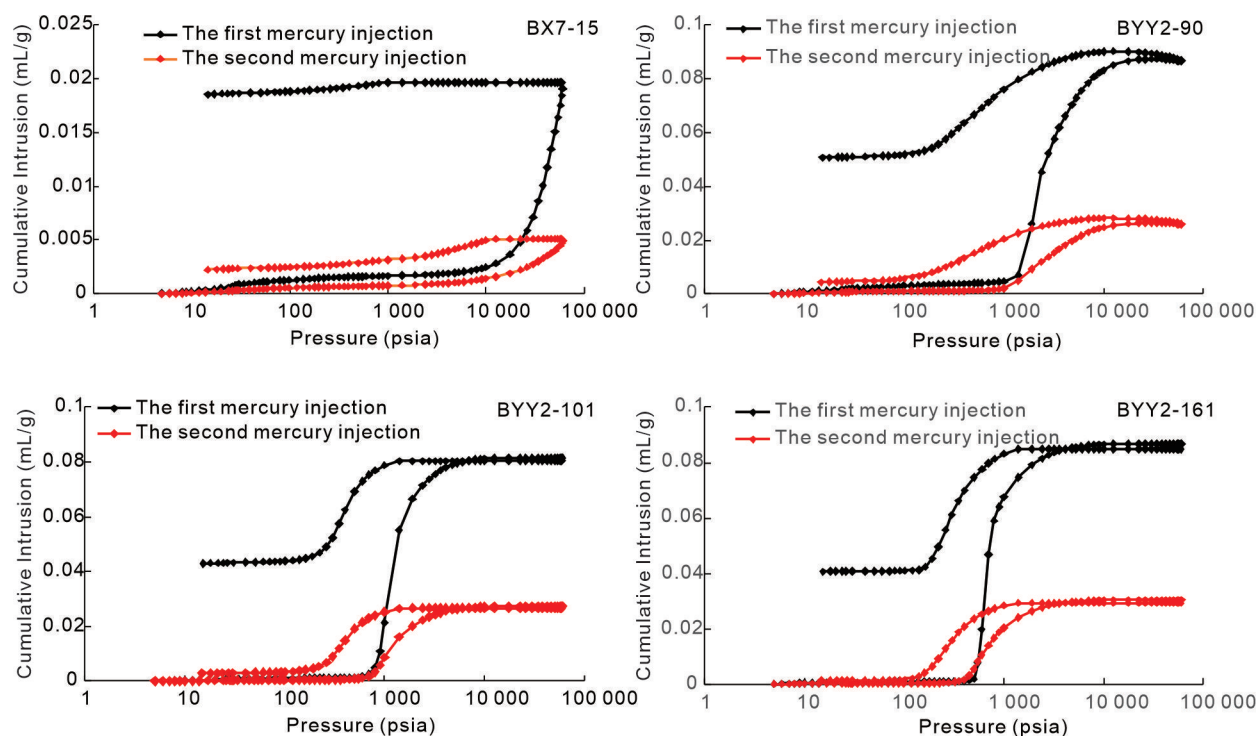


Figure 7. Variations in mercury contents in double mercury injection.

ed into macropores (diameter > 50 nm), mesopores (2–50 nm), and micropores (< 2 nm) (Sing, 1985).

Table 2 shows changes in pore structure before and after extraction with terpolymer solvent. The difference between pore volume before and after extraction was taken as the storage space available for retained hydrocarbons. Retained hydrocarbons are present in all three pore types (Table 1). Figure 8 shows the retained hydrocarbon distribution revealed by combining the results from nitrogen adsorption and high-pressure mercury injection before and after extraction. The results show that residual hydrocarbons in Well BX7 mostly occur in pore spaces of less than 20 nm, and also in micron-scale pores, and that residual hydrocarbons in Well BYY2 generally occur in pore spaces of less than 200 nm and in micron-scale pores.

3.2 Spatial Characteristics of Movable Oil

The double mercury injection results are shown in Figure 7. Due to problems with some of the samples, secondary mercury injection experiments were successfully carried out only on four samples. The results show that the amount of mercury injected in the second injection was significantly less than in the first injection in all samples. Table 2 shows that, compared with the first injection, calculated porosity based on the second mercury injection decreased by 57.88% on average, and the calculated total pore volume decreased by 68.89% on average, indicating that the proportion of effective connected pores in the study samples was less than 50% of the total connected pores. Figure 9 shows the throat characteristics of mercury injection based on two mercury injections. In the sample from Well BX7, the amount of mercury injected in the second injection was significantly less than in the first injection, but was still able to reach pores of 2 nm. This indicates that many pores had remained unfilled during the first injection but were filled during the second injection. Comparing the first injection with the second injection reveals that residual mercury was mainly concentrated in pore throats less than 15 nm in diameter after the first mercury injection. This indicates that pores with throat diameters less than 15 nm are primarily responsible for restricting oil flow in Well BX7. Figure 8 shows that the accommodation space for retained hydrocarbons in Well BX7 is mainly in pores with throat diameters less than 20 nm. Improvement of connectivity in pores with throat diameters less than 15 nm is therefore the most important issue for obtaining industrial oil flow in Well BX7. In Well BYY2, the relationship between mercury retention and pore throat diameters varied between different lithofacies samples. In the lamellar dolomitic mudstone facies, the residual mercury was mainly concentrated in pores with throat diameters 10–200 nm, with pores with throat diameters around 100 nm being the main restriction on shale oil flow. In the bulk argillaceous dolomite facies, the residual mercury was mainly concentrated in pores with throats 60–300 nm in diameter, with pores with throat diameter around 200 nm being the

Table 1 Pore structure characteristics of wells BX7 and BYY2 before and after extraction

Sample	Depth (m)	TOC		S_i (mg/g)	Not extraction			Extraction			Specific pore volume difference		
		(wt. %)			Micropore (cm ³ /g)	Mesopore (cm ³ /g)	Macropore (cm ³ /g)	Micropore (cm ³ /g)	Mesopore (cm ³ /g)	Macropore (cm ³ /g)	Micropore (cm ³ /g)	Mesopore (cm ³ /g)	Macropore (cm ³ /g)
BX7-1	3 046.49	2.07		4.71	0.000 77	0.008 20	0.024 74	0.002 02	0.017 35	0.024 80	0.001 26	0.009 15	0.000 06
BX7-2	3 046.98	2.87		5.87	0.000 89	0.008 78	0.011 61	0.002 01	0.015 63	0.016 46	0.001 12	0.006 85	0.004 85
BX7-6	3 049.02	1.4		3.76	0.001 27	0.013 73	0.019 27	0.002 66	0.018 95	0.027 01	0.001 39	0.005 22	0.007 74
BX7-15	3 053.72	2.43		5.15	0.001 88	0.018 08	0.030 70	0.003 38	0.027 83	0.042 44	0.001 50	0.009 75	0.011 74
BX7-18	3 055.32	0.815		2.06	0.000 30	0.003 14	0.016 43	0.000 75	0.006 12	0.016 56	0.000 45	0.002 98	0.000 14
BYY2-21	2 817.45	1.83		4.24	0.000 27	0.001 93	0.009 29	0.000 33	0.004 77	0.022 61	0.000 06	0.002 84	0.013 32
BYY2-28	2 817.67	2.4		7.25	0.000 34	0.002 61	0.013 60	0.000 59	0.007 49	0.014 00	0.000 25	0.004 87	0.000 40
BYY2-90	2 820.34	2.44		9.85	0.001 03	0.010 07	0.033 64	0.000 76	0.019 00	0.062 27	-0.000 27	0.008 93	0.028 63
BYY2-101	2 820.64	2.05		7.91	0.000 70	0.007 31	0.024 62	0.000 73	0.014 68	0.049 26	0.000 02	0.007 36	0.024 65
BYY2-161	2 823.36	1.15		7.18	0.000 82	0.008 03	0.021 16	0.000 40	0.014 61	0.037 37	-0.000 42	0.006 58	0.016 21

main restriction affecting shale oil flow. Figure 7 shows that, during the second mercury injection, almost all the mercury was ejected from the pores after the pressure was released. Therefore, the smallest pore throat that mercury can enter during the second injection can be regarded as a reference value for the minimum pore throat diameter for movable oil. In Well BYY2 this value is 40 nm, with shale oil in pores above this size showing good mobility (Figure 9). Xiao (2018) also concluded that 40 nm is the minimum pore size for movable oil in the Eq3⁴-10 cyclothem in the Qianjiang depression (Figure 10), in that case by comparing the changes in T_2 peak NMR spectra before and after centrifugation. The similarity of

these results confirms the reliability of the double mercury injection technique.

3.3 Factors Influencing the Effectiveness of Connected Pores

Figure 9 shows that the development of effective connected pores is closely related to pore throat distribution. A lateral comparison between Well BX7 and Well BYY2 shows that there are significant differences in pore connectivity between the two. Pore throats in Well BX7 are mostly less than 20 nm, while in Well BYY2 they are mostly more than 10 nm. The influence of compaction is part of the explanation for this, but a further reason lies in

Table 2 Pore structure parameters of double mercury injection

Samples	HPMI	BX7-15	BYY2-90	BYY2-101	BYY2-161
Porosity (%)	Once	4.590 8	18.025	17.472 2	18.728 9
	Twice	1.476 9	8.636 2	8.941 1	6.978 6
Pore volume (mL/g)	Once	0.019 1	0.086 7	0.081 4	0.086 7
	Twice	0.004 9	0.026 4	0.027 2	0.030 3

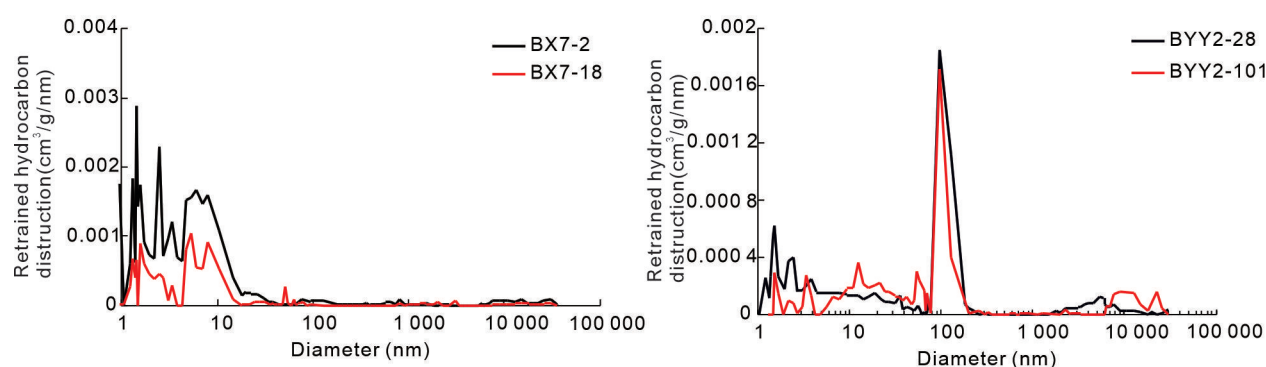


Figure 8. Retained hydrocarbon distributions for the shale samples from the Eq3⁴-10 cyclothem.

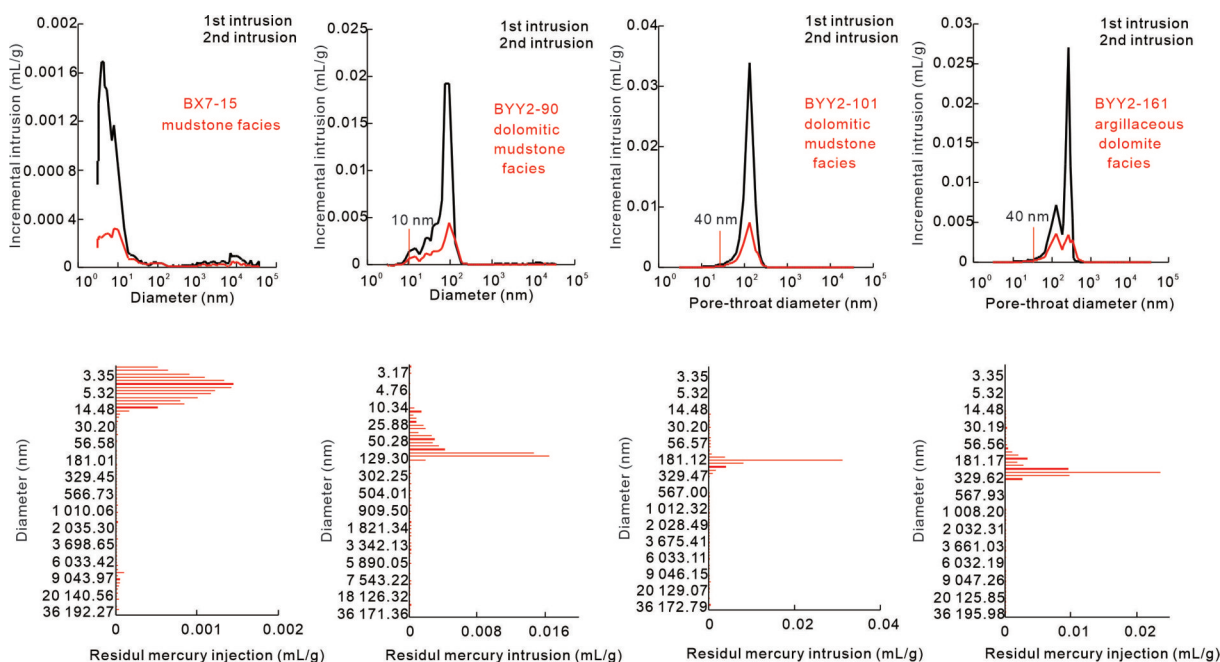


Figure 9. Pore size distribution in shale samples from the Eq3⁴-10 cyclothem under double mercury injection.

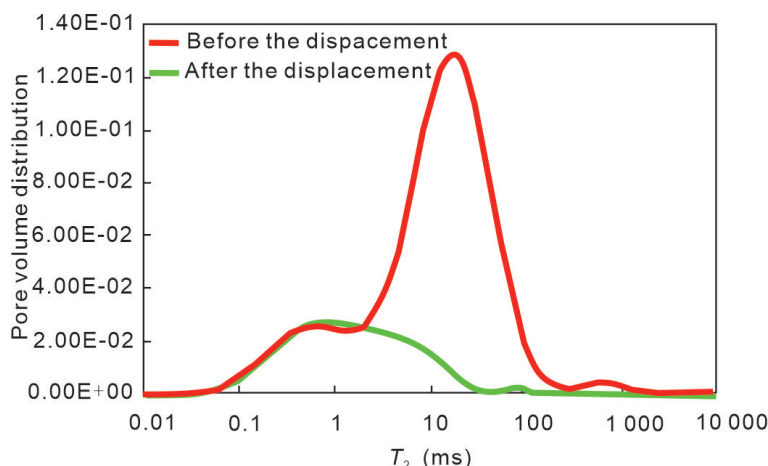


Figure 10. Characteristics of T_2 peak spectra before and after centrifugation of the Eq3⁴-10 cyclothem under NMR (Xiao, 2018).

the difference in sedimentary backgrounds (Sun et al., 2020). The Qianjiang depression is influenced by its north-west oriented provenance. Well BX7 is relatively close to the provenance, so the mineral composition is mainly terrigenous detritus. As Figure 3 shows, the pores of samples from Well BX7 are mainly terrigenous clastic intergranular pores and clay interlayer pores. These pores are affected by diageneses such as compaction, which reduces pore throat diameters and increases pore complexity. The large hysteresis ring in Well BX7 (Figure 4) indicates a complex pore structure and 'ink-bottle'-shaped pores, which make it difficult for shale oil to flow. Well BYY2 is less affected by terrigenous debris, and a stable deepwater environment provided favorable conditions for stratification. In laminar samples, both euhedral and sub-rounded (Figure 3f) bacterially-induced dolomite crystals were observed in the porous dolomite beds (Sun et al., 2022a). In addition to these biogenic dolomites, chemical dolomites are also present. As water salinity increases and depth decreases, chemical dolomite precipitates, producing sediments with high dolomite contents and large numbers of dissolved pores. Dolomite is very hard, so it effectively preserves and supports the pores. The pores in Well BYY2 are therefore generally larger in diameter and better shaped than those in Well BX7.

The pore complexities of wells BX7 and BYY2 were visualized in a previous study by combining the fractal dimension (see Sun et al., (2022b) for the calculation of fractal dimension). The fractal dimension D_1 and D_2 are mainly affected by the roughness of sample surface and the irregularity of pore structure. The value 3 represents the completely irregular surface and pore structure, and the value 2 represents the completely smooth surface and regular pore structure (Li et al., 2018; Khalili et al., 2000; Giri et al., 2012). The roughness of pore surfaces is similar in both wells, but the pore structure in Well BX7 is much more complex than that of Well BYY2 (Figure 11). This is one of the reasons why mercury was not easily ejected after injection in the BX7 sample. In addition, pore-throat connectivity analysis reveals poor connectivity in both wells ($D_3 > 2.5$; D_{3-1} and D_{3-2} represent the frac-

tal dimensions of large and small pore throats of well BYY2, respectively), which means significantly lower proportions of effective connected pores.

Longitudinal comparison of the two wells also shows that connected pores in different lithofacies in the same well are quite different. In Well BX7, the characteristics of connected pores in mudstone facies are better than those in calcareous mudstone facies and dolomite mudstone facies. The lithofacies reflects the mineral composition, so the terrigenous clastic content of mudstone facies is higher than that of calcareous mudstone facies and calcareous mudstone facies. As shown in the SEM images, the pores in Well BX7 are mainly composed of terrigenous detritus. More terrigenous detritus means more developed pores and better pore connectivity. Sun et al. (2022a) showed that clay and quartz have a good positive correlation with pore development in Well BX7, while dolomite is negatively correlated. According to Sun et al.'s (2022b) correlation of mineral composition with the fractal dimension, quartz is the principal mineral supporting pores and promoting pore connectivity, while increase in the amount of dolomite makes pore connectivity worse. In Well BYY2, the laminated dolomitic mudstone facies is superior to the argillaceous dolomite facies and the calcareous mudstone facies (Table 3). The reason is that dolomite is generally biogenic during laminar development and a large number of intercrystalline pores can form (Figures 3f, 3g). Analysis of the correlation between mineral and pore throat fractal dimensions (Sun et al., 2022b) shows that quartz generally forms small diameter pore throats, while calcite forms large pore throats. Increase in the contents of quartz and calcite will therefore lead to poor pore connectivity and inhibit the flow of shale oil.

Salt rock also has a crucial influence on pore connectivity. According to Sun et al.'s (2022b) correlation between salt minerals and throat fractal dimensions, salt minerals have a strong blocking effect on small pore throats and consequently reduce the proportion of effective connected pores. Improvement of the connectivity of pores and promotion of salt mineral dissolution and repre-

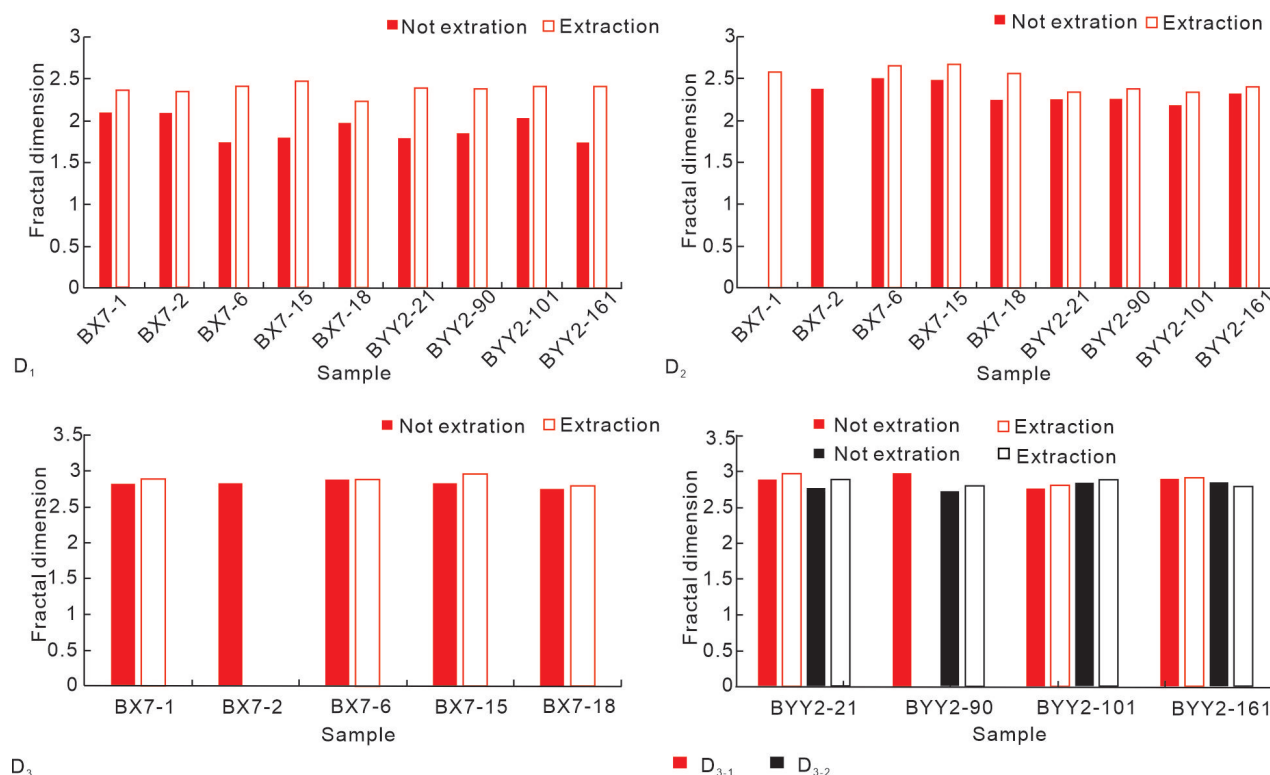


Figure 11. Fractal dimension values based on N_2 gas adsorption and high-pressure mercury injection data reconstruction (Sun et al., 2022b). Note: D_1 is the fractal dimension of pore surface, D_2 is the fractal dimension of pore structure, D_3 is the fractal dimension of throat connectivity (D_{3-1} is the fractal dimension of small pore throat, and D_{3-2} is the fractal dimension of large pore throat).

cipitation will therefore be the key to increasing shale oil storage and production in future development.

4 CONCLUSIONS

This paper evaluates the characteristics of connected pores in shale samples from the Eq3⁴-10 rhythm of the Qianjiang Formation in the Qianjiang depression, and investigates the occurrence of pores containing movable shale oil. The principal conclusions are as follows.

(1) Because of the influence of compaction and sedimentary environment in the Qianjiang Formation, the types, sizes, and degrees of deformation of pores in Wells BX7 and BYY2 are different. The pores in Well BX7 are mostly mixed intergranular pores composed of quartz, clay, and carbonate minerals, as well as clay interlayer pores. The pore diameters are mostly less than 50 nm, with a peak distribution value of about 5–10 nm. The pores in Well BYY2 are mostly dolomite intercrystalline pores and mixed intergranular pores, with a small number of clay mineral interlayer pores. The pores are mostly less than 600 nm, and micron-scale pores are widely developed. In Well BX7, pore development in mudstone facies is better than in carbonaceous mudstone and dolomitic mudstone facies while, in Well BYY2, pore development is best in dolomitic mudstone facies, followed by argillaceous dolomite facies and argillaceous limestone facies.

(2) Effective connected pores in Eq3⁴-10 rhythmic samples from the Qianjiang Formation account for less

than 50% of all connected pores, and the effective connected porosity of Well BX7 is inferior to that of Well BYY2. In Well BX7, pores with throat diameters smaller than 15 nm are the principal limitation on shale oil mobility. In Well BYY2, residual mercury from mercury injection testing was mainly concentrated in pores with throats of 10–200 nm in lamellar dolomitic mudstone facies. In bulk argillaceous dolomite facies, the residual mercury was mainly concentrated in 60–300 nm pores. The sizes of pore with retained hydrocarbons can be 5 nm, or even smaller, while the sizes of pores with movable shale oil are generally larger than 40 nm.

(3) Excluding the influence of differences in wettability, the mobility of shale oil in Eq3⁴-10 rhythmic samples from the Qianjiang Formation is affected by differences in lithofacies, the degree of pore deformation caused by diagenesis, the complexity of pore structures, and the connectivity of pore throats. Halite dissolution and reprecipitation also inhibit the mobility of shale oil.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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