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Research Article

Study on Heterogeneity of Pore Throats at Different Scales and Its Influence on Seepage Capacity in Different Types of Tight Carbonate Reservoirs

Chunyan Qi,[1] Yun Liu,[2] Fengjuan Dong,[3,4] Xixiang Liu,[2] Xing Yang,[3,4] Yan Shen,[2] and Hai Huang[3,4]

[1]*China National Petroleum Institute of Engineering Technology, Beijing 100086, China*
[2]*Southwest Oil and Gas Field Branch, Chengdu, Sichuan 610041, China*
[3]*College of Petroleum Engineering, Xi'an Shiyou University, Xi'an, Shaanxi 710065, China*
[4]*Shaanxi Key Laboratory of Advanced Stimulation Technology for Oil & Gas Reservoirs, Xi'an Shiyou University, Xi'an, Shaanxi 710065, China*

Correspondence should be addressed to Fengjuan Dong; dfj_1222@126.com

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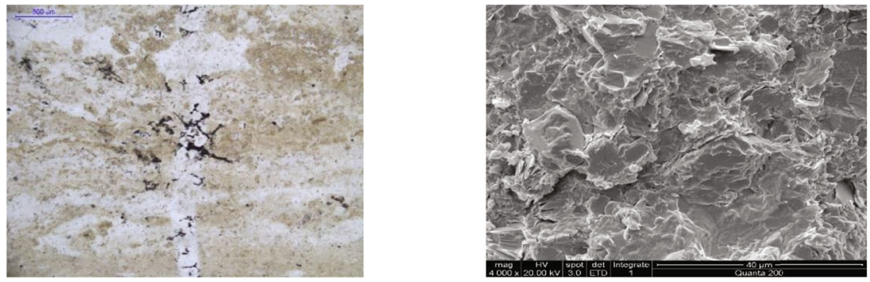
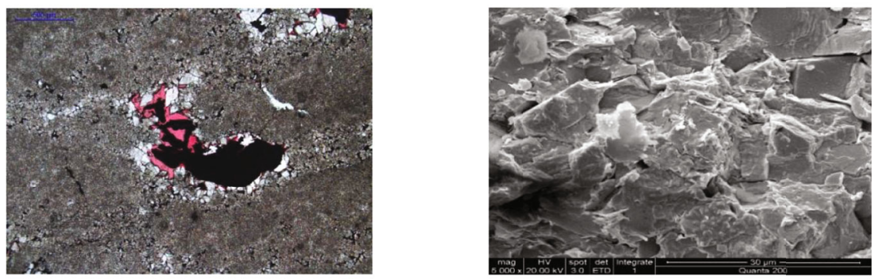
The carbonate reservoirs in the middle Sichuan area have undergone complicated tectonics, resulting in various types of reservoir space, large secondary changes, and multiple complexities. Taking the tight carbonate gas reservoir of the Deng-4 member in this area as an example, based on casting thin sections, scanning electron microscopy, and high-pressure mercury injection experiments, the reservoir space and microstructural characteristics of the micropore throats were studied, and the influence of the microscale heterogeneity in different types of reservoirs on the seepage capacity was analyzed by applying fractal theory. The results showed that the reservoir space in the tight carbonate rock of the Deng-4 member in the study area could be divided into 3 types: pore-hole-fracture, pore-hole, and pore types. The distribution characteristics of the pore throat diameter were multimode wide type, double-mode high and low asymmetrical type, and single-mode concentrated type. The fractal dimension and seepage capability of the pore throat increased successively in sizes from less than 0.1 μm to 0.1~1.0 μm and greater than 1.0 μm. On the one hand, the development of karst caves and fractures controlled the percolation ability of tight carbonate reservoirs; on the other hand, it enhanced the heterogeneity of the micropore throat structure. However, the development degree of dissolved pores and microfractures has a weak contribution to the connectivity and seepage capacity of the reservoir space. Acidification, fracturing, and other measures can be adopted to enhance the connectivity between pores to improve the productivity of the gas reservoir. This study provides a scientific basis for the efficient exploration and development of tight carbonate reservoirs.

1. Introduction

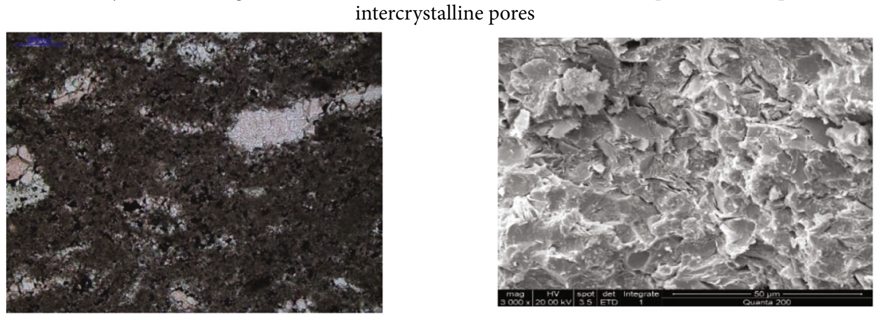
The structure of pore throats directly controls the adsorption capacity and seepage characteristics of a reservoir and affects the hydrocarbon production capacity of the reservoir [1]. Due to the particularity of the complex pore throat characteristics, the parameters of permeability and porosity can no longer satisfy the research needs for accurate description and characterization of tight carbonate reservoirs. Therefore, only by starting from the pore structure can we grasp the regulation of how oil and gas are generated and accumulated, and we should then pay more attention to forecasting the location of superior carbonate reservoirs and enhancing oil recovery [2, 3]. In recent years, many theories and methods about rock pore structure and its evolution and fluid seepage simulation have emerged, and some achievements have been made [4–6]. It has been widely accepted by numerous scholars over the last few years that reservoir pores are self-similar within a certain range, and this kind of similarity should be resolved into the fractal structure [7, 8]; the fractal



G115 mainly consists of algal dolomite and a small amount of micrite dolomite,develops fractures, dissolution pores and intercrystalline pores



G25 mainly consists of algal dolomite and arenaceous dolomite and develops dissolution pores and intercrystalline pores



G15 micrite dolomite has dense rock, inlaid grain contact and intercrystalline pores

Figure 1: Reservoir spatial characteristics of different types of reservoirs.

dimension of capillary pressure has been used to quantitatively describe the complexity of the pore structure [9–11]. Taking the tight carbonate reservoirs of the Deng-4 member in the central Sichuan basin as an example, in this study, we analyzed the correlations among the porosity, permeability, permeability contribution, and fractal dimension of pores at different scales, which were calculated based on fractal theory and data from experiments with casting thin sections, scanning electron microscopy, and high-pressure Hg injection to provide a theoretical basis for the exploration and development of tight carbonate gas reservoirs.

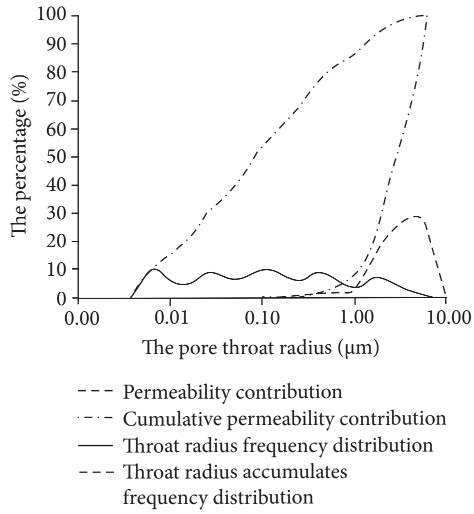
2. Methods

2.1. Test Method. A 2.5 cm diameter plunger sample is drilled from the core for use in wafer grinding, physical properties, and high-pressure mercury pressure tests.

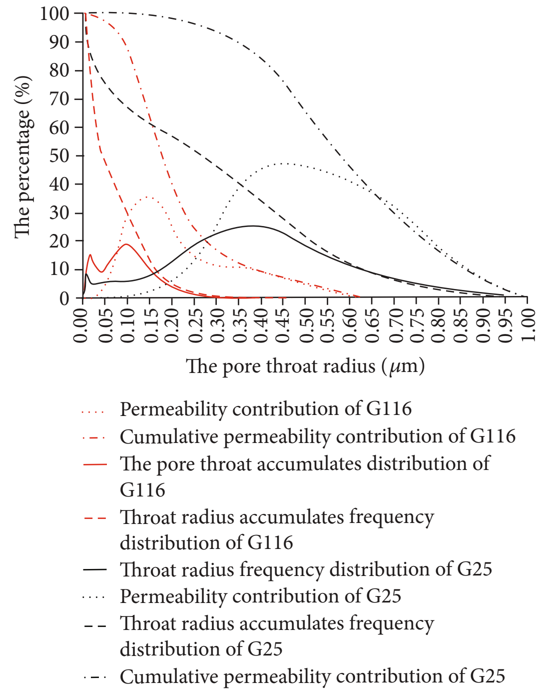
(1) *Before Testing, Wash the Sample with Oil.* The sample was washed with methanol and dichloromethane mixture in the Soxhlet extractor. When the fluorescence of the washing fluid was very low and unchanged, the washing oil was considered to be finished, and the sample was dried continuously by microwave at 100°C for 24 h.

(2) *Casting Sheet Observation*. After the treatment, the samples were injected into the red casting body, and the thin slices with a thickness of 0.03 mm were ground. Under the polarized light microscope, the statistics and study of petrology and pores were carried out by the point-meter method (300 points were counted for each sample). The experimental methods were strictly carried out in accordance with SY/T 5913-2004 “Rock Thin Section Preparation” [12].

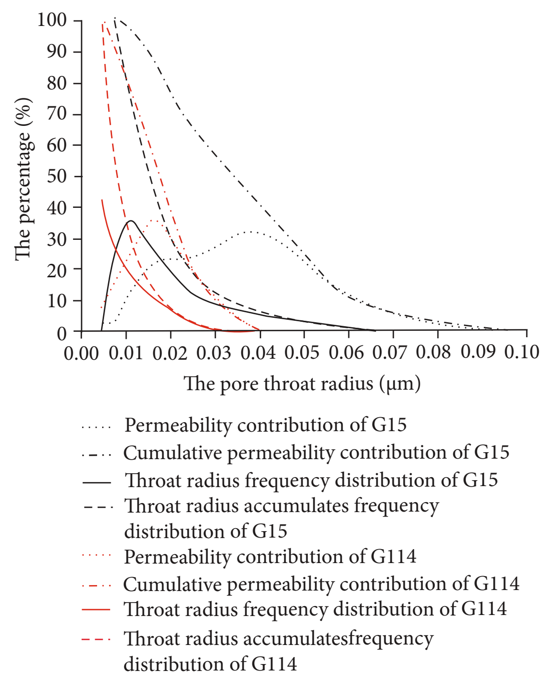
(3) *Petrophysical Tests*. The experimental methods were strictly carried out in accordance with SY/T6385-1999 “Test Method for Porosity and Permeability of Overburden Rocks” [13]. The FYKS-1 porosity-permeability tester with high temperature and overburden pressure was used to test the porosity and permeability. The main technical parameters are as follows: (1) The effective pressure of simulated formation is less than 70 MPa, (2) the effective



(a) Pore-hole-fracture type (G115)



(b) Pore-hole-type (G116 and G25)



(c) Pore type (G15 and G114)

Figure 2: Pore throat radius distribution and permeability contribution of different types of reservoirs.

temperature of simulated formation is less than 150°C, (3) applicable core is $\Phi 25 \times 25$~80 mm or $\Phi 38 \times 40$~80 mm, and (4) measurement precision of permeability is less than 10% for low permeability reservoir and is less than 5% for middle and high permeability reservoirs; measurement precision of porosity is 0.5%.

(4) *High-Pressure Mercury Injection Experiment*. AutoPore IV mercury injection test was conducted under the conditions of 22°C room temperature, 46% to 68% relative humidity, and 0.49 N/m interfacial tension of mercury. The experimental method was strictly carried out in accordance with GB/T29171-2012 “Rock Capillary Pressure Measurement” [14].

Table 1: Fractal dimensions of pore throat at different scales in different tight carbonate reservoirs.

Sample number	Throat radius <0.1 μm Fractal dimension	Percentage (%)	0.1~1.0 μm Fractal dimension	Percentage (%)	>1.0 μm Fractal dimension	Percentage (%)	Total fractal dimension	Reservoir types
G115	2.3203	43.4932	2.3219	39.0921	2.3813	17.4147	2.3315	Pore-hole-fracture type
G25	2.3107	66.3617	2.3573	33.6383	—	—	2.3264	Pore-hole type
G116	2.315	70.1	2.3446	29.9	—	—	2.3239	Pore-hole type
G15	2.1839	100	—	—	—	—	2.1839	Pore type
G114	2.197	100	—	—	—	—	2.1970	Pore type

2.2. Fractal Theory. Fractal theory expressed in terms of fractal dimensions provides an important method in the study of irregular forms with complex structures and self-similarity. Only within a certain scale can the pore throat structure have fractal characteristics for low permeability sandstone reservoirs [7, 8, 15]. Furthermore, the complex sedimentary, diagenetic, and tectonic superposition transformation of carbonate reservoirs creates complicated reservoir spaces and leads to the obvious heterogeneity in different kinds of reservoirs or various scales of pore throats. (Carbonate reservoirs developed complicated reservoir spaces, leading to the obvious heterogeneity of pore throats at different scales or in various kinds of reservoirs.) These features imply the necessity of quantitatively expressing the porosity and throat heterogeneity of tight carbonate reservoirs in the Deng-4 member in the central Sichuan basin with the technology of high-pressure Hg injection.

The fractal geometry formula of pore distribution [16] can be written as

$$S = \left[\frac{r}{r_{\max}}\right]^{3-D}.. \quad (1)$$

In the formula, r is the pore radius, mm; $r_{\max}$ is the maximum pore radius, mm; S is the cumulative pore volume fraction of pores whose radius is less than r; and D is the fractal dimension.

Then, a new formula can be obtained by taking the logarithm of both sides of formula (1):

$$\mathrm{Lg}S = (3-D)\mathrm{Lg}r + (D-3)\mathrm{Lg}r_{\max}. \quad (2)$$

According to the above formula, the fractal dimension D can be calculated by using linear regression to fit the data.

If the weights of pore throats in different scales (less than 0.1 μm, 0.1 μm to 1.0 μm, and greater than 1.0 μm) are w_1, w_2 , and w_3, respectively, the corresponding fractal dimensions are D_1, D_2, and D_3, respectively, then

$$w_1 + w_2 + w_3 = 1. \quad (3)$$

By weighting the fractal dimensions of pore throats in different scales, the total fractal dimensions (D_p) of the entire pore space can be obtained as follows:

$$D_p = D_1 w_1 + D_2 w_2 + D_3 w_3. \quad (4)$$

3. Discussions

3.1. Reservoir Space and Micropore Structure Characteristics. The Deng-4 member in central Sichuan has undergone a changeable diagenetic environment and complex diagenesis attributed to 7 major tectonic movements and continuous transformations during approximately 600 million years of geologic history, which resulted in the diversity of reservoir space; the primary pores have been mostly destroyed, and a system of secondary pores, holes, and fractures currently prevails [17–19]. Depending on the formation and combination modes, reservoir space in the study area can be divided into 3 major categories as listed below (Figures 1 and 2). By comprehensively analyzing the data from casting thin sections, hydrargyrum driving, and electron microscopy, we determine that reservoirs of pore, hole, and fracture types (core G115) mainly consist of algal dolomite with little microcrystalline dolomite, which developed fractures, dissolved pores, and intergranular holes; in contrast, pore-hole-type (core G25) reservoirs consist of algal dolomite and arenaceous dolomite, which developed fractures and dissolved pores; and pore-type (core G15) reservoirs are made up of mosaic cemented dolomicrite, which developed intergranular holes.

The diversity of reservoir spaces and combination modes led to a heterogeneous distribution of reservoir pore throats [20]. After comparative analysis of casting thin sections, scanning electron microscopy, and pore diameter distribution characteristics (Figure 2), we determined that reservoirs of the pore-hole-fracture type developed pores, holes, and fractures spanning a very large scale of diameters in a multimodal broad distribution mode, with a 1.132 μm average pore throat diameter and 17.42% of pore throats greater than 1.0 μm. Reservoirs of the pore-hole type developed both pores and holes in a bimodal high and low asymmetrical mode with a relatively low pore throat diameter (0.099 μm average diameter for core G116 and 0.144 μm for core G25, for example), whereas pore-type reservoirs developed only

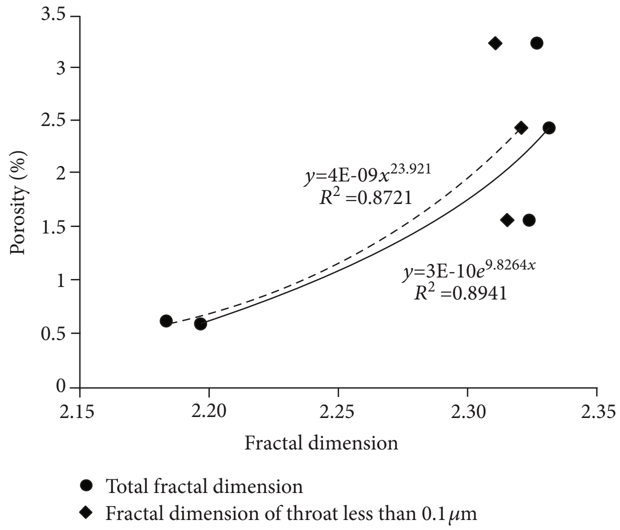


Figure 3: Relationship between fractal dimension of pore throats and porosity.

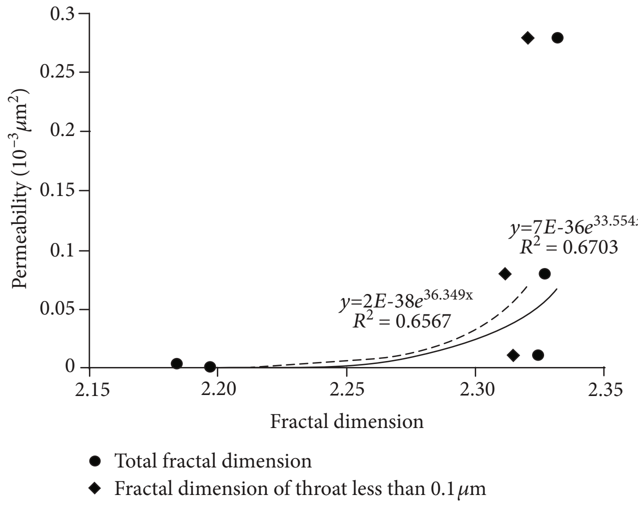


Figure 5: Relationship between fractal dimension of pore throats and permeability.

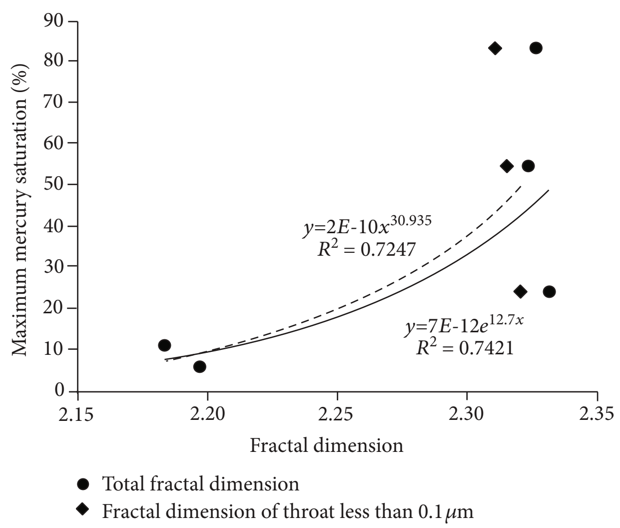


Figure 4: Relationship between fractal dimension of pore throats and maximum mercury saturation.

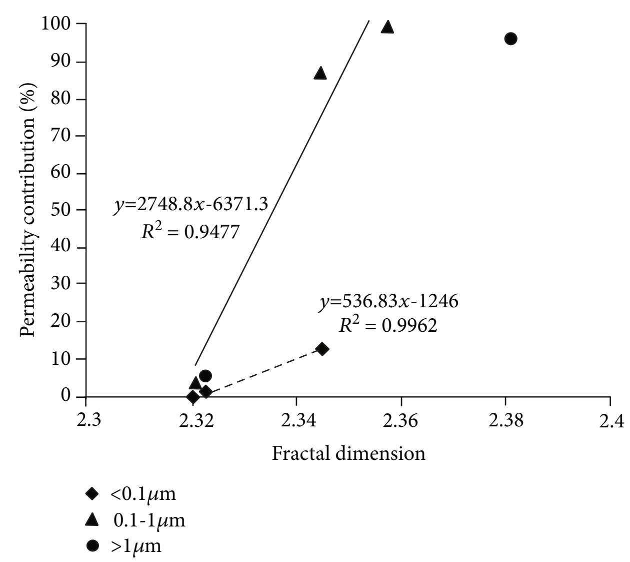


Figure 6: Relationship between fractal dimension of pore throats at different scales and permeability contribution.

intercrystalline pores in a simpler unimodal centralized distributed mode with a diameter less than 0.1 μm (0.024 μm average diameter for core G15 and 0.012 μm for core G114, for example).

The differences in the combination modes of pores and throats for various reservoirs led to obvious distinctions in the microflow characteristics (Figure 2). We found several consequences by analyzing the contribution ratios of pores of different sizes (>1.0 μm, 0.1~1.0 μm, and <0.1 μm). First, pore-type reservoirs developed isolated intergranular pores with poor connectivity, and the permeability contribution value of pore throats with diameters less than 0.1 μm reached almost 100%; in addition, the low mercury saturation and mercury withdrawal near 0 indicated the poor storage and filtration capacity of this type of reservoir. Second, the proportions of pores smaller than 0.1 μm and 0.1~1.0 μm were approximately equal; nevertheless, the former contributed little to infiltrability, which was reflected in the extremely low mercury withdrawal rate; the contribution of 0.1~1.0 μm pore throats to permeability was more than 70%, and mercury easily exited after entering, indicating that the seepage capacity of this type of reservoir was mainly controlled by 0.1~1.0 μm pore throats. Third, the proportions of pore throats smaller than 0.1 μm, 0.1~1.0 μm, and greater than 0.1 μm in pore-cavity-fracture reservoirs and the difficulty of mercury removal decreased in order, while the contribution of permeability and the mercury removal efficiency increased sequentially; greater than 1.0 μm pore throat controlled the seepage capacity of this type of reservoir, and the development of fractures enhanced the connectivity of pores and caves and the seepage capacity of the reservoir. As a result, the tight carbonate reservoirs in the Deng-4 member with pore throats greater than 1.0 μm, 0.1~1.0 μm, and less than 0.1 μm had successively weakened storage and filtration capacities in the study area.

3.2. Quantitative Characterization of Heterogeneity in Pore Throats at Different Scales. We found that by counting and analyzing the data for different reservoirs (Table 1), the fractal dimensions of pore-type, pore-hole-type, and pore-hole-fracture-type reservoirs increased successively, with mean values of 2.1905, 2.3251, and 2.3315, respectively. Moreover, the fractal dimensions of pores of various sizes ($d < 0.1$ μm, 0.1~1.0 μm, and >1.0 μm) were significantly different. Pore-type reservoirs merely developed pore throats smaller than 0.1 μm with an average fractal dimension of 2.1905; meanwhile, pore-hole-type reservoirs developed pore throats smaller than 0.1 μm and 0.1~1.0 μm, and their average fractal dimensions were 2.3409 and 2.3140, respectively; finally, reservoirs of the pore-hole-fracture type developed pore throats smaller than 0.1 μm, 0.1~1.0 μm, and greater than 1.0 μm with average fractal dimensions of 2.3403, 2.3219, and 2.3813, respectively. In the Deng-4 member in the study area, the proportions of pore throats greater than 0.1 μm, 0.1~1.0 μm, and greater than 1.0 μm decreased successively, while the fractal dimension increased successively, which was closely related to the development of karst caves and fractures.

3.3. Influence of Pore Throat Heterogeneity on Reservoir Space and Seepage Capacity. The relationship between fractal dimension and porosity, maximum mercury saturation, permeability, and permeability contribution was plotted to explore the relationship between pore throat heterogeneity and the size, connectivity, and percolation capacity of the reservoir space (Figures 3–6). The fractal dimension of the pore throat is positively correlated with porosity, permeability, and maximum mercury saturation. The correlation between fractal dimension and porosity, permeability, and maximum mercury saturation was better than that of less than 0.1 μm pore throat, which also indicated that the development of dissolved pores and microfractures had a greater contribution to the size of reservoir space, connectivity, and seepage capacity and had a greater impact on the complexity of the pore structure. However, the correlation between fractal dimension and permeability and maximum mercury saturation is worse than that between porosity, indicating that the development degree of dissolved pores and microfractures has a weak contribution to the connectivity and seepage capacity of the reservoir space. Acidification, fracturing, and other measures can be adopted to enhance the connectivity between pores to improve the productivity of the gas reservoir.

By analyzing the relationship between the contributions of the permeability and the fractal dimension of different reservoir samples (smaller than 0.1 μm, 0.1~1.0 μm, and greater than 1.0 μm) (Figure 6), a good positive linear correlation could be seen between the contributions of the fractal dimension and the permeability, and the correlation coefficient R^2 was greater than 0.9. The percolation capacity of carbonate would be larger, while the fractal dimension increased due to the development of large pore throats (dissolved pores and microfractures) in tight reservoirs, which not only increased the heterogeneity of reservoirs but also controlled the seepage capacity of reservoirs.

4. Conclusions

(1) The complicated diagenetic environment of the Deng-4 member in the central Sichuan basin leads to diversified reservoir spaces. The primary pores have mostly been destroyed, and the reservoirs can mainly be divided into pore type, pore-hole type, and pore-hole-fracture type with the pore throat radius distribution characteristics of multimode wide, double-mode high/low asymmetrical, and single-mode concentrated distribution, respectively

(2) The fractal dimension of pore throats in the Deng-4 member of the study area increases successively as the proportions of pore throat smaller than 0.1 μm, 0.1~1.0 μm, and greater than 1.0 μm decrease successively, which is closely related to the development of dissolution pores and fractures

(3) The development of dissolution pores and fractures, on the one hand, controls the percolation capacity of tight carbonate reservoirs and, on the other hand, leads to increases in the fractal dimensions of pore throats of such reservoirs and the enhancement of microstructural heterogeneity of pore throats. However, the development degree of dissolved pores and microfractures has a weak contribution to the connectivity and seepage capacity of the reservoir space. Acidification, fracturing, and other measures can be adopted to enhance the connectivity between pores to improve the productivity of the gas reservoir

Data Availability

The data supporting the results of our study are included within the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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