Research Article

Study on Micro-Nano Pore Characteristics and Classification of Tight Sandstone Reservoir Based on Q-Cluster

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To realize the quantitative classification and comprehensive evaluation of the tight oil reservoir in the 4th of Quantou Formation in Songliao Basin, the pore structure of tight oil reservoir was quantitatively analyzed. In this study, experiments based on the constant-speed mercury injection, nuclear magnetic resonance, and micron CT are based on the observation of cast thin sections, and scanning electron microscope is conducted. The result shows that a tight oil reservoir space is mainly composed of the intergranular dissolved pore, residual intergranular pore, and intragranular dissolve pore. There are few intercrystalline pore and fracture at the same time. The average pore radius is 1.28~4.58 μm, and the average throat radius is 0.52~1.27 μm. Hence, there is a typical micro-nano throat combination with micropores. The pore throat composition and pore structure of reservoirs differ in reservoir with different physical properties. The reservoir quality depends on pore structure especially the throat radius. And the microthroat is a critical factor for permeability. Based on Q-cluster analysis, tight oil reservoirs are classified into three types. The analysis was based on the data such as max throat radius, average throat radius, displacement pressure, median pressure, and permeability. Finally, the reservoirs in the study area are mainly II and I types.

1. Introduction

Tight oil is the abbreviation of tight reservoir oil. It exists in source rocks in an adsorbed or free state. Some others are interbedded with source rocks and accumulate near reservoir rocks, such as tight sandstone and carbonate formations. As conventional oil and gas exploration decreases and becomes more complex, unconventional oil and gas, represented by tight oil, shale gas, and volcanic gas, have become the most critical area for China to increase oil reserves and raise oil production [1–4]. Especially, the successful exploration and large-scale commercial development of tight oil in Alberta Basin, Williston Basin, Anadarko Basin and Maverick Basin in North America not only make people realize the huge resource potential of tight oil, but also make tight oil a new hot spot of global unconventional oil exploration after shale gas [5–8]. The tight oil resources in China are widely distributed. At present, exploration breakthroughs have been made in the tight sandstone of Yanchang Formation in Ordos Basin, Jurassic shell limestone and tight sandstone in Sichuan Basin, Permian silty dolomite and dolomitic siltstone in Junggar Basin, and Cretaceous Quantou Formation sandstone in Songliao Basin. Large-scale reserves have been formed and developed [9–11]. Songliao Basin is China’s main area for tight oil exploration and development. After several stages of exploration and development, such as regional exploration, large-scale lithologic reservoir exploration, and integrated accelerated exploration since
1959, a tight oil-rich area with an area of about 10,490 km² and a geological reserve of nearly $1.7 \times 10^8$ t has been discovered in Sanzhao sag and Qijia-Gulong sag. In addition, the annual oil production of $5.1 \times 10^4$ t/year has been continuously stable for 13 years through geologically and engineering integration technologies such as horizontal well volume fracturing, CO$_2$ stimulation and moderate fracturing, and elastic development of vertical wells on the platform [12, 13]. The main problems in the exploration and development of tight oil in the 4th of Quantou Formation of the Songliao Basin are the low grade of resources. The difficulty in effectively utilizing the proven unexploited reserves, and the remaining exploration targets are mainly low-grade and tight reservoirs. Besides, the remaining exploration targets are...
mainly low-grade and tight reservoirs. Complex pore structure and widely developed micro-nano pores have become the key factors that restrict the efficient development of tight oil.

With the deepening of exploration and development of unconventional oil and gas, such as tight oil and shale gas, the pore structure and quantitative characterization of tight reservoirs as unconventional oil and gas carriers have attracted extensive attention in the oil industry [14–18]. The microscopic pore structure of tight oil reservoir is extremely complicated because of the low porosity and permeability, often associated with extensive compaction and cementation. The 3-D network of pores of different shapes and sizes in tight reservoirs is the critical factor in controlling fluid flow and determining oil and gas productivity [19, 20]. Microscopic pore structure can significantly impact fluid flow in tight oil reservoir since they may contain immobile, capillary-bound waters that are only in diffusional contact with mobile pores waters. Therefore, research on the pore structure characteristics in tight sandstone is necessary for attributes in tight oil mechanisms and development [21, 22]. In that case, quantitative classification and evaluation of tight reservoirs based on pore structure analysis are essential for the efficient development of tight oil and gas [23]. With the development of experimental, kinds of pore structure testing technologies have been formed in recent years. Consequently, many qualitative and practical approaches have been carried out to study tight sandstone pore structure characteristics [24–27]. And the hybrid of qualitative and quantitative analysis methods has been utilized to obtain insight into the microscopic pore structure. The technologies are mainly casting thin section, scanning electron microscopy (SEM), transmission electron microscopy (TEM), constant-speed mercury intrusion porosimetry (MIP), micro-nano CT, and nuclear magnetic resonance (NMR) [26]. The research on different levels of pores has leaped from 2-D, qualitative to 3-D and quantitative, which provides favorable support for the study of pore characteristics of tight oil and gas reservoirs [4, 14, 15, 26–32]. However, all of these techniques have their strengths and limitations. SEM and TEM can directly observe the size, morphology, and type of pores from the nano- to micron-scale. Furthermore, it is difficult to obtain the quantitative parameters such as pore volume and size distribution using these techniques. The extensive development of tight reservoirs micro-nano pores has inevitably enhanced the reservoir pore structure’s complexity. Besides, the pore parameters obtained by single testing technology have been challenging to meet the needs of high-precision pore structure analysis [33–36]. Multiscale qualitative and quantitative data fusion becomes necessary to improve the characterization accuracy of tight reservoir pore structure and evaluate the pore structure. Microscopic pore structures were systematically characterized based on multiple experimental analyses. Consequently, the tight oil reservoir is quantitatively classified. The relationship between pore size distribution and physical properties of the tight oil reservoir in the 4th of Quantou Formation is obtained. In this study, many tests, such as high-pressure mercury injection, constant-speed mercury injection, micron CT, and nuclear magnetic resonance, were carried out. Then, pore structure parameters and permeability related to physical properties were selected for Q-type clustering. The quality of the I-type reservoir is better than that of the II-type and III-type. The quality of the I-type reservoir is better than that of the II-type and III-type, which is the best reservoir for tight oil development.

2. Geological Setting

Songliao Basin is a large-scale Mesozoic-Cenozoic sedimentary basin superimposed on Paleozoic basement in China, with an apparent double structure of lower fault and upper depression, mainly filled with Mesozoic-Cenozoic clastic rocks [19, 37–39]. From bottom to top, the formations are Quantou Formation of the lower Cretaceous and Qingshan-kou Formation, Yaojia Formation, Nenjiang Formation, and Sifangtai combined Mingshui Formation of the upper Cretaceous (Figure 1). The 4th of Quantou Formation is the central pay zone of tight oil in North Songliao Basin. It is a shallow delta distributary channel and underwater distributary channel sandstone. And it was formed under the control of multiple sources around the basin [14, 15, 33, 34, 40]. Sanzhaow area, east of central depression, is a delta-distributed secondary depression controlled by several deep basement faults. It is characterized by west-high to east-low slope from the edge of the depression to the center of

| Number | Sample number | Depth/m | Lithology   | Helium porosity/% | Permeability/$\times 10^{-3}$ μm$^2$ | Connected pore volume/% |
|--------|---------------|---------|-------------|-------------------|--------------------------------------|-------------------------|
| 1      | Z132-1        | 1855.6  | Fine sandstone | 10.74             | 0.399                                | 91.00                   |
| 2      | Z132-2        | 1895.7  | Fine sandstone | 5.88              | 0.002                                | 42.35                   |
| 3      | Y7            | 1782    | Fine sandstone | 6.84              | 0.003                                | 85.71                   |
| 4      | F42           | 1905    | Fine sandstone | 9.30              | 0.140                                | 43.63                   |
| 5      | F381-1        | 1917.5  | Fine sandstone | 4.55              | 0.003                                | 63.40                   |
| 6      | F381-2        | 1892.5  | Fine sandstone | 6.88              | 0.003                                | 23.10                   |
| 7      | S51           | 1686.1  | Fine sandstone | 6.20              | 0.008                                | 19.92                   |
| 8      | Z57           | 2049.1  | Fine sandstone | 7.47              | 0.107                                | 79.81                   |
| 9      | F50           | 1810.4  | Fine sandstone | 9.92              | 0.004                                | 12.70                   |
| 10     | Z48           | 1949.4  | Fine sandstone | 4.38              | 0.001                                | 33.30                   |
the depression (Figure 1). The channel sand bodies in the 4th member of Quanquan are close to the lacustrine high-quality source rocks of the first member of Qingshankou Formation, and the matching relationship between source and reservoir is good, which provides a good geological basis for the formation of tight oil.

The tight oil reservoir in the 4th of Quantou Formation is dominated by silty-fine sandstone, characterized by fine grain size, good sorting, complex clastic components and cementation types, and poor physical properties. The content of feldspar and debris in the clastic particles is the highest, which are 34.8~38.2% and 29.8~38.1%, respectively, with an average of 36.4% and 33.8%, while the content of quartz is only 26.1~32.9%. The cement is mainly kaolinite and calcite, followed by siliceous and chlorite. Porosity is concentrated in 6~14%, with an average of 9.40%. The permeability distribution ranges from $0.01 \times 10^{-3} \mu m^2$ to $10 \times 10^{-3} \mu m^2$, and 80% of the samples are less than $1 \times 10^{-3} \mu m^2$, with an average of $0.95 \times 10^{-3} \mu m^2$. It is a typical tight sandstone.

3. Samples and Analytical Methods

Ten samples were taken from the 4th of Quantou Formation, Sanzhao sag, and the lithology was lithic feldspar fine sandstone and feldspar lithic fine sandstone, with porosity of 4.38~10.74% and permeability of $0.001 \sim 0.399 \times 10^{-3} \mu m^2$. The petrophysical profile is listed in Table 1. Regular column samples of 30 mm in length and 25 mm in diameter
were drilled on stable lithological sections. And ensure that the end face is parallel to the bedding plane to eliminate the influence of lithological heterogeneity on the experimental results as much as possible. Firstly, the residual asphalt in the sample was removed with the mixture of alcohol and chloroform and then dried at 110°C for 24 hours. Then, the porosity and permeability of the sample were measured, and high-pressure mercury intrusion, nuclear magnetic resonance, constant-speed mercury injection, scanning electron microscope, and micro-CT were performed in turn.

Nuclear magnetic resonance (NMR) is to carry out NMR in the saturated and centrifugal state on MARAN-2 NMR instrument. Standard CPMG pulse sequence, echo interval of 0.256 ms, waiting time of 6 s, and 128 scans were adopted during the experiment. Before measurement, the sample was saturated in saline solution with similar salinity to formation water for 24 h. After measuring the NMR of the saturated sample, centrifuge the sample for 30 min with a centrifuge (equivalent centrifugal pressure is 2.7 MPa), and perform the NMR test of the centrifuged sample. The constant-speed mercury injection experiment was carried out on ASPE-730 instrument. The mercury injection rate was kept at 5 × 10⁻⁵ mL/min, the maximum mercury injection pressure was 6.17 MPa, and the lower limit of throat radius was 0.12 μm. The micron CT experiment was completed on MicroXCT-400 micron CT scanner, with the highest resolution up to 65 nm. Avizo was used to segment the image and reconstruct the pore volume to obtain the 3-D distribution of the pore volume. Then, the pore distribution obtained by constant mercury injection and nuclear magnetic resonance was compared.

4. Result

4.1. Pore Types and Characteristics of Tight Oil Reservoir. In this study, the pores are mainly intragranular dissolved, intergranular dissolved, and residual intergranular pores. Besides, there are a small number of intergranular pores and microcracks. The intragranular dissolved pores are beaded, elongated, or honeycomb pores. They were formed by selective dissolution of debris particles (Figure 2(a)). When the corrosion is substantial, only the mold holes with the same shape as the debris components remain (Figure 2(b)). Then, the pore size is about 2~30 μm, the plane porosity is 2.63%, accounting for 42.3% of all pores. The intergranular dissolved pores are irregular and jagged. They were formed by the dissolution of debris particles and carbonate cement (Figure 2(c)). The pore size is about 1~18 μm, and the plane porosity is about 0.84%, accounting for 18.2% of all pores. It was associated with intragranular dissolved pores, which developed at the contact between particles. It acted as the throat to enhance permeability. The intergranular dissolved pores are irregular and jagged. They were formed by the dissolution of debris particles and carbonate cement (Figure 2(c)). The pore size is about 1~18 μm, and the plane porosity is about 0.84%, accounting for 18.2% of all pores. It was associated with intragranular dissolved pores, which developed at the contact between particles. It acted as the throat to enhance permeability. The intergranular dissolved pores are irregular and jagged. They were formed by the dissolution of debris particles and carbonate cement (Figure 2(c)). The pore size is about 1~18 μm, and the plane porosity is about 0.84%, accounting for 18.2% of all pores. It was associated with intragranular dissolved pores, which developed at the contact between particles. It acted as the throat to enhance permeability.

The residual intergranular pores are unfilled primary pores left after compaction and cementation. They are primarily triangular and irregular (Figure 2(d)) and distributed at the edges of rigid particles. The pore size is about 1~20 μm, and the plane porosity is about 1.62%, accounting for 25.6% of all pores. The intergranular pores are intergranular honeycomb micropores in authigenic clay minerals. And the pore size is generally less than 3 μm (Figure 2(e)). The microfractures are about 1~10 μm wide, extending in a linear and dendritic manner. They cut through many debris particles and communicate with different types of
The scanning electron microscope and cast thin section observation show that the throat of tight oil reservoir in the study area is primarily curved and tube bundle-shaped, and there are a few necking throats as well, and a few necking throats can be seen. The curved throat is mainly distributed on the surface of the quartz. And it is formed by the reduction of primary pores caused by compaction and autogenous quartz cementation and is commonly filled with clay minerals (Figure 2(g)). The content of clay minerals in the study area is high. The tube bundle channel formed by intercrystal pores of clay minerals is also one of the critical throat structure parameters, and has large pores at both ends (Figure 2(i)).). The neck-constricted throat is mainly formed by the dissolution of cement, and the expansion of particle gap is caused by the dissolution. The throat is flat and has large pores at both ends (Figure 2(j)).

4.2. The Distribution of Pore Size of Tight Oil Reservoir. The size and distribution of pore can significantly impact the flow of oil and water within the tight oil reservoir, and the preservation and distribution of microscopic pore structure are essential for developing tight oil. Pore size is an important variable as it directly correlates with reservoir quality. Therefore, the micropore has been defined based on pore and pore throat size [41–43]. Choquette and Pray [44] defined micropores as voids with average diameters of less than 64 μm, and an upper limit of 10 μm may have more significance as the greater upper limit includes small molds and vugs. Hassall et al. [45] consider nano-pore to have a pore throat diameter of less than 0.5 μm, while micropores are defined as pore throat diameters between 0.5 and 5.0 μm, while micropores have throats greater than 5.0 μm. The International Union of Pure and Applied Chemistry (IUPAC) divided the pores into three kinds, such as micropores, mesopores, and macropores; micropores have been defined as having throats with a smaller dimension of less than 2 nm, while the throat of mesopores is between 2 nm and 50 nm, and the throat of macropores is greater than 50 nm [46, 47]. However, most classifications of pore size are developed on conventional reservoir, the reservoir of tight oil is a typical unconventional reservoir, and the pore size is smaller than that in conventional reservoir. In this paper, pores in tight oil reservoir were divided into three types: nano-pore (<1 μm), micropore (1~1000 μm), millimeter-pore (>1000 μm) [48, 49].

The tight oil reservoir in the study area is small in pore size and diverse in shape. However, there is a difference in the research purpose and test accuracy of the test technique, so it is challenging to meet the requirements of high-precision pore structure analysis by a single test alone. Therefore, it is necessary to quantitatively analyze and classify the tight reservoir structure using various analysis methods [50]. In this study, the T2 spectrum of nuclear magnetic resonance was calibrated by the cumulative porosity curve provided by ten high-pressure mercury injection samples, and the T2 spectrum of relaxation time was transformed into pore size distribution [16, 51]. The results show that the pore throat radius of tight oil has a wide distribution range, ranging from 0.1 μm to 400 μm, and the maximum is 989 μm. The pore diameter curves of most samples have bimodal characteristics (Figure 3). They represent the pores and throats of tight oil reservoir, respectively. The pore radius is concentrated in 1.82~18.42 μm, with an average of 3.88 μm, and the throat radius is mainly distributed in 0.02~1.46 μm, with an average of 0.54 μm, indicating that micron-sized pores and micro-nano throats are developed in tight oil reservoir in the study area (Table 2).

The test of micron CT shows the similar results. The pore radius varied greatly, ranging from 1.0 μm to 943 μm. And the average pore radius ranges from 1.28 μm to 4.58 μm. Besides, the throat radius ranges from 0.05 to 2.93 μm, with the average value ranging from 0.52~1.27 μm (Figure 4). It also shows that tight oil reservoir is composed of micro pores and micro-nano throats. There is the most remarkable difference in throat characteristics among samples with different physical properties. There are few throats in Well P381, only 286 throats have been found and the throat radius ranging from 0.5 to 2.31 μm, and the corresponding physical properties are the worst. Well Z48 has the most developed throats, with about 1,076 throats and

| Number | Sample number | Nuclear magnetic resonance of water saturation of core (%) | Centrifugal analysis of movable fluid saturation controlled by different throat radius (μm) intervals (%) |
|--------|---------------|----------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
|        |               | 21 psi (1.0 μm) | 42 psi (0.5 μm) | 208 psi (0.10 μm) | 417 psi (0.05 μm) | >1.0 | 1.0–0.5 | 0.5–0.10 | 0.10–0.05 | <0.05 |
| 1      | Z132-1        | 76.34          | 65.51           | 53.2             | 48.51             | 23.66 | 10.83   | 12.31    | 4.69      | 51.49 |
| 2      | Z132-2        | 98.96          | 97.58           | 95.72            | 94.41             | 1.04  | 1.38    | 1.86     | 1.32      | 5.59  |
| 3      | Y7            | 97.37          | 93.05           | 88.16            | 83.97             | 2.63  | 4.32    | 4.89     | 4.19      | 16.03 |
| 4      | F42           | 96.22          | 91.55           | 71.54            | 64.71             | 3.78  | 4.67    | 20.02    | 6.83      | 35.29 |
| 5      | F381-1        | 97.94          | 94.19           | 89.47            | 85.11             | 2.06  | 3.75    | 4.72     | 4.36      | 14.89 |
| 6      | F381-2        | 98.29          | 95.94           | 92.19            | 88.17             | 1.71  | 2.35    | 3.75     | 4.02      | 11.83 |
| 7      | S51           | 94.68          | 92.98           | 90.96            | 89.71             | 5.32  | 1.7     | 2.02     | 1.25      | 10.29 |
| 8      | Z57           | 94.45          | 90.81           | 85.79            | 81.69             | 5.55  | 3.64    | 5.02     | 4.1       | 18.31 |
| 9      | F50           | 98.6           | 96.16           | 93.18            | 91.38             | 1.4   | 2.44    | 2.98     | 1.8       | 8.62  |
| 10     | Z48           | 97.8           | 96.56           | 93.93            | 92.05             | 2.2   | 1.24    | 2.63     | 1.88      | 7.95  |
throat radius ranging from 0.5 to 5.37 μm and with the best permeability (Table 3).

4.3. Influence of Pore Throat Structure on Physical Property of Tight Oil Reservoir. Micro-nano pore throats widely developed in tight oil reservoir lead to extremely complex pore throat structure. Constant-speed mercury injection injects mercury into rock pores at low speed and distinguishes pores from throats. Constant-speed mercury injection analysis of 10 samples shows that pore structure is the main factor affecting reservoir quality. Throat characteristics are the key to restricting permeability (Figure 5). When the porosity is less than 8%, nano-throats with a radius less than 1 μm are the most developed reservoirs, accounting for 52.78~94.84% of the total pore throat volume, with an average of 74.53%.

These tiny nano-throats are not conducive to fluid seepage. And the volume of microthroats with a pore diameter greater than 1 μm is only 25.47%, which plays a crucial role in improving reservoir permeability (Figure 6). When the porosity is greater than 8%, the reservoir is dominated by micron pores with a pore diameter greater than 2 μm. Although the volume of nano-throats with a radius less than 1 μm is as high as 38.45%, its contribution to permeability is limited, while the volume of microthroats with a radius less than 1 μm is only 18.72%, but it is the main factor determining the reservoir permeability.

The high-pressure mercury injection provides numerous pore throat structure, such as the pore size, selectivity, and connectivity of pore throat. These pore throat structure parameters suggest that tight oil reservoir in the study area...
Table 3: Micro-CT results of tight sandstone in the 4th of Quantou Formation.

| Number | Sample number | Connected pore volume/% | Pore number | Pore volume/×10⁶ μm³ | Pore radius/μm | Number of throats | Throat volume/μm³ | Throat radius/μm |
|--------|---------------|--------------------------|-------------|----------------------|---------------|-------------------|------------------|-----------------|
| 1      | Z132-1        | 91                       | 333919      | 248600               | 1.84 ~ 891/4.58 | 439               | 1852170         | 0.50 ~ 4.00/0.73 |
| 2      | Z132-2        | 42.35                    | 369961      | 11900                | 1.22 ~ 1089/3.67 | 998               | 625627          | 0.50 ~ 2.51/0.62 |
| 3      | Y7            | 85.71                    | 935862      | 364320               | 1.24 ~ 927/3.86 | 582               | 1613021         | 0.50 ~ 4.72/0.96 |
| 4      | F42           | 43.63                    | 346621      | 30120                | 1.22 ~ 1036/3.82 | 876               | 563064          | 0.50 ~ 3.29/0.82 |
| 5      | F381-1        | 34.6                     | 278293      | 13762                | 1.22 ~ 1236/3.52 | 774               | 846796          | 0.50 ~ 3.13/0.59 |
| 6      | F381-2        | 23.1                     | 422931      | 15659                | 1.20 ~ 446/3.36 | 1085              | 659320          | 0.50 ~ 2.32/0.65 |
| 7      | S51           | 19.92                    | 839536      | 7534                 | 1.22 ~ 865/3.32 | 1076              | 23833           | 0.50 ~ 2.37/0.52 |
| 8      | Z57           | 79.81                    | 273088      | 27600                | 1.23 ~ 943/3.85 | 286               | 1850921         | 0.50 ~ 2.92/0.66 |
| 9      | F50           | 12.7                     | 763294      | 5820                 | 1.22 ~ 862/3.15 | 349               | 1402361         | 0.50 ~ 5.37/1.09 |
| 10     | Z48           | 33.3                     | 329728      | 12670                | 1.22 ~ 693/3.51 | 761               | 984867          | 0.50 ~ 2.31/0.55 |

Figure 5: Tight oil pore distribution and cumulative pore radius distribution.

Figure 6: Relationship between pore with different aperture and reservoir quality.
has the characteristics of a small pore throat radius, high displacement pressure, and low mercury removal efficiency. The maximum pore throat radius and the average pore throat radius represent pore size. The maximum pore throat radius of tight oil reservoir in the study area is 0.027–9.2 μm, with an average of 1.20 μm, and the average pore throat radius is 0.01–4 μm, with an average of 0.38 μm, indicating that the pores in tight oil reservoir are mainly micropores and nano-pores. The displacement pressure, median pressure, and mercury removal efficiency reflect pore connectivity; the displacement pressure ranges from 2.88 MPa to 85.47 MPa, with an average of 29.28 MPa; and the median pressure ranges from 1.58 MPa to 37.91 MPa, with an average of 9.54 MPa. The mercury removal efficiency is 32.54–69.61%, with an average of 46.52%, indicating that the porosity connectivity of tight oil reservoir is generally poor. The relative sorting coefficient, feature structure coefficient, and homogenization coefficient reflect the sorting characteristics of pores, and they are widely distributed in the study area. The relative sorting coefficient is 2.42–110.12, with an average of 22.64, and the feature structure coefficient is 0–9.68, with an average of 3.08, while the homogenization coefficient is 0.16–0.73, with an average of 0.33, indicating that the reservoir of tight oil is the mixed of different kinds of pores and throats. The relationship between physical properties and pore structure parameters provides that the size and connectivity of pore have a better

Figure 7: Relationship between structure parameters and reservoir quality.

Figure 8: Reservoir classification of the tight oil reservoir in the study area.
relationship with physical properties, especially the permeability (Figure 7). With the decrease of pore throat radius and connectivity, the permeability decreases sharply. The physical properties become worse, indicating that the pore size and connectivity are the main controlling factors for physical properties in tight oil reservoir.

5. Discussion

5.1. Reservoir Classification in Tight Oil. The micropore structure characteristics of tight oil composed of microporous throats and pores are the internal factors that affect the physical properties of reservoirs and are also the vital basis for reservoir classification and evaluation [52, 53]. The production wells in the study are divided into three kinds. Based on the oil testing and oil capacity, researchers defined a high yield well with a capacity greater than 10 t/d. A stripper well is defined as having a production capacity between 10 t/d and 5 t/d. A dry well has a capacity of less than 5 t/d. However, the capacity of oil is not only controlled by reservoir quality. The testing method and perforating position can influence the production capacity. Slurry intrusion during drilling can also destroy the pore structure and cut down the capacity at the same time. The micropore and nanopore are the main migration channels for flow, and the capacity and the reservoir quality of tight oil are greatly influenced by pore structure. In that case, quantitative evaluating the tight oil reservoir according to the physical porosity and pore structure is an effective measure to enhance the development effect. In this study, the structural parameters, such as the largest pore throat radius, average pore throat radius, displacement pressure, and median pressure, are closely related to physical properties. We divide the tight oil reservoir into three kinds according to Q-cluster analysis on the base of structural parameters selected (Figure 8). The pore sizes and distribution are the critical factor in controlling the fluid flow and determining oil and gas productivity. Therefore, the I-type, II-type, and III-type reservoirs are categorized based on their permeability and pore radius. The reservoirs with a permeability greater than $0.8 \times 10^{-3} \mu m^2$ and pore radius median greater than $1 \mu m$ are defined as I-type reservoirs. In addition, the reservoir with permeability between $0.8 \times 10^{-3} \mu m^2$ and $0.1 \times 10^{-3} \mu m^2$ and pore radius median ranging from $1 \mu m$ to $0.3 \mu m$ is defined as a II-type reservoir. Besides, the reservoir with permeability and pore radius median less than $0.1 \times 10^{-3} \mu m^2$ and $0.3 \mu m$ is defined as a III-type reservoir. The clustering results of 126 samples show that the physical properties and pore structure characteristics of different reservoirs tend to be consistent (Table 4). The classification results are beneficial to the deployment of horizontal wells in tight oil and the design of production enhancement measures in the study area.

5.2. Characteristics of Different Types of Reservoirs. The I-type reservoir is mainly composed of fine sandstone and siltstone in the meandering, distributary channel, with the best physical properties. With a porosity and permeability of 10–12% and 0.3–1.0 $\times 10^{-3} \mu m^2$, respectively, the reservoir mainly composed of secondary pores such as feldspar intragranular dissolved pores and cement dissolved pores, with a small amount of residual intergranular pores and intergranular pores. The pore throat combination is micron pore micronano throat (Figure 9), with pore radius ranging from 1.50 to $7.0 \mu m$ and throat radius ranging from 0.34 to 1.20 $\mu m$. The displacement pressure is generally less than 5 MPa, ranging from 0.04 MPa to 12.63 MPa, with an average of 4.79 MPa, and the conjoined volume is generally 80–90%. In the northern part of the study area, Shengping, Changde, and Xingcheng are distributed in a strip shape, extending steadily on the plane, with the thickness of a single layer generally greater than 3 m. Oil and gas show generally at oil immersion level or above, oil saturation usually greater than 50%, and single well output typically greater than 1 t/d.

The II-type tight oil reservoir is mainly composed of fine sandstone in the meandering channel, siltstone, siltstone in the distributary channel, and underwater distributary channel. And the physical properties are relatively fine, with porosity of 8–10% and permeability of 0.1–0.3 $\times 10^{-3} \mu m^2$. The compacted residual intergranular pores in the reservoir are high, and there are a certain number of dissolved pores in feldspar grains and cement. The pore-throat combination is micron pore nano-throat, with pore radius of 0.75–2.16 $\mu m$ and throat radius of 0.32–0.78 $\mu m$. Displacement pressure is relatively high, ranging from 0.14 MPa to 18.63 MPa, with an average of 9.64 MPa. The volume of connected pore throat in reservoir is 45–80%. The sand bodies are distributed in sheet

| Parameter                        | I-type       | II-type       | III-type      |
|----------------------------------|--------------|---------------|---------------|
| Permeability/$10^{-3} \mu m^2$   | 0.80–9.32    | 0.30–0.80     | 0.02–0.30     |
| Pore radius median/\mu m         | 1.00–3.0     | 0.30–1.00     | 0.63          |
| Porosity/%                       | 10.00–14.50  | 8.00–10.00    | 8.62          |
| Maximum pore throat radius/\mu m | 1.23–9.20    | 0.55–1.52     | 0.43          |
| Average pore throat radius/\mu m | 0.23–4.00    | 0.06–0.54     | 0.37          |
| Displacement pressure/MPa        | 2.88–15.17   | 12.00–45.32   | 28.62         |
| Median pressure/MPa              | 1.58–5.15    | 9.54–28.58    | 17.73         |
| Mercury removal efficiency/%     | 53.18–69.61  | 39.23–54.22   | 44.32         |
| Relative sorting coefficient     | 20.00–110.00 | 12.00–19.00   | 17.00         |

Table 4: Classification standards of micropore structure in tight oil reservoir.
form in Toutai oilfield in the southwest of the study area and the Shengping area in the northeast. Still, the scale of sand bodies is small, and the thickness of a single layer is generally 2~3 m. The oil and gas show are usually oil traces, oil spots, and oil immersion. Besides, the oil saturation is generally 45~65%, and the single well output after fracturing is about 1~0.3 t/d [54, 55].

The III-type reservoirs are mainly siltstone and argillaceous siltstone deposited by underwater distributary channel and crevasse fan. The porosity is less than 10%, generally 5~8%, and permeability of $0.02 \sim 0.1 \times 10^{-3} \mu m^2$. The reservoir space is mainly intergranular and residual intergranular pores, with a small amount of cement dissolved pores. The reservoir is composed of micro-nano pore and nano-throat, with pore radius ranging from 0.4 to 1.85 $\mu m$ and throat radius ranging from 0.08 to 0.32 $\mu m$. Displacement pressure is generally greater than 3 MPa, ranging from 2.06 MPa to 27.65 MPa, with an average of 13.55 MPa. The connectivity is poor, and the volume of the connected pore throat is 20~45%. In the study area, there is lenticular distribution

**Figure 9:** Characters of micropore structure in different types of tight oil reservoir.
in the west satellite, the Pubei oilfield, and the Changling area in the southeast. The thickness of sand body is generally thin, the thickness of single layer is less than 2 ms, and it is interbedded with adjacent mudstone. The oil and gas are usually oil traces and spots, the oil saturation is less than 40%, and the single well output is less than 0.3 t/d.

6. Conclusion

(1) The tight oil reservoir in the 4th of Quantou Formation consists mainly of intergranular dissolved, residual intergranular dissolved, and intergranular dissolved pores with a few intergranular pores. The average pore radius is 1.28–4.58 μm, and the average throat radius is 0.52–1.27 μm. It is a micron ore submicron-nanometer throat

(2) Pore structure is the key factor that restricts physical properties, especially permeability. Microthroat with pore size larger than 1 μm positively affects physical property improvement, while nano-throat smaller than 1 μm has limited contribution to permeability

(3) The tight oil reservoir can be divided into three kinds according to Q-cluster analysis. Physical properties and pore structure characteristics differ in different reservoirs, and tight oil reservoirs are mainly II and I types in the study area

Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

Conflicts of Interest

The authors declare no conflicts of interest. To the best of our knowledge, the named authors have no conflict of interest, financial, or otherwise.

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