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Research Article

Analysis on the Difference of Micropore Structure Characteristics and Physical Properties of Mixed Rock Reservoir

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The accumulation of multiple source components leads to the superposition of multiple pore throat systems and similar pore throat distribution may correspond to different seepage capacity in the mixed rock reservoir. Taking the mixed rock reservoir of III+IV oil formation in Nanyishan Oilfield, Chaidamu Basin, as an example, the development characteristics of pore throat system and its controlling factors in the mixed rock were summarized by means of thin slice, scanning electron microscopy, X-ray diffraction and high pressure mercury injection, and the reservoir physical property differences and their genetic controlling mechanism were analyzed. The results show that the reservoir space of the mixed reservoir mainly consists of intergranular pore fracture, micropore fracture, and micropore-dissolution pore. The diverse and complex pore types make the reservoir space combination type, capillary pressure curve shape and reservoir physical properties are not completely corresponding. The higher the content of brittle minerals, the higher the reservoir permeability. However, the development of iron dolomite mainly destroys the reservoir. The permeability of reservoir is mainly controlled by the development degree of macropores and the pore size which is the main contribution to permeability, and the proportion of macropores increases with the increase of permeability.

1. Introduction

Mixed deposition is a transitional sedimentary type between clastic rock and carbonate rock, which can be widely developed in continental lakes, sea-land transitional shelf, and slope environments [1–3]. The mixed sedimentary rocks in continental lacustrine basin are characterized by fine-grained deposition, diverse lithology, frequent thin bed interaction, complex pore throat structure, and strong heterogeneity, which are mainly formed by the mixed deposition of terrigenous clastic and lacustrine carbonate components [4–6]. As a result, the oil-water relationship is complicated and the mining is difficult. In recent years, much attention has been paid to the research of mixed rock reservoir in China, which mainly focuses on the classification, naming, occurrence description, sedimentary model, and genesis mechanism of mixed rock [7–10]. However, only the microstructures of several main lithologies (such as siltstone, dolomite, and mudstone) in the mixed rocks have been characterized and compared [11–13], and the difference of reservoir physical properties and its genetic control mechanism have not been involved. Therefore, taking the mixed rock of III+IV oil formation in Nanyishan Oilfield, Chaidamu Basin, as an example, combined with casting thin section observation, scanning electron microscopy, X-ray diffraction and high-pressure mercury injection, the development characteristics of pore throat system and its controlling factors in mixed rock are summarized, and the reservoir physical property differences and their genetic control mechanism are analyzed.

Table 1: Reservoir physical properties and petrological parameters of rock samples.

Sample no.	Lithology	Porosity (%)	Permeability ($\times 10^{-3}\ \mu m^2$)	Mineral component content (%)						Type of reservoir space
				Quartz	Potassium feldspar	Sodium feldspar	Calcite	Ankerite	Clay	
1	Stucco siltstone	20.38	0.09	11.4	5.9	2.8	0	43.6	13.0	B
2	Sand mudstone	20.23	11.24	17.8	0	5.9	17.5	8.9	35.2	A
3	Calcareous mudstone	20.45	3.62	8.8	0.6	3.4	5.6	47.1	29.2	B
4	Micritic dolomite	20.84	1.94	8.9	0	4.3	11.6	51.2	13.8	C
5	Silty mudstone	21.05	0.51	5.9	1.1	6.2	11.5	31.5	7.2	C

A, B, and C represent intergranular pore fracture, micropore fracture, and micropore-dissolution pore.

2. Experimental Methods and Basic Characteristics of Sample

Nanyishan is located near the central area of the Chaixi Basin, and its terrain is gentle on the whole, with only local ups and downs. The carbonate shoals and stucco flats are mainly deposited in shallow and semi-deep lake environment. The oil formations I~V in the Nanyishan reservoir belong to the Neogene Upper Neocene Youshashan Formation, in which the oil formations I~IV belong to the upper Youshashan Formation, and the oil formation V belongs to the lower Youshashan Formation. The lithology of the lower Youshashan Formation is gray mudstone and gray calcareous mudstone interbedded with thin limestone, marl, and a small amount of sandstone.

In this study, 5 rock samples of III+IV oil formation in Nanyishan Oilfield of Chaidamu Basin were selected to carry out casting thin section observation, scanning electron microscopy, X-ray diffraction, and high-pressure mercury injection according to the corresponding national standards.

Five rock samples were selected in the III+IV oil group of Nanyishan Oilfield, including 1 rock sample containing merely siltstone, 2 rock samples containing sandy mudstone, 1 rock sample containing silty mudstone, and 1 rock sample containing sandy mudstone. The porosity was 20.23%~21.05%, and the permeability was $0.09 \times 10^{-3}\ \mu m^2 \sim 11.24 \times 10^{-3}\ \mu m^2$ by a gas logging method. The porosity distribution range is similar, but the permeability is very different (in Table 1), and it shows relatively high quartz and low feldspar, which is related to the decrease of feldspar content away from the source.

3. Discussions

The reservoir quality is affected by the micropore structure [5–14]. The complex pore structure of mixed reservoir leads to poor reservoir characterization based on mercury injection curve shape or pore throat distribution and other parameters. It is necessary to conduct in-depth discussion on pore throat system types and classification methods from the perspective of pore structure genesis, so as to fully reveal the micropore structure and quality differences of mixed reservoir.

3.1. Reservoir Space Types. The pore throat system is closely related to pore type and distribution. When a certain type of pore is dominant and has a certain continuous seepage length, this type of pore and its formed throats (narrow parts of pores) constitute a complete pore throat system. If a certain type of pore throat system in the rock is obviously dominant and plays a leading role in the seepage, the whole rock can be classified as one type of pore throat system. However, when multiple pore throat systems coexist and contribute equally to the seepage, the whole rock can be classified as a mixed pore throat system, combined with the previous classification schemes of pore types in tight reservoirs [5]. The pore types and distribution were identified by casting thin sections and SEM, and the development proportion of different types of pores was calculated to determine the reservoir space combination types of mixed rock. The intergranular cementation of the III+IV oil group in Nanyishan Oilfield is mainly iron dolomite, and the reservoir space combination types were intergranular pore fracture, micropore fracture, and micropore-dissolution pore, as shown in Figure 1.

3.2. Characteristics of Capillary Pressure Curve. Based on the high-pressure mercury injection test results, combined with the cast thin section and SEM analysis results, the mixed rock reservoirs of the III+IV oil group in Nanyishan Oilfield were divided into three categories by selecting the parameters of displacement pressure, maximum mercury intake saturation, median radius, and mercury removal efficiency (in Figure 2). There were significant differences in the characteristic parameters of pore throat system in different types of reservoirs, as shown in Table 2. Class I reservoir (4#, 5# rock samples) showed low displacement pressure, gentle curve, and high mercury removal efficiency. Class II reservoir (1#, 2# rock samples) showed high displacement pressure, steep curve, and high mercury removal efficiency. Class III reservoir (3# rock samples) showed high displacement pressure, gentle curve, and low mercury removal efficiency.

The comparative analysis (Table 1, Figures 1 and 2) found that the reservoir types divided based on the shape of mercury injection curves were not completely corresponding to the reservoir space combination types and physical properties. Among them, type C reservoir space was

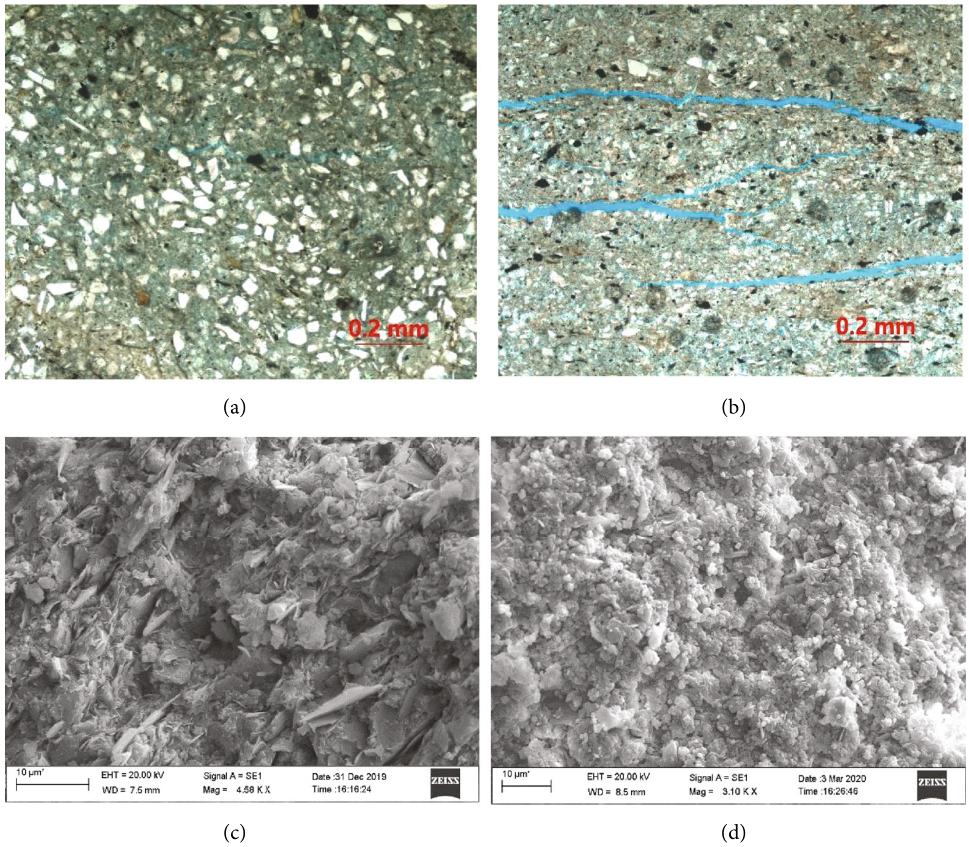


Figure 1: Reservoir space types of the III+IV oil group in Nanyishan Oilfield. (a) 1# Stucco siltstone, micropore fracture. (b) 2# Sandy mudstone, intergranular pore fracture. (c) 3# Calcareous mudstone, micropore fracture. (d) 5# Silty mudstone, micropore-dissolution pore.

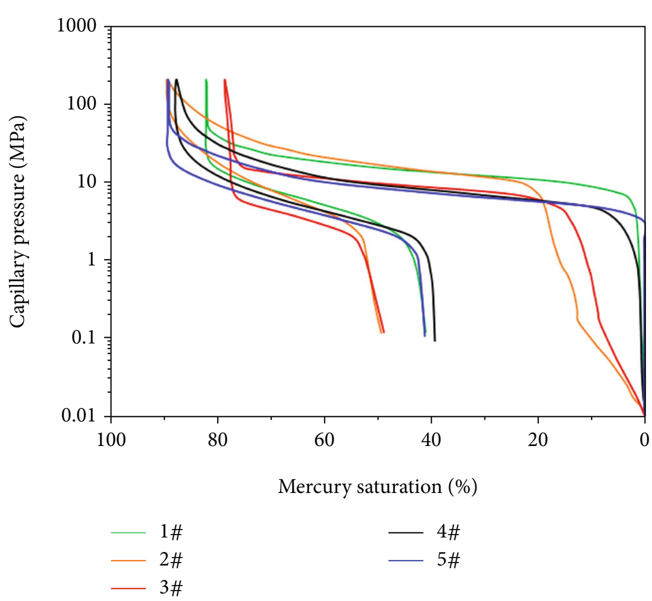


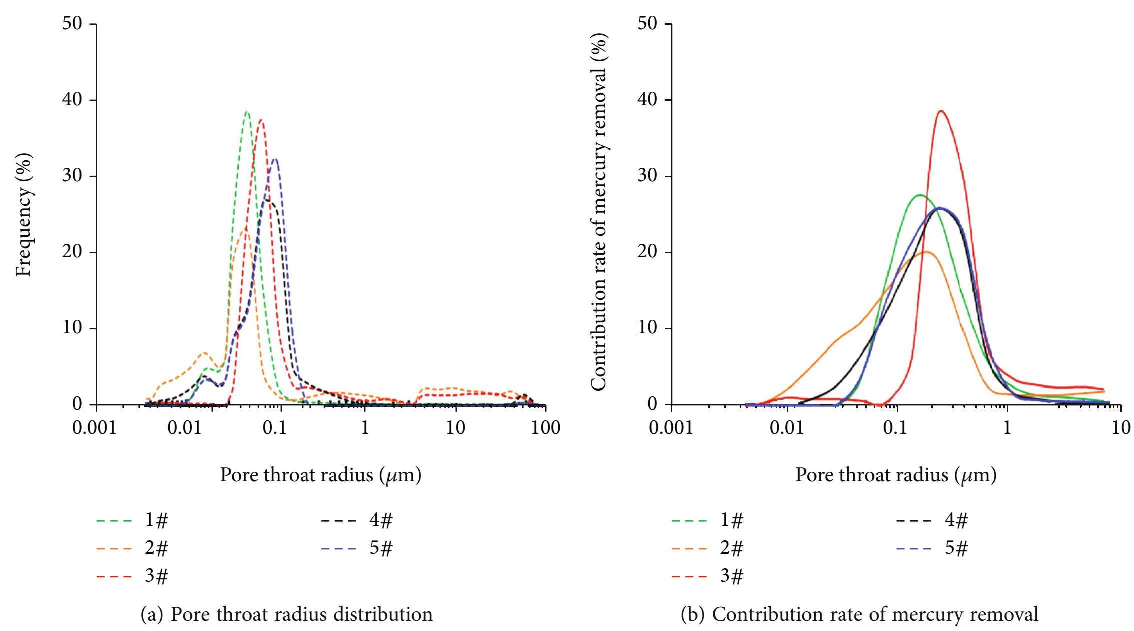
Figure 2: Capillary pressure curve of the III+IV oil group in Nanyishan Oilfield.

developed in class I reservoir. Type A and type B reservoir space was developed in class II reservoir, and type B reservoir space was developed in class III reservoir. The pore space structure characteristics of different types of reservoirs were obviously different, which was related to the complex pore throat structure and diverse assemblage relationship of mixed rock reservoirs. In type A reservoir space, intergranular pores and a few microfractures were mainly

Table 2: Microscopic pore structure characteristic parameters of the III+IV oil group in Nanyishan Oilfield.

Reservoir types	Serial number	Platoon drive pressure (MPa)	Maximum connected pore throat radius (μm)	Median radius (μm)	Maximum mercury intake saturation (%)	Mercury removal efficiency (%)	Type of reservoir space
I	4	4.28	0.172	0.079	88.11	55.14	C
	5	4.07	0.181	0.085	89.64	53.73	C
II	1	8.07	0.091	0.046	82.32	49.89	B
	2	6.97	0.106	0.042	89.82	44.71	A
III	3	5.45	0.135	0.073	78.97	37.73	B

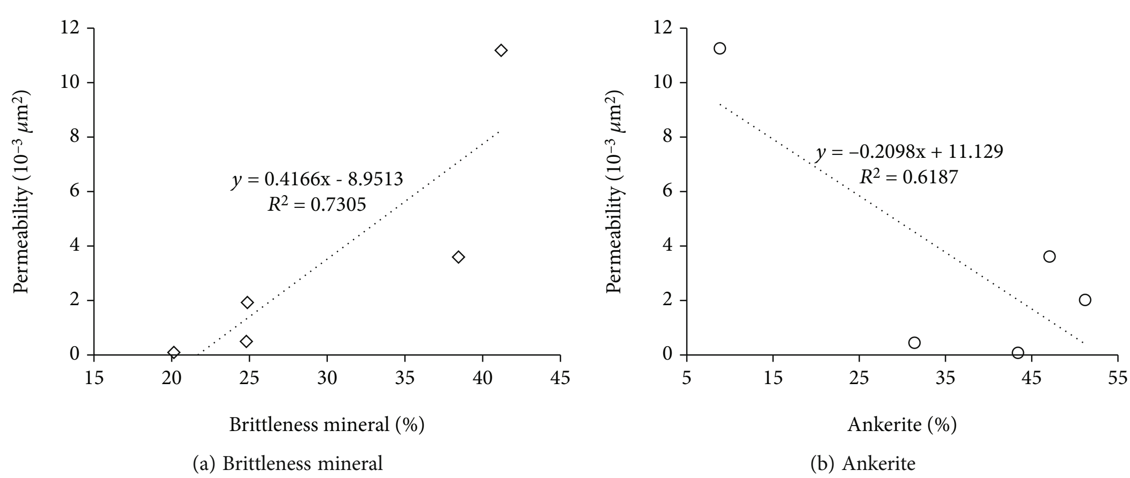
A, B, and C represent intergranular pore fracture, micropore fracture, and micropore-dissolution pore.



(a) Pore throat radius distribution

(b) Contribution rate of mercury removal

Figure 3: Pore throat radius distribution and contribution rate of mercury removal.



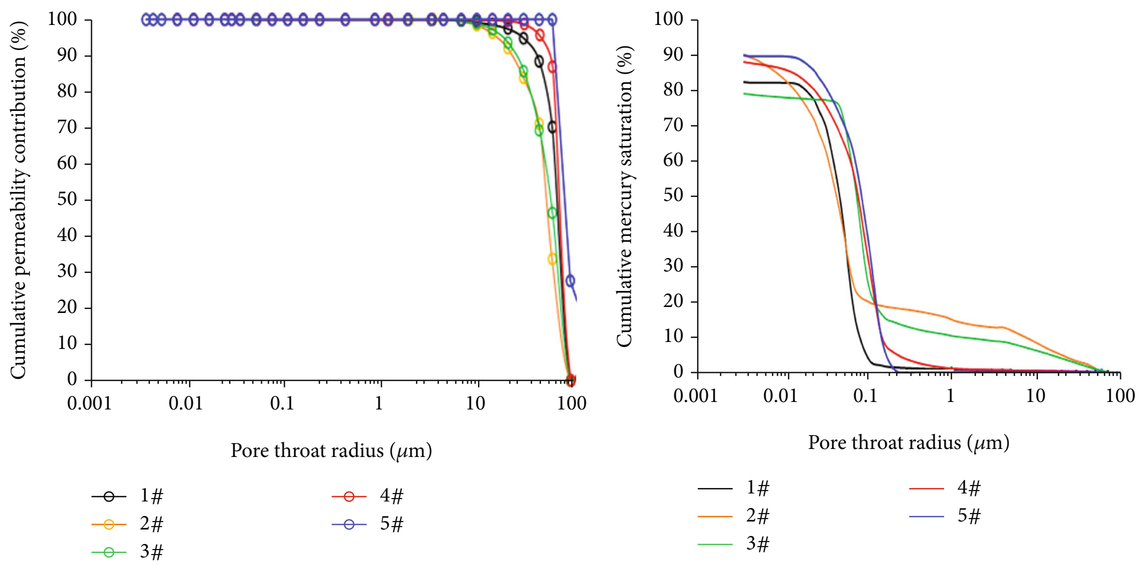
(a) Brittleness mineral

(b) Ankerite

Figure 4: Relationship between rock composition and permeability.

developed, and large pores account for a large proportion. Micro pores and a few microfractures were mainly developed in type B reservoir space, while macropores were relatively few. Micropores and dissolution pores were mainly developed in type C reservoir space, and the dissolution pores produced by dissolution strengthen the connectivity between pores.

3.3. Pore Throat Distribution Characteristics. Pore throat distribution is more closely related to pore throat system.



(a) Cumulative permeability contribution

(b) Cumulative mercury saturation

Figure 5: Control of pore throat size on porosity and permeability.

Table 3: Control of macropores on reservoir physical properties of the III+IV oil group in Nanyishan Oilfield.

Serial number	The lithology	Porosity (%)	Permeability ($\times 10^{-3}\ \mu m^2$)	>10.0μm pores control the proportion of space (%)	Contribution of >10.0 μm pore control to permeability (%)
1	Gray-sandy mudstone	20.383	0.09	0.73	98.53
2	Sandy mudstone	20.23	11.24	7.84	96.14
3	Gray-sandy mudstone	20.467	3.62	7.01	97.28
4	Sandy mudstone	20.838	1.94	2.14	99.79
5	Silty mudstone	21.052	0.51	0.39	99.94

The pore throat radius of the III+IV oil group in Nanyishan Oilfield mainly showed multipeak distribution, with the main peak range of 0.04 μm to 0.11 μm accounting for 28.34% to 38.3%, as shown in Figure 3(a). However, in the process of mercury removal, the pore size of 0.10 μm to 0.30 μm contributed significantly, and the peak contribution rate reached 19.4%-37.7%, as shown in Figure 3(b). The pore throat distribution and the main peak value of mercury removal contribution rate were different in different types of pore throat systems, but the evolution law showed consistency. The main peak of class I reservoir moved to the right relative to class II and III reservoirs, while the main peak of class II reservoir moved to the left relative to class III reservoir. At the same time, the contribution rate of mercury removal from small pores (<0.10 μm) developed in class I and II reservoirs was significantly higher than that in class III reservoirs.

Based on the above analysis, it was not difficult to see that the distribution characteristics of pore throat radius and reservoir types divided based on mercury injection curve were not exactly corresponding, which was related to the composition of mixed rock. According to the composition characteristics of the mixed rocks in the III+IV oil group of Nanyishan Oilfield, there were two types of mud-sand mixed rocks and stucco mixed rocks. On the whole, the connectivity of the pore throat system of the mud-sand mixed reservoir was better than that of the stay-sand mixed reservoir. The reason was that the connectivity of pore throat system in mud-sand mixed reservoir mainly depended on the size of rock particles and the content of clay, while the connectivity of pore throat system in the stay-sand mixed reservoir was generally controlled by feldspar/carbonate minerals, and the connectivity of the pore throat system deteriorated as the ratio decreased.

3.4. Analysis on the Difference of Physical Properties

3.4.1. Influence of Rock Composition on Permeability. Brittle minerals are mainly quartz, feldspar, and calcite, and their content is usually used to reflect the fracturing ability of the reservoir. The higher the content of brittle minerals, the stronger the fracturing ability of the reservoir, and the easier it is to form microfractures [15, 16]. By analyzing the relationship between brittle mineral content and permeability of five crock samples with similar porosity in the III+IV oil group of Nanyishan Oilfield (Figure 4(a)), it showed that there was a positive and strong correlation between them ($R^2 = 0.7305$). Therefore, the more brittle minerals in the III+IV oil group of Nanyishan Oilfield, the stronger the fracturing ability of the reservoir, the easier the formation of microfractures, and the greater the permeability of the reservoir permeability.

However, carbonate cementation was widely developed in the III+IV oil group of Nanyishan Oilfield, and the cementation type was mainly iron dolomite, the content of which was 8.9%~51.2%, with an average value of 36.5%. By analyzing the relationship between ferridolomite content and permeability of 5 rock sample with similar porosity in the III+IV oil group of Nanyang Yishan Oilfield (Figure 4(b)), it showed that they were negatively correlated with strong correlation ($R^2 = 0.6187$). Therefore, the development of iron dolomite in the III+IV oil group of Nanyishan Oilfield was mainly destructive to the reservoir.

3.4.2. Control of Pore Throat Size on Reservoir Physical Properties. The proportion of pore volume controlled by pore throat at different scales is an important parameter to characterize the size of reservoir space. The larger the proportion of pore volume controlled by pore throat at a certain scale, the greater the contribution of pore throat to the size of reservoir porosity. By analyzing the contribution rate of pore throats at different scales to pore volume of five rock samples with similar porosity in the III+IV oil group of Nanyishan Oilfield (Figure 5), it showed that the size and distribution characteristics of pore throats were closely related to reservoir permeability, and permeability was mainly affected by the larger pore throat radius.

When the mercury intake reached the peak of the pore throat radius (about 0.10 μm), the cumulative mercury saturation curve was relatively steep, but the cumulative mercury saturation was only 20% to 30%, as shown in Figure 5(b). With the continuous injection of mercury, the cumulative mercury saturation curve was steeper, indicating that although a small pore throat (less than 0.10 μm) could allow mercury to enter the pore, it had a smaller effect on permeability but a larger contribution to porosity.

The contribution rate of pore size to permeability is an important parameter to characterize the percolation capacity of rock. And the larger the pore size that plays a major role in permeability, the better the percolation capacity of rock. By analyzing the contribution rate of pore sat different scales to permeability of five rock samples with similar porosity (Table 3 and Figure 5(b)) in the III+IV oil group of Nanyishan Oilfield, it showed that pores larger than 10.0 μm contributed significantly to permeability, and the cumulative permeability contribution values were all greater than 96.0%. However, pores larger than 10.0 μm were less developed, with a distribution frequency of only 0.3% to 7.0%. At the same time, the pore size of the rock samples with permeability greater than 3.0×10^{-3} μm^2 (2# and 3#) was significantly larger than that of other rock samples, and the development degree of macropores (greater than 10.0 μm) was better than that of other rock samples. Therefore, the permeability of the III+IV oil group in Nanyishan Oilfield was mainly controlled by the development degree of macropores and the pore scale that played a major role in permeability. The larger the proportion of large pore control space is, the larger the pore scale that plays a major role in the permeability, and the greater the permeability of the reservoir.

4. Conclusions

(1) The mixed reservoirs of III+V oil formation in Nanyishan Oilfield mainly developed three types of reservoir spaces: intergranular pore fracture, micropore fracture, and micropore-dissolution pore. Various and complex pore types made the types of reservoir space assemblages, capillary pressure curves, and reservoir physical properties not completely correspond, resulting in similar reservoir porosity and great permeability differences. The connectivity of pore throat system of mud-sand mixed reservoir is better than that of stucco sand mixed reservoir

(2) Quartz, feldspar, and calcite were the main brittle minerals in the III+IV oil formation of Nanyishan Oilfield, while the carbonate cementation was generally developed in the II+V oil formation of Nanyishan Oilfield, and the cementation type was mainly iron dolomite. The higher the content of brittle minerals, the stronger the fracturing ability of the reservoir, the easier the formation of micro fractures, and the higher the permeability of the reservoir. The development of ferridolomite mainly destroyed the reservoir

(3) The permeability of reservoir was mainly controlled by large pores (>10.0 μm), which accounted for a small proportion of pore volume. Macros pores developed in reservoirs with permeability greater than 3.0×10^{-3} μm^2, and the pore size that contributed to permeability was also large. However, the contribution of small pores to reservoir space was much greater than its contribution to permeability

Data Availability

The data used to support the results of this study are included within the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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