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Article

Classification and Controlling factors of Different Types of Pore Throat in Tight Sandstone Reservoirs Based on Fractal Features-a Case Study of Xujiahe Formation in Western Sichuan Depression

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Abstract: The effects of high debris content on tight sandstone reservoirs are multifaceted. Pore structure is an important factor controlling reservoir quality. Clarifying the effects of different types of rock debris on reservoirs is necessary to study the pore structure and their control factors of tight sandstones. The Western Sichuan Depression with complex rock components, containing multiple types of rock debris, leads to strong heterogeneity of pore throats, so it is necessary to study the factors controlling the development of different types of pore throats in tight reservoirs. In this paper, the Fourth member of Xujiahe Formation (T_3X^4) is taken as the research object. Based on high-pressure mercury intrusion experiments and the fractal theory, the types of pore throats and their heterogeneity in tight reservoirs were studied, the relationship of fractal dimensions with reservoir physical properties, pore structure, and rock compositions were investigated, and then the controlling factors for the development of different types of pore throats are clarified. The studies show that there are four types of pore throats developed in the T_3X^4 of the western Sichuan depression, including primary intergranular pore-throats, residual intergranular pore-throats, dissolution pore-throats, and intercrystalline pore-throats, among which the homogeneity of dissolution pore-throats are the best, followed by residual intergranular pore-throats and intercrystalline pore-throats, and the primary intergranular pore-throats the most heterogeneous. Brittle minerals such as quartz and metamorphic debris, as well as early developed films of chlorite and illite mainly control the development of intergranular pore-throats. Potassium feldspar mainly controls the development of dissolution pore-throats, while plastic debris, volcanic debris, and kaolinite play a destructive role for all types of pore-throats. The high-quality reservoirs in the T_3X^4 are controlled by the development of primary intergranular pore throats and dissolution pore throats, and they are mainly developed in environments with strong hydrodynamic conditions, large rock grain sizes, high content of brittle minerals such as quartz and metamorphic debris, extensive development of chlorite and illite films, and low content of mudstone debris, matrix, and cemented materials. This study is of guiding significance in clarifying the causes of heterogeneity in different types of pore-throat systems in tight sandstones and the formation mechanism of high-quality reservoirs in tight sandstones with high content of debris.

Keywords: Pore-throats heterogeneity; fractal features; tight sandstone; Xujiahe Formation; Sichuan Basin

1. Introduction

Tight sandstone gas is one of the most important unconventional natural gas resources, generally presenting the characteristics of widely distributed gas-bearing area but local dessert enrichment [1,2], while the formation and distribution of the sweet spots are mainly controlled by the reservoir quality of tight sandstone [3]. Tight sandstone reservoirs are characterized by low porosity and low-extra-low permeability, and their formation and evolution are jointly influenced by sedimentation and diagenesis [3,4]. After having experienced the destruction effects by compaction and cementation and the improvement effects by dissolution, tight reservoirs develop a variety of pore types and complex pore throat combination relationship [5]. The degree of pore changes caused by diagenetic processes is influenced by sedimentary properties such as rock composition, grain size, sorting, and matrix content [6]. Sandstones deposited in different microfacies can correspond to very different reservoir qualities after experienced the similar diagenetic environments, resulting in a strong heterogeneity in pore-throat structure. Systematically revealing the heterogeneity of the pore-throat structure of tight sandstones and their controlling factors (sedimentary properties or diagenesis) are of great significance in clarifying the formation mechanism of high-quality tight sandstone reservoirs.

Many researches have been carried out on characterizing the heterogeneity of pore structure in tight sandstone reservoirs and their influence factors [7,8]. In terms of characterization, many experiments, such as high-pressure mercury intrusion, nuclear magnetic resonance, and low temperature nitrogen adsorption are employed individually or jointly to reveal the pore-throat and pore size distribution of tight reservoirs, and with the full-scale pore size characterization technique [9] the contents of pores within different intervals are determined to characterize the heterogeneity of pore structure. In addition, many scholars introduced the fractal theory [10] to reveal the microscopic heterogeneity and the complexity of pore structure through the pore-throat fractal features. Liu Yang et al.[11] categorized the reservoir space of the Yan'an Formation in the Ordos Basin into large pore-throats and small pore-throats based on the fractal inflection points, and then explored the relationship of fractal dimensions with mineral compositions and pore structures. However, tight sandstones develop many types of pore-throat combinations, and their formation conditions and influence factors vary greatly. Therefore, only by clarifying the heterogeneity and influence factors of different types of pore-throats, as well as their contributions to reservoir properties, can the formation mechanism of tight sandstone reservoirs be deeply revealed. In terms of controlling factors for the heterogeneity of pore structure, previous researchers have studied from the aspects of depositional environment [12], petrological characteristics [13,14], diagenesis [12,13,15], and mineral compositions [16,17], and have concluded that the compaction deeply reduces porosity, dissolution promotes porosity, brittle minerals resist compaction, chlorite film protects pore space, and cement reduces pore space, etc., which jointly control the development of tight reservoirs. However, it is inevitably different that the content and fractal characteristics of different types of pore throats have different effects on reservoir physical properties. Currently, there is no research on the control of mineral composition on the development of different types of pore throats using fractal methods. The impact of debris types and clay types on the heterogeneity of various pore-throats and the development of tight reservoirs is not yet comprehensive.

Sichuan Basin is the second-largest tight gas producing area in China after the Ordos Basin. The Upper Triassic Xujiahe Formation is an important exploration target of lacustrine tight gas in the Sichuan Basin [18]. The tight sandstone reservoirs with complex rock components, containing multiple types of rock debris, leads to strong heterogeneity of pore throats. In this paper, we take the tight sandstone reservoirs of the fourth Member of Xujiahe Formation (T_{3x^4}) of the Western Sichuan Depression as the research object, and characterize the pore structure based on the experimental methods such as thin section, field emission scanning electron microscopy, physical properties, and high-pressure mercury intrusion. Through fractal methods, different types of pore-throat systems in T_{3x^4} are classified, and their fractal characteristics and heterogeneity are analyzed. The impacts of rock debris types, various minerals composition, and diagenesis on the pore-throat heterogeneity are clarified, revealing the control factors of the formation of high-quality tight reservoirs.

2. Geological Settings and Experimental Methods

2.1. Characteristics of Geological Structure

The Sichuan Basin is a multi-cyclonic superimposed sedimentary basin located on the Middle and Upper Yangtze craton [19]. Due to the influence of peripheral plate tectonic activity and regional marine transgression and regression events, multiple regional unconformities were developed in the basin [19]. Based on the major regional faults and structural deformation, the Sichuan Basin can be divided into five structural units: the eastern high steep structural belt, the southern low steep structural belt, the central gentle structural belt, the western depression belt, and the front edge fold belt of the Micangshan-Dabashan (Figure 1a). The study area is mainly located in the central and western parts of the Sichuan Basin, including the western depression belt and the central gentle structural belt (Figure 1a). The Xujiahe Formation was formed at the end of the Late Triassic during a period of massive deposition of clastic rocks [20], and it can be divided into T_3x^1 to T_3x^6 according to the lithological characteristics from bottom to top (Figure 1c). T_3x^6 in the study area is basically denuded, and T_3x^1 , T_3x^3 and T_3x^5 are dominated by mudstone, coal, and siltstone interlayers, corresponding to three main source rocks (Figure 1c). T_3x^2 and T_3x^4 are mainly composed of gray-white medium to fine sandstone, which are the main reservoir section. T_3x^4 mainly develops fan-delta sedimentary in the west and delta sedimentary in the east and center (Figure 1b), including the microfacies of distributary channel, sheet sand, and distal bar, and the lithology is dominated by gray and grayish-white fine to medium sandstones, interbedded with black thin mudstone and coal seams. At the bottom of T_3x^4 , conglomerate and conglomerate bearing sandstone are developed [21]. The thickness of T_3x^4 in the study area ranges from 450 to 700 m.

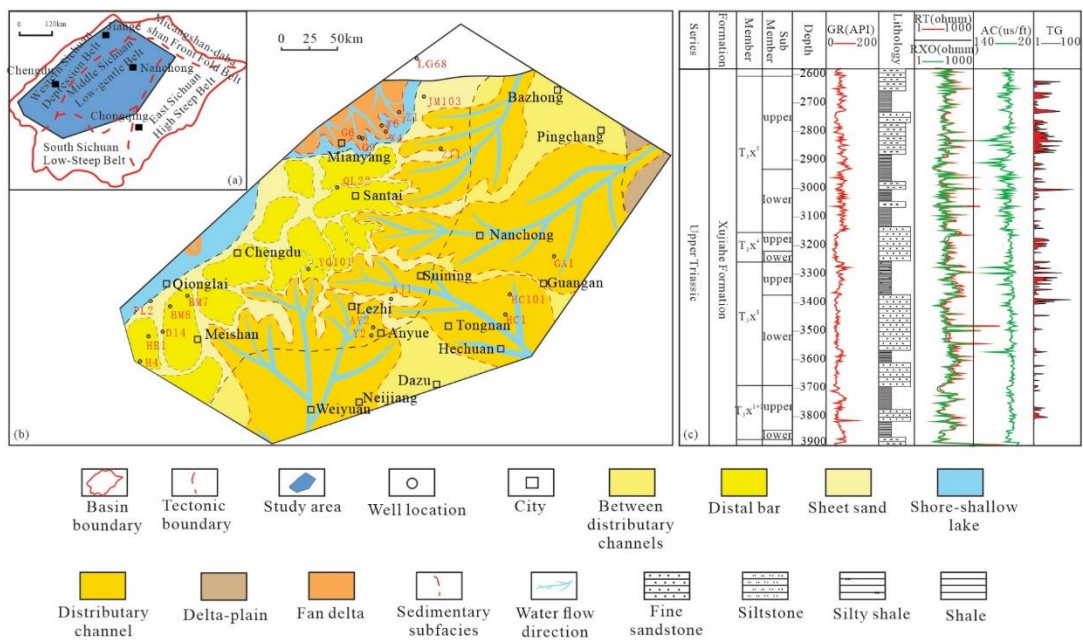


Figure 1. Geological features, sedimentary environment, and stratigraphic column of the study area. (a) location of the study area; (b) structural location and sedimentary microfacies of T_3x^4 in the Western Sichuan Depression; and (c) comprehensive stratigraphic column of the Triassic Xujiahe Formation.

2.2. Experimental Methods

Considering the sedimentary microfacies and lithology, 65 samples were selected from the T_3x^4 Formation in the western Sichuan depression, on which the thin section observations, X-ray diffraction (XRD) whole rock, physical properties, scanning electron microscopy (SEM), and high-pressure mercury intrusion (HPMI) testing were performed. Meanwhile, porosity and permeability testing results of 358 sandstone samples in the study area were collected.

2.2.1. Physical Properties, Thin Section and Field Emission Scanning Electron Microscopy

The samples were cleaned in vacuum and then dried in an oven at 100 °C for 24 h. Porosity and permeability were measured at normal temperature and pressure. Porosity was measured using an UltraPore 300 helium porosimeter. Permeability was measured on an UltraPerm 400 gas permeameter. The treated samples were polished and made into thin sections. The rock samples were impregnated with blue epoxy resin under vacuum to impregnate the pore throats and observed under a polarized light microscope. ZEISS GeminiSEM 500 field emission scanning electron microscopy was employed to observe pore types, with a maximum resolution of 10 nm.

2.2.2. XRD whole Rock Test

In this quantitative whole-rock analysis of sandstone samples using an Ultima IV X-ray diffractometer, the sandstone samples were pulverized and screened using 200 mesh to increase the test contact area. The instrument follows the SY/T 5163-2018 standard with a scanning step of 0.01°, and the content of each mineral was calculated based on the area of each peak as a percentage of the total area of the spectrum.

2.2.3. High Pressure Mercury Intrusion

High pressure mercury intrusion reflects the size distribution of pore-throat, by measuring the volume sum of the throats and the pores connected to these throats under a certain intrusion pressure, which is commonly used for characterizing the pore structure of tight reservoirs [22]. According to the Washburn equation [23], the intrusion pressure can be converted into the corresponding pore throat radius, and the pore throat size distribution of the sample was obtained. The high-pressure mercury intrusion experiment was conducted using the Autopore IV 9500 mercury porosimeter, with the maximum mercury intrusion pressure of 243 MPa, corresponding to a minimum detected radius of about 3 nm.

2.3. Fractal Method of Mercury Intrusion Curves

Mandelbrot [24] first proposed the fractal theory in the 1970s, based on which the fractal dimension was commonly used to characterize the complex pore structure features [25], heterogeneity [26,27], and fracture prediction of reservoirs. The fractal dimension of pore spaces in tight reservoirs ranges from 2 to 3. Values closer to 2 indicate the weaker heterogeneity and closer to 3 indicate the stronger heterogeneity of the pore spaces. The fractal dimension of reservoir can be obtained through various experiments [28], including low-temperature nitrogen adsorption, high-pressure mercury intrusion, constant rate mercury intrusion, and nuclear magnetic resonance, among which high-pressure mercury intrusion curves were commonly used to calculate the fractal dimension of pore throat structure in tight sandstone reservoirs and characterize the complexity of different types of pore-throat systems.

The fractal geometric formula of pore distribution can be expressed as [29]:

$$\lg(1 - S_{Hg}) = (D - 3)\lg P_c - (D - 3)\lg P_s \quad (1)$$

In log-log coordinate, D can be obtained from the slope by fitting the relationship between P_c and $(1-S_{Hg})$.

3. Results

3.1. Petrological Characterization

Based on thin section observations, the rock types of T₃x⁴ mainly include feldspathic quartz sandstone, lithic feldspathic sandstone, feldspathic lithic sandstone, and lithic sandstone. The lithology is mainly composed of medium and fine sandstone, with a small amount of coarse and coarse to medium sandstone, corresponding to medium to good sorting. Based on the XRD test (Table 1), minerals in T₃x⁴ are dominated by quartz (meaning 69.62%), followed by plagioclase (meaning 9.45%), and potassium feldspar is relatively low (meaning 5.73%). The cement is mainly clay minerals

(meaning 9.85%), and the content of calcite and dolomite is relatively low (meaning 5.79% and 4.28%, respectively) (Table 1). Clay is dominated by chlorite and illite (with the relative content of meaning 34.35% and 41.1%, respectively), followed by kaolinite (relative content of meaning 23.81%), and illite/montmorillonite mixed layer is the lowest.

Table 1. The lithologies, porosity, and mineral component of tight sandstone samples in T₃x⁴.

Samples ID	Depth (m)	Lithology	porosity (%)	permeability (mD)	Mineral content by XRD(%)					Relative content of clay (%)			
					Quartz	K-feldspar	Plagioclase	Calcite	Dolomite	Clay	Kaolinite	Chlorite	Illite
JM103-1	4194.58	SC	2.52	0.3081	51.3	0	0	20.3	22.4	4.8	54.8	11.3	25.0
JM103-2	4196.21	MS	4.67	0.1860	78.5	0.3	0.4	0.8	0.6	18.3	63.0	7.9	19.6
JM103-5	4203.95	S	2.09	0.0743	54.3	0	0.4	7.4	5.2	30.3	47.1	13.6	30.6
GA1-4	1903.91	MS	ND	ND	80.7	8.8	6.5	0.4	0	3.4	9.9	35.3	50.5
GA1-7	1911.52	FS	ND	ND	88.5	2.4	4.4	0.2	0.5	3.5	8.6	37.6	47.4
GA1-10	1918.64	FS	6.23	0.4868	77.6	4.9	10.4	0.3	0.8	5.8	17.3	34.6	39.0
GA1-19	1926.65	FS	7.05	0.4676	63.2	5.0	18.1	1.3	2.9	9.5	17.4	61.3	16.3
GA1-21	1934.21	MS	11.23	3.7255	68.6	15.0	9.1	0.9	0.2	6.2	14.3	66.7	13.1
AJ1-9	2168.28	FS	8.15	0.4586	65.1	4.5	18.9	0.4	1.8	8.9	8.4	31.2	48.6
HC101-2	2073.69	FS	4.27	0.3438	65.1	7.4	15.0	0.3	0.2	11.3	9.4	31.5	48.0
HC101-4	2076.25	MS	6.77	4.4631	81.0	4.6	9.1	0.2	0	4.4	9.5	40.6	32.9
YQ101-1	2753.14	FS	4.19	0.2190	50.2	5.1	13.8	23.9	0	5.6	7.3	33.7	48.1
YQ101-3	2758.12	FS	7.94	0.4151	62.5	7.3	18.8	0.4	0	11.0	18.0	40.2	33.8
YQ101-14	2774.05	MS	4.39	0.6499	61.7	3.9	6.5	9.3	0.9	16.5	8.3	27.2	49.2
YQ101-16	2778.97	MS	5.93	0.3146	81.7	4.2	7.0	0.4	0.2	6.2	13.1	38.2	42.2
QL22-3	3542.55	MFS	12.48	0.9218	60.9	6.1	19.6	0.4	0.8	11.9	17.1	56.9	16.0
QL22-6	3557.39	MS	6.25	0.3114	76.1	7.3	2.1	0.6	0	13.9	8.9	37.0	44.6
QL22-17	3574.20	MFS	2.09	0.0962	63.0	6.5	3.8	15.0	1.0	9.3	6.3	13.4	66.9
PL2-1	3229.30	FS	7.56	13.4186	78.1	0	13.0	0	1.4	7.5	46.0	13.0	35.0
PL2-2	3237.30	FS	4.89	0.3098	75.7	0	14.3	0	0	9.3	51.0	12.0	29.0
PL2-3	3244.00	FS	7.41	0.1613	82.4	0	9.4	0	1.1	6.3	81.0	3.0	12.0
H4-5	3060.42	MFS	4.78	0.1944	79.2	0	5.4	0	0	13.5	22.0	12.0	22.0
Z1-2	3717.55	SC	ND	ND	8.7	0	0.8	36.2	51.3	3.0	0	58.0	27.0
W4-1	3516.60	FS	ND	ND	79.2	3.3	4.9	1.6	0	11.0	0	53.0	40.0
W4-2	3518.40	S	ND	ND	68.4	3.8	2.2	4.2	0	15.5	0	58.0	33.0
W4-3	3522.15	MS	6.96	9.9057	77.2	5.4	0	5.0	0	8.5	0	43.0	45.0
W4-5	3525.16	MFS	1.90	1.2002	50.5	3.3	0	28.7	0	13.1	0	40.0	46.0
W4-6	3533.70	MS	9.25	1.1261	81.8	3.5	0	0.7	1.7	12.2	0	43.0	30.0
W4-7	3535.25	MFS	11.31	0.5372	76.8	7.2	2.9	1.2	0	10.2	0	45.0	25.0
W4-8	3541.84	MS	ND	ND	90.0	2.0	0	2.3	0	5.1	0	35.0	58.0
W4-9	3547.58	FS	7.03	0.5029	79.0	5.0	0	3.9	0	10.1	0	21.0	74.0
W4-10	3549.32	MS	6.21	ND	88.2	1.4	0	6.2	0	3.4	0	43.0	51.0
W4-11	3554.25	MS	10.06	1.0137	81.7	3.7	0	5.2	0	9.4	0	55.0	39.0
W4-12	3560.50	MS	6.29	0.2490	70.3	6.2	0	12.3	0	10.0	0	41.0	51.0
W4-14	3571.38	C	ND	ND	38.1	1.1	0	36.5	0	3.6	9.0	26.0	53.0
W4-15	3574.68	S	ND	ND	52.8	7.6	0	1.2	9.2	29.1	0	43.0	40.0
W6-1	3664.20	MS	10.52	1.2276	83.5	0	3.2	3.9	0	8.7	0	16.0	80.0
W6-2	3667.30	MFS	13.31	3.8826	83.3	0	4.0	1.5	0	11.2	0	25.0	65.0
W6-3	3678.40	FS	6.67	0.2192	64.0	13.8	3.2	4.1	0	14.0	0	29.0	66.0
W6-5	3709.70	MS	ND	ND	92.2	0	0	1.3	0	6.5	0	42.0	51.0
AY2-5	2016.80	FS	10.12	0.6670	74.9	4.8	14.1	0.2	1.1	4.6	ND	ND	ND
AY2-6	2019.35	FS	5.95	0.1370	52.5	6.8	19.0	1.8	2.9	17.0	ND	ND	ND
AY2-8	2066.70	MFS	9.31	0.5070	69.0	6.9	15.4	0.3	1.1	7.1	ND	ND	ND
HC1-6	2041.85	MFS	11.16	0.4950	76.8	6.2	9.3	0.2	0.4	6.9	ND	ND	ND
HC1-8	2044.13	MS	12.38	0.7540	77.0	0	9.6	0.3	3.1	10.0	ND	ND	ND
HC1-9	2044.62	MS	9.56	0.4350	72.5	8.3	8.7	0.5	2.7	7.1	ND	ND	ND
HC1-11	2048.06	FS	7.03	0.2740	64.6	10.1	10.0	0.4	1.2	11.8	ND	ND	ND
Y2-3	2054.90	FS	7.10	0.0437	59.6	7.4	18.6	0.5	0.6	13.3	ND	ND	ND
Y2-4	2057.82	FS	2.84	0.0070	53.7	6.9	17.9	18.2	0.3	3.0	ND	ND	ND

Notes: SC: sandy conglomerate; C: conglomerate; MS: Medium sandstone; MFS: Medium-fine sandstone; FS: fine sandstone; S: siltstone; ND: not detected.

Based on thin section images and quantitative identification and statistical analysis of rock composition, it is found that various types of rock debris are developed in the sandstones of T₃x⁴, with obvious differences in particle size and content (Table 2, Figure 2). The content of rock debris varies from 23% to 29%, with a mean value of 25.5%. Rock debris include mudstone debris (dark sheet-like shape in single polarized light), siltstone debris (clear boundaries between debris and interstitial material under the microscope), carbonate rock debris (premium white in orthogonal polarized light), metamorphic rock debris, volcanic rock debris, and chert (felsitic texture under the microscope, cleaner in orthogonal polarized light) (Figure 2). Among them, chert (Figure 2a, c) is the largest, ranging from 89.68 to 603.58 μm (meaning 271.72 μm) in grain size, but its content is the lowest (meaning 0.76%) (Table 2). The metamorphic debris is mainly composed of metamorphic quartzite debris (unequigranular texture and sutural contact between grains) (Figure 2), with a particle size (meaning 259.83 μm) slightly smaller than chert and a relatively high content (5.60%) (Table 2); Volcanic debris which is mainly composed of acidic eruption rock debris (often with felsitic texture in orthogonal polarized light and cloudy gray or reddish-brown clays in single polarized light) is second in size, ranging from 50.92 to 457.54 μm (meaning 197.5 μm), and a relatively low content (2.51%); The sandstone debris (Figure 2) is smaller in size (meaning 189.62 μm) and the highest in content (6.82%); Mudstone and carbonate debris are the smallest (Figure 2a, b), meaning 160.22 μm and 148.93 μm, respectively, and they are lower in content (4.98% and 1.15%, respectively).

Table 2. The rock debris content of tight sandstone samples in T₃x⁴.

Samples ID	Depth(m)	Mudstone debris(%)	Sandstone debris(%)	Carbonate rock debris(%)	Metamorphic rock debris(%)	Volcanic rock debris(%)	Chert(%)
GA1-10	1918.64	0.00	8.21	0.00	9.94	4.76	0.00
GA1-21	1934.21	0.17	8.27	0.00	12.47	1.29	5.91
AJ1-9	2168.28	7.64	0.00	1.55	0.00	4.31	0.00
HC101-2	2073.69	0.80	12.98	0.70	11.16	1.29	0.00
YQ101-1	2753.14	4.04	0.85	5.98	0.00	4.16	0.00
YQ101-3	2758.12	10.32	2.08	0.00	5.26	0.00	0.97
YQ101-16	2778.97	7.77	6.36	0.00	3.45	1.35	0.00
QL22-3	3542.55	8.88	0.36	0.00	3.83	2.87	0.00
PL2-2	3237.30	1.91	18.65	0.58	3.56	5.28	0.00
PL2-3	3244.00	1.25	17.82	0.00	2.31	6.79	2.10
W4-11	3554.25	0.83	6.07	1.96	15.86	1.53	1.16
AY2-5	2016.80	10.58	5.18	0.10	1.81	0.47	0.16
AY2-6	2019.35	14.96	2.55	2.48	2.33	0.00	0.00
HC1-8	2044.13	0.00	10.60	0.30	10.81	2.52	1.14
Y2-4	2057.82	5.57	2.31	3.56	1.20	1.03	0.00

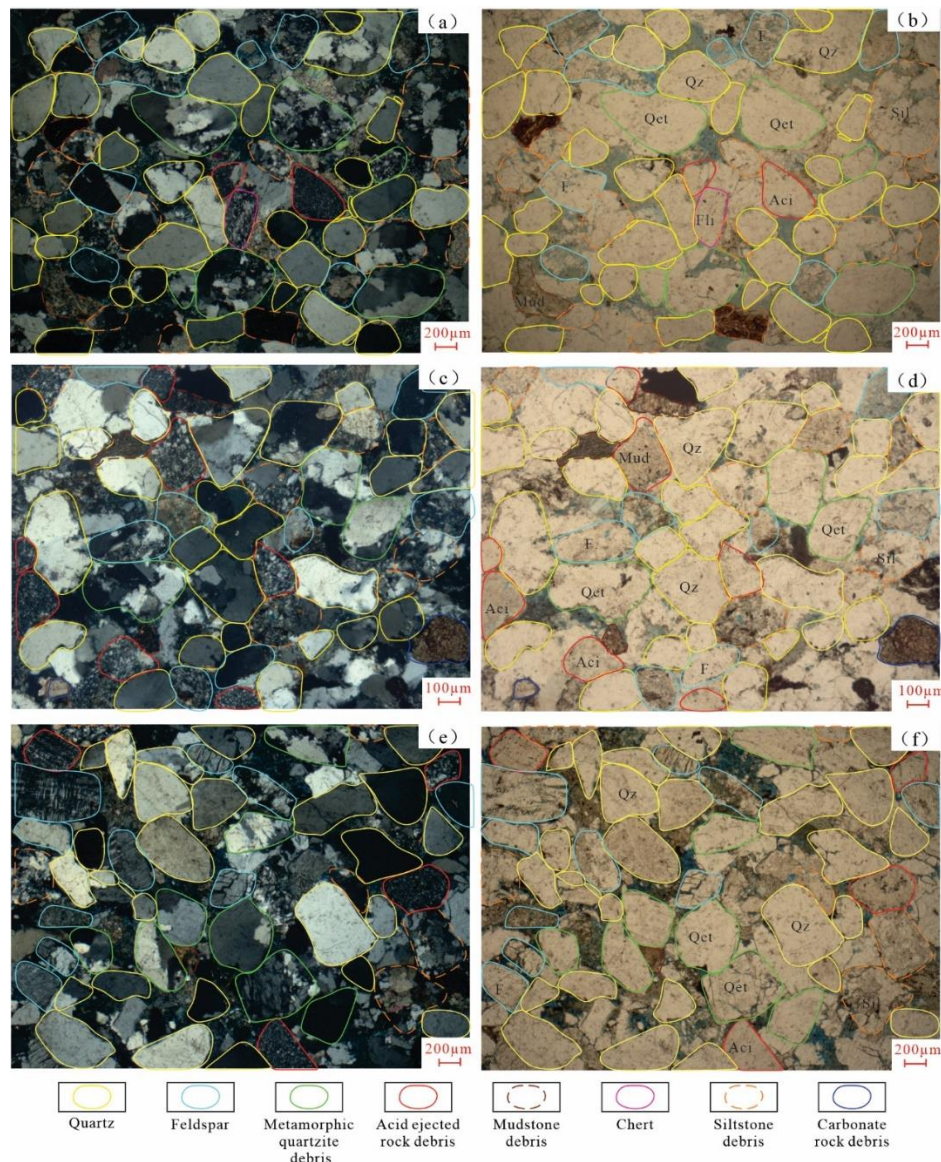


Figure 2. Microscopic characteristics of rock composition in the T_3x^4 of the western Sichuan depression. (a) observation of the orthogonal light, W4-11; (b) Same field of view as a, single polarized light; (c) observation of the orthogonal light, PL2-3; (d) Same field of view as c, single polarized light; (e) observation of the orthogonal light, GA1-21; and (f) Same field of view as e, single polarized light. Notes: Qz: Quartz; F: feldspar; Met: Metamorphic quartzite debris; Aci: Acid ejected rock debris; Mud: Mudstone debris; Che: Chert; Sil: Siltstone debris; Car: Carbonate rock debris.

3.2. Physical Property Features

Based on the testing result of 40 tight sandstone samples in T_3x^4 , the porosity ranges from 1.9% to 13.3%, with an average value of 7.38% (Table 1), Among which, porosities below 9% accounts for more than 70%, while the permeability ranges from 0.0437 to 9.9 mD (Table 1), with an average value of 1.01mD, among which, permeabilities lower than 0.5mD accounts for 60%. Therefore, the reservoirs of T_3x^4 generally belong to tight sandstone category. The correlation between porosity and permeability in T_3x^4 is weak (Figure 3), and samples with microcracks have significantly higher permeability. Under the same porosity, the distribution range of permeability can span 1-2 orders of magnitude, which may be related to complex pore structures [30,31]. Medium-fine sandstone and medium sandstone have the highest porosity (mean 9.94% and 8.23%, respectively), while some ones have lower porosity due to the influence of calcareous and siliceous cementation, followed by fine sandstone (mean 6.59%), and siltstone has the lowest porosity (2.09%) (Figure 3).

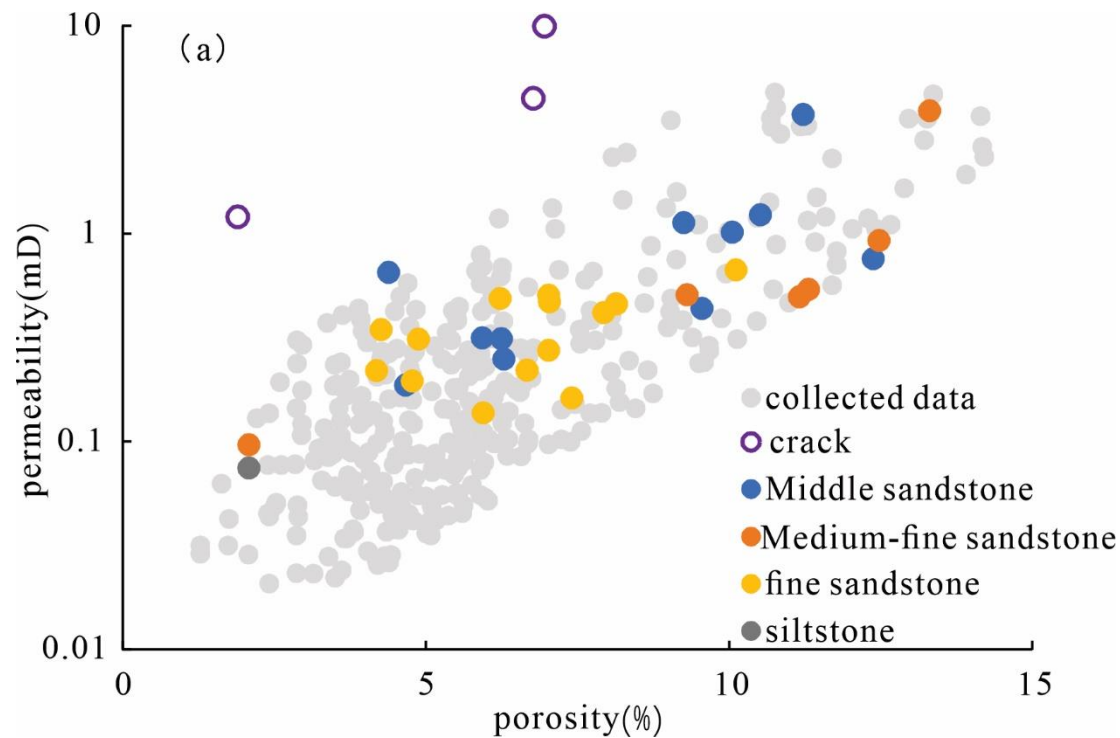


Figure 3. The correlation between porosity and permeability of tight sandstones with different lithologies in the T_3x^4 of the western Sichuan depression.

3.3. Pore structure Characteristics

3.3.1. Types of Reservoir Spaces

According to the observations of thin section images and scanning electron microscopy, the reservoirs of T_3x^4 exhibit five types of pores, including primary intergranular pores, residual intergranular pores, dissolution pores, intercrystalline pores, and microcracks (Figure 4). Primary intergranular pores (Figures 4a, d), located between grains and largely unfilled by cementation, are often triangular or polygonal shaped and usually develop thin films of chlorite and illite on the pore wall (Figures 4d, e). These pores are mostly greater than 30 μm in radii, providing excellent pore throat connectivity for tight reservoirs [32]. Residual intergranular pores (Figures 4a, i) are the remaining spaces after the intergranular pores being filled with cement and matrix. These pores are usually less than 10 μm , resulting in a slightly decrease in pore connectivity. Dissolution pores are relatively well-developed in T_3x^4 and can be divided into intergranular dissolution pores and intragranular dissolution pores. Intergranular dissolution pores (Figure 4b) are primarily formed by the dissolution of intergranular cements and detrital grains, often filled with clay minerals. Intragranular dissolution pores (Figures 4a, b, g, h) are mainly formed by the dissolution of lithic fragments (volcanic debris and siltstone debris) and feldspar. Debris dissolution primarily occurs at the edges of the particles, while feldspar dissolution typically begins along cleavage planes and may lead to the formation of casting pores (Figure 4b). Intercrystalline pores (Figures 4a, e, f, g) are mainly developed within clay minerals and matrix, with the smallest pore radii. Although these pores increase porosity, they have a weak impact on permeability. Microcracks (Figure 4c) mainly include bedding microcracks and structural microcracks. Bedding microcracks are often found near bedding planes, while structural microcracks typically traverse entire particle, with widths mostly exceeding 10 μm , and are rarely filled (Figure 4c).

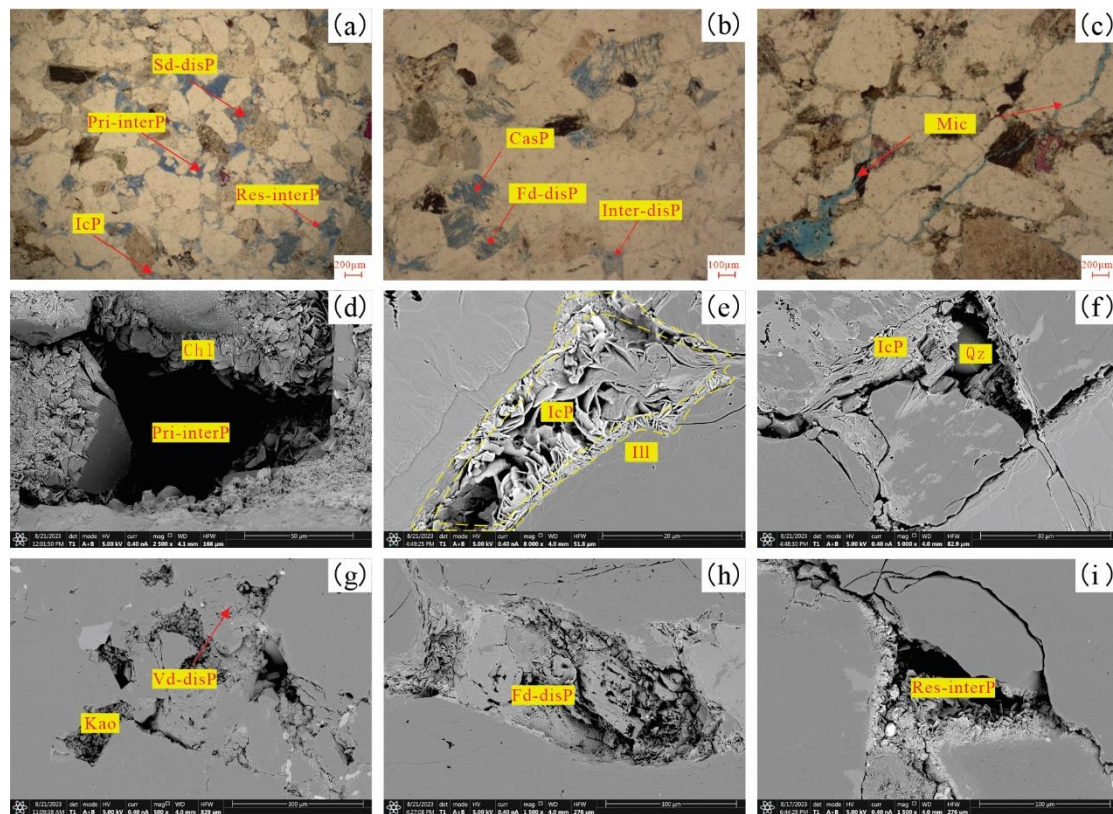


Figure 4. Microscopic characteristics of pores and microcracks in the tight sandstone reservoir of T_{3x4} in the western Sichuan depression. (a) intergranular pores, dissolution pores of sandstone debris, and intergranular pores of clay developed in medium to fine sandstone, W6-2; (b) feldspar dissolution pores and intergranular dissolution pores developed in fine sandstone, W4-9; (c) microcracks developed in medium sandstone, W4-3; (d) primary intergranular pores developed in medium to fine sandstone and pore surfaces enveloped by chlorite, QL22-3; (e) residual intergranular pores and clay intergranular pores developed in fine sandstone, and pore walls wrapped in illite, AJ1-9; (g) dissolution pore developed in volcanic rock debris, PL2-3; (h) dissolution pore developed in feldspar, W4-11; and (i) residual intergranular pores developed in medium sandstone, HC1-8. Notes: Pri-interP: Primary intergranular pore; Res-interP: Residual intergranular pore; Sd-disP: siltstone debris dissolution pore; Vd-dis: Intragranular dissolution pore of volcanic rock debris; Fd-disP: Intragranular dissolution pore of feldspar; Inter-disP: Intergranular dissolution pore; IcP: Intercrystalline pore in clay; Mic: Microcracks; CasP: Casting Pore; Qz: Quartz; Ill: Illite film; Chl: Chlorite film; Kao: Kaolinite.

3.3.2. Distribution Characteristics of Pore Throats

Through high-pressure mercury intrusion experiments, the pore structure of tight sandstone reservoir of T_{3x4} were studied. The maximum mercury saturation ranges from 31% to 86%, with an average of 63%, among which nearly 60% of the samples have a saturation greater than 63%, indicating that mercury can enter most of the pore spaces under high pressure. According to the morphology of intrusion curves, tight samples can be classified into four types (Figure 5a): concave downward shaped, straight line shaped, double platform shaped, and convex upward shaped, corresponding to different pore-throat combinations [31,32]. The concave downward shaped samples (red line) exhibit lower displacement pressures, higher mercury saturations, and moderate withdraw efficiency (35.76%), and this type of samples corresponds to a weak bimodal pore-throat size distribution, with the main peak in the range of 0.2-0.8 μm , which are related to the development of primary intergranular pores and residual intergranular pores in this type (Figure 4a). The straight line shaped samples (green line) exhibit moderate displacement pressures and higher withdraw efficiency (41.07%), and correspond to a bimodal pore-throat size distribution with peaks in the range

of 0.01-0.05 μm and 0.4-0.5 μm , which is related to the development of various pores, including residual intergranular pores, dissolution pores, intercrystalline pores (Figure 4f), and microcracks. The double platform shaped samples (orange line) exhibit lower displacement pressures and the highest mercury withdraw efficiency (44.51%), the intrusion curves are composed of two convex upward segments, and the pore-throat size distribution exhibits obviously bimodal, with the left peak in the range of 0.016-0.06 μm and the right peak in the range of 0.2-0.5 μm , which is related to the joint development of primary intergranular pores, dissolution pores, and intercrystalline pores (Figures 4d, h). The convex upward shaped samples (blue line) exhibit the highest displacement pressures and the worst mercury withdraw efficiency (28.9%), and the pore-throat size distribution exhibits unimodal, with the peak in the range of 0.004-0.01 μm , which is mainly attributed to the development of intercrystalline pores and some dissolution pores.

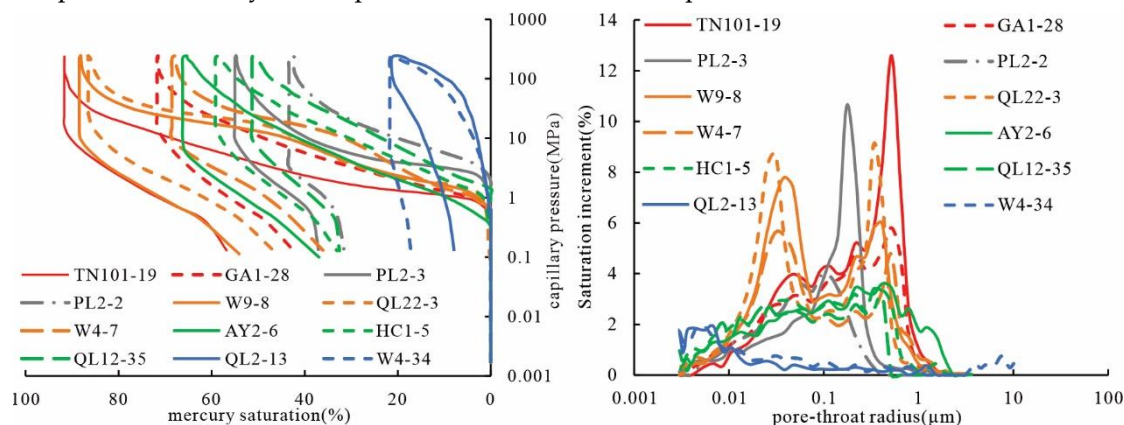


Figure 5. Characteristics of high pressure mercury intrusion testing data in the tight sandstone reservoir of the Xujiahe Formation in the western Sichuan depression. (a) mercury intrusion/extrusion curves and (b) characteristics of pore-throat size distribution.

According to the pore-throat size distribution measured by mercury intrusion, it is found that micropores are dominated (with an average proportion of 49.1%) in tight sandstones, followed by mesopores and small-pores (meaning 18.3% and 18.1%, respectively), and macropores are the lowest (meaning 13.2%). From concave downward shaped to straight line shaped, then to double platform shaped and finally to convex upward shaped, the proportion of macropores increases (meaning 1.2%, 14.9%, 15.6%, and 19%, respectively) and the proportion of micropores decreases (meaning 56%, 51.4%, 44.5%, and 42.1%, respectively).

3.4. Fractal Characteristics of Pore Structure

In the double logarithmic coordinates (Figure 6), the fractal curves of all samples exhibit multi segment linear, with each segment having a high fitting accuracy ($R^2 > 0.9$), indicating that the pore space of tight sandstone reservoirs exhibits multi fractal features. The inflection points of the fractal curves are located at the intrusion pressures of 2.1 MPa, 9.7 MPa, and 45 MPa, based on which the pore-throats can be divided into four intervals [33], namely micropores (<16nm), small pores (16-75nm), mesopores (75-350nm), and macropores (>350nm), with the different fractal dimensions between the adjacent intervals (Figure 6), indicating the development of different pore-throat types.

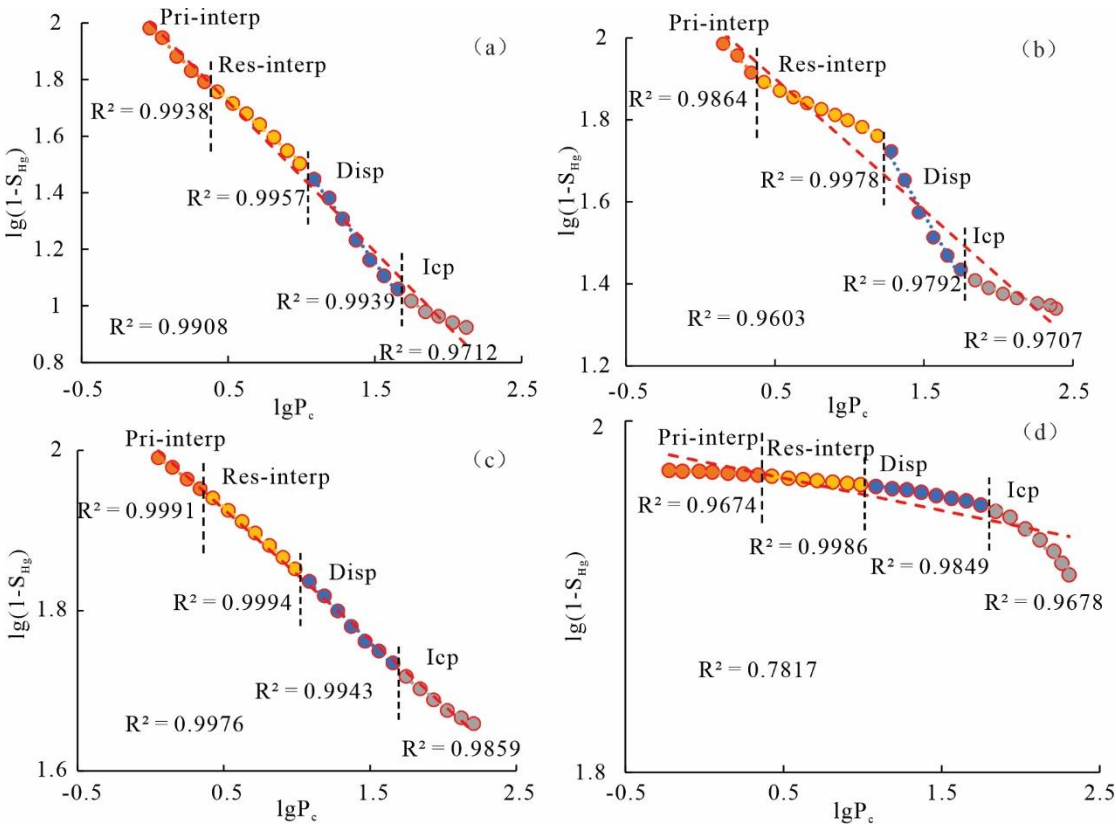


Figure 6. Fractal features of mercury intrusion curves in tight sandstone reservoirs of the Xujiahe Formation in the western Sichuan depression. (a) sample TN101-19; (b) sample QL22-3; and (c) sample HC1-5; (d) sample QL2-13. Notes: Pri-interP: Primary intergranular pore-throat system; Res-interP: Residual intergranular pore-throat system; DisP: dissolution pore-throat system; IcpP: Intercrystalline pore-throat system in clay.

The overall fractal dimension D and fractal dimensions of pore-throats within different intervals (including D1, D2, D3, and D4) were showed in Table 3. D value ranges from 2.58 to 2.91, with a mean of 2.78, and as the grain size decreases, D gradually increases. The medium sandstone having the smallest D (meaning 2.74), followed by medium-fine sandstone (meaning 2.75), and fine sandstone having the highest D (meaning 2.82), indicating that the larger the grain size of tight sandstone, the stronger the homogeneity of the pore-throats(Table 3).

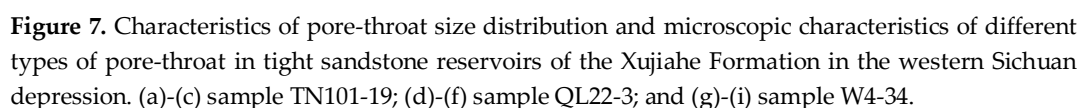
Table 3. Fractal Dimension distribution of pore-throats within different intervals for tight sandstones with different Lithology.

Lithology	D	D1	D2	D3	D4
	Min – Max (average)	Min – Max (average)	Min – Max (average)	Min – Max (average)	Min – Max (average)
medium sandstone	2.65-2.83 (2.74)	2.8-2.86 (2.83)	2.81-2.87 (2.83)	2.35-2.69 (2.53)	2.75-2.91 (2.85)
medium-fine sandstone	2.58-2.91 (2.75)	2.77-2.93 (2.86)	2.7-2.89 (2.82)	2.15-2.95 (2.64)	2.56-2.98 (2.82)
fine sandstone	2.75-2.88 (2.82)	2.78-2.99 (2.9)	2.79-2.89 (2.83)	2.58-2.89 (2.82)	2.7-2.96 (2.84)

4. Discussions

4.1. Classification of Pore-throat Types

Through the morphology of the high-pressure mercury injection pore-throat distribution curve, combined with thin sections and scanning electron microscopy, the study area mainly develops four types of pore-throats: primary intergranular pore-throats, residual intergranular pore-throats,



The fractal dimensions D1, D2, D3, and D4 vary greatly [35]. D1 related to primary intergranular pore-throats is the largest (meaning 2.86), followed by D4 related to the intercrystalline pore-throats (meaning 2.84), D2 related to residual intergranular pore-throats is moderate (meaning 2.82), and D3 related to the dissolution pore-throats is the lowest (meaning 2.66), indicating that the homogeneity of the dissolution pores is the best, while that of primary intergranular pores are the worst. D1 and

D3 increase with decreasing grain size, while the impact of grain size on D2 and D4 is not significant (Table 3).

4.2. Control Factors of Different Types of Pore-throat Development

By analyzing the correlation between the proportion and fractal dimension of different types of pore-throat and microscopic pore throat structural parameters as well as macroscopic rock physical properties of the tight sandstone (Figures 8 and 9)[33,36], it is concluded that the physical properties of the tight reservoir of the Xujiahe Formation decrease with the decrease of the contents of primary intergranular pore-throats, residual intergranular pore-throats and dissolution pore-throats (Figures 8),while the overall fractal dimension D is significantly negatively correlated with permeability and porosity(Figures 9), indicating that the heterogeneity of pore-throats obviously affects physical properties of tight reservoir [37–39], i.e., the larger the fractal dimension, the more heterogeneity of pore-throats, and the worse the reservoir quality. The permeability has a better relationship with the proportion and fractal dimension of primary intergranular pore-throats and residual intergranular pore-throats(Figures 8a and 9a; Table 4), which indicates that the contents and heterogeneity of primary intergranular pore-throats and residual intergranular pore-throats mainly affect the permeability [40]. The relationship between porosity and the proportion and fractal dimension of primary intergranular pore-throats and dissolution pore-throats is better(Figures 8b and 9b; Table 4), which indicates that the contents and heterogeneity of primary intergranular pore-throats and dissolution pore-throats mainly affect the amount of reservoir space. Although the contents of residual intergranular pores and primary intergranular pores are relatively low, their heterogeneities and proportions play a controlling role in porosity and permeability, respectively.

Table 4. Correlation coefficient between the proportion and fractal dimension of different types of pore-throat and microscopic pore throat structural parameters as well as macroscopic rock physical properties of the tight sandstone.

Parameter	Total D/Proportion	Macropore D1/Proportion	Mesopore D2/Proportion	Small-pore D3/Proportion	Micropore D4/Proportion
permeability	0.55/ND	0.46/0.58	0.52/0.41	0.44/0.38	0.32/0.7
porosity	0.53/ND	0.36/0.45	0.3/0.21	0.57/0.32	0.21/0.45
Mercury removal efficiency	0.15/ND	0.06/0.37	0.11/0.33	0.21/0.31	0.04/0.25
R15	0.34/ND	0.4/0.7	0.47/0.49	0.22/0.41	0.22/0.61

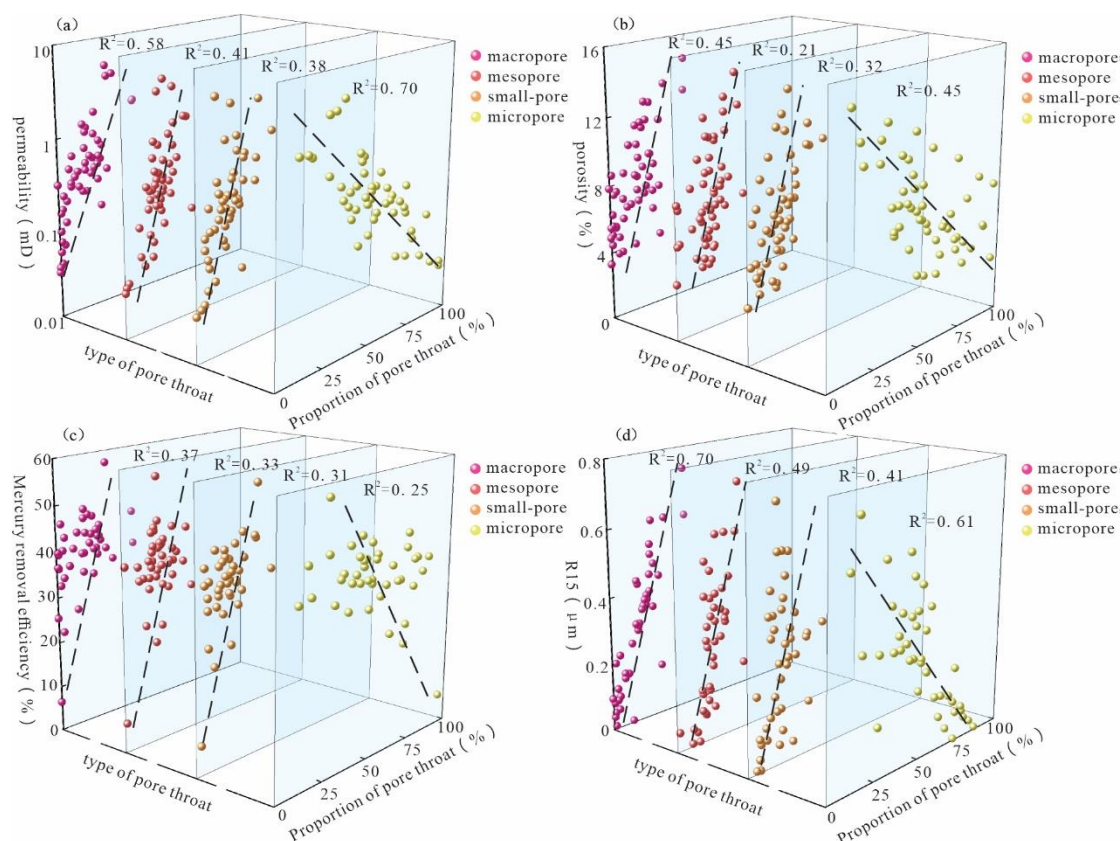


Figure 8. Relationship between proportion of pore-throat, physical properties, and pore structure of the Xujiache Formation in the western Sichuan depression. (a) the correlation between proportion of pore-throat and porosity; (b) the correlation between proportion of pore-throat and permeability; (c) the correlation between proportion of pore-throat and mercury withdraw efficiency; (d) the correlation between proportion of pore-throat and percolation throat radius R_{15} .

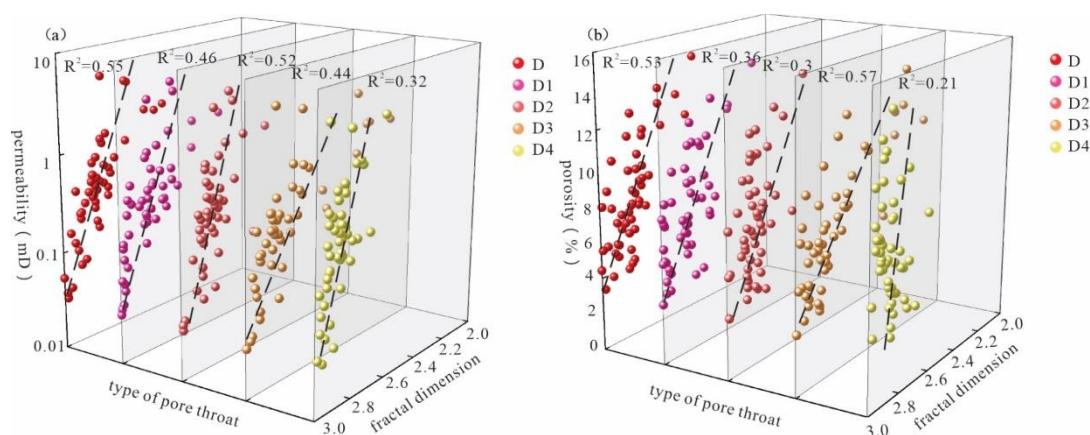


Figure 9. Relationship between fractal dimension, physical properties of the Xujiache Formation in the western Sichuan depression. (a) the correlation between fractal dimensions and permeability; (b) the correlation between fractal dimensions and porosity.

Mercury withdraw efficiency is an important parameter reflecting the pores connectivity [41], which is related to the pore and throat combinations. The combination of large pores connected with narrow throats (ink bottle shaped) will be affected by shielding effects [40,42], leading to low mercury withdraw efficiency, while the combinations with smaller pore throat ratio correspond to high mercury withdraw efficiency. The mercury withdraw efficiency of tight sandstones of the Xujiache Formation is positively correlated with the proportion of primary intergranular pore-throats and

residual intergranular pore-throats (Figure 8c; Table 4), reflecting that the higher the contents of primary intergranular pore-throats and residual intergranular pore-throats, the higher the mercury removal efficiency [43]. This indicates that primary intergranular pores and residual intergranular pores have smaller pore throat ratio than others, which is related to the smaller difference between pores and throats, and the better connectivity between pores and throats [40,44]. This is different from the fact that the mercury removal efficiency is mainly affected by the mesopore throats of reservoir of the Upper Triassic Yanchang Formation [43]. R15, the throat radius corresponding to mercury saturation of 15%, is commonly used to reflect the percolation paths in tight sandstone. R15 has a good correlation with the proportion of primary intergranular pore-throats and residual intergranular pore-throats (Figure 8d; Table 4), indicating that the percolation paths of the Xujiahe Formation are mainly controlled by primary intergranular and residual intergranular pore-throats. The relationship of the proportion and fractal dimension of intercrystalline pore-throats with reservoir properties and pore structure is worse (Figures 8, 9; Table 4), indicating that the intercrystalline pore-throats has a weak impact on reservoir quality [40].

4.3. Influence of Rock Composition on Fractal Dimension

Tight sandstones of T₃X⁴ are composed of many rock components, including quartz, feldspar, debris, and clay cement, which affect the diagenesis evolution and the formation of tight reservoir [36,45]. Based on the relationship between fractal dimensions and rock components (Figure 10), the impacts of different components on pore structure are studied. D1 is inversely correlated with the relative content of illite and chlorite and metamorphic rock debris, while positively correlated with the relative content of kaolinite and sedimentary rock debris (Figure 10). The proportion of primary intergranular pore throats is positively correlated with the relative content of illite, chlorite, and metamorphic rock debris (Figures 11b, d, e), while inversely correlated with the relative content of kaolinite, volcanic rock debris, and plastic mineral content (Figures 11a, c, f). This indicates that the homogeneity of primary intergranular pore-throats is affected by illite, chlorite, and metamorphic debris. Early formed films of illite and chlorite can inhibit quartz enlargement and resist compaction [46–48] (Figures 4d, e), while metamorphic rock debris (Figure 2) with a large particle size and high hardness can effectively resist compaction, providing protection for primary intergranular pore-throats. Zhong Yijiang [49] opines that the mixture film of illite and chlorite retains primary intergranular pore throats. D2 is inversely correlated with the content of quartz and positively correlated with the content of volcanic rock debris (Figure 10). Quartz promotes the development of early quartz cementation [50,51], which leads to the conversion of primary intergranular pore-throats to residual intergranular pore-throats (Figures 4f, i) and enhance the homogeneity of residual intergranular pore-throats; while volcanic rock debris can be dissolved (Figure 2b, Figure 4b) to precipitate kaolinite [52], which fills the intergranular pores (Figure 4g) and enhance the heterogeneity of residual intergranular pore-throats. D3 is inversely correlated with the relative content of chlorite and potassium feldspar, and positively correlated with sedimentary rock debris. The proportion of dissolved pore-throats is positively correlated with the content of metamorphic rock debris and the relative content of chlorite (Figure 11b, d), and inversely correlated with the content of plastic minerals (Figure 11a). It indicates that the dissolution is affected by the content of potassium feldspar and the development of chlorite film. The chlorite film can protect primary intergranular pores, provide fluid exchange channels [53], and lead to the enhanced dissolution of potassium feldspar (Figures 4a, b, h); The sedimentary rock debris include mudstone rock debris, siltstone rock debris, and carbonate rock debris, among them, the mudstone and siltstone rock debris with a smaller particle size are easily compacted (Figure 2), while the carbonate rock debris releases calcium and magnesium ions to promote the calcite cementation in the early stage [54], leading to a decrease in fluid exchange channels. Therefore, the sedimentary rock debris is not conducive to the development of dissolution pores. D4 is inversely correlated with the content of quartz and potassium feldspar, and positively correlated with the content of volcanic rock debris and sedimentary rock debris (Figure 10). Quartz cementation (Figure 2a) and clay cementation (illite and chlorite) related to the precipitation of the dissolution of potassium feldspar (Figure 4f) promote the

homogeneity of intercrystalline pore-throats, while the book-like kaolinite related to the dissolution of volcanic rock debris increases the heterogeneity of intercrystalline pore-throats.

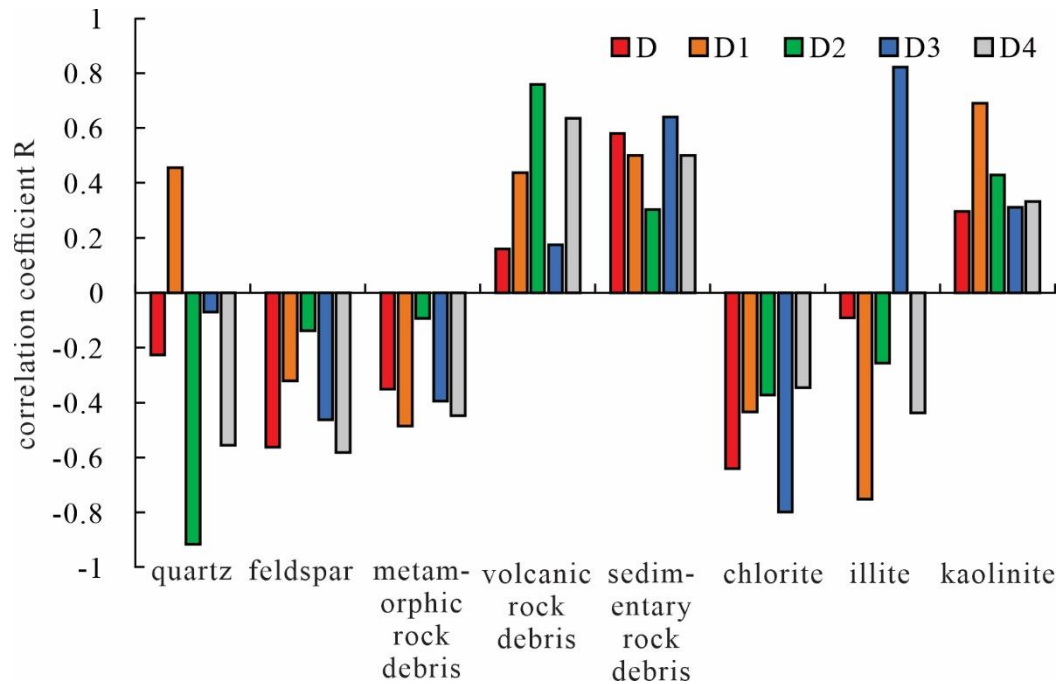


Figure 10. The correlation coefficient between fractal dimension and rock compositions of T_3X^4 in the western Sichuan depression.

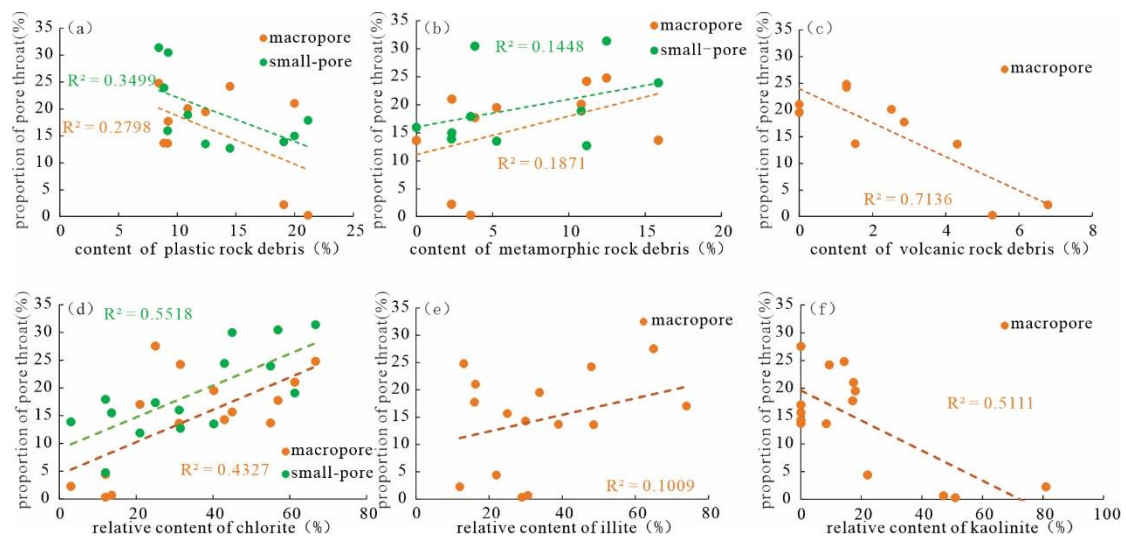


Figure 11. The correlation coefficient between proportion of pore-throat and rock compositions of T_3X^4 in the western Sichuan depression. (a) plastic rock debris; (b) metamorphic rock debris; (c) volcanic rock debris; (d) chlorite; (e) illite; (f) kaolinite.

The overall fractal dimension D is inversely correlated with potassium feldspar, metamorphic rock debris, and the relative content of chlorite, and positively correlated with sedimentary rock debris and kaolinite (Figure 10), which is the same as $D1$ and $D3$. This indicates that the primary intergranular pores and dissolution pores control the homogeneity of pore structure of tight sandstones. Metamorphic rock debris and chlorite film affect the development and homogeneity of primary intergranular pores, while the potassium feldspar and chlorite affect that of dissolution pores, therefore, these three rock compositions promote the homogeneity of pore structure of tight sandstone. The sedimentary rock debris and kaolinite have a negative impact on the homogeneity of

pore structure. Other rock compositions, such as quartz and volcanic rock debris, have a weaker impact (Figure 10).

4.4. Control Factors for the Development of Tight Sandstone Reservoirs

Sedimentation and diagenesis jointly control the development of the tight sandstone reservoir [55]. Sedimentary facies control the particle size, sorting, and rock composition of clastic rocks [56]. Based on the above analysis, the primary intergranular pores and dissolution pores are the key to the development of high-quality reservoirs of T_3X^4 . The sedimentary environment of the T_3X^4 is mainly composed of fan delta facies and delta sedimentary facies, including the microfacies of underwater distributary channels, sheet sand, and distal bar. In the underwater distributary channels microfacies, with strong hydrodynamic conditions, a large amount of medium sandstones and medium to fine sandstones with larger particle size and medium to good sorting are deposited, which develop many brittle rock compositions (quartz, feldspar, and metamorphic rock debris) and low content of sedimentary rock debris. The brittle rock compositions, especially metamorphic rock debris, have strong compaction resistance and are conducive to the early developed films of chlorite and illite, which promotes the preservation of intergranular pores. The dissolution of potassium feldspar further improves the reservoir space and enhances the homogeneity of pore-throats. Therefore, high-quality reservoirs are widely developed in sandstones of underwater distributary channels. Near the central and southwestern parts of the basin, the hydrodynamic conditions are weakened, and a large amount of fine sandstone and siltstone are deposited in the sheet sand and distal bar microfacies, in which the content of sedimentary rock debris increases and grain size decreases. It leads to the deterioration of the anti-compaction ability, the absence of chlorite films and enhanced dissolution of feldspar, and then causes the stronger heterogeneity of primary intergranular pores and dissolution pores, which is not conducive to the formation of the high-quality reservoirs.

5. Conclusions

(1) Based on fractal inflection points, the pore-throats of T_3X^4 are divided into macropores (>350nm), mesopores (75-350nm), small-pores (16-75nm), and micropores (<16nm), mainly corresponding to the primary intergranular pore-throats, residual intergranular pore-throats, dissolution pore-throats, and intercrystalline pore-throats, respectively.

(2) The pore-throats of the Xujiahe Formation exhibits four segment fractal features, and the overall fractal dimension D increases with the decrease of particle size. The proportion of intercrystalline pore throats in clay is the largest, followed by residual intergranular pore throats and dissolution pore throats, and the proportion of primary intergranular pore throats is the smallest. The degrees of homogeneity and content of primary intergranular pore-throats, residual intergranular pore-throats and dissolution pore-throats respectively controls the permeability and porosity of the reservoirs of the Xujiahe Formation.

(3) The homogeneity of primary intergranular pore-throats is mainly controlled by chlorite film, illite film, and metamorphic rock debris, that of residual intergranular pore-throats is mainly controlled by quartz content, and that of dissolution pore-throats is mainly controlled by chlorite film and potassium feldspar. The overall fractal dimension D is controlled by potassium feldspar and chlorite film.

(4) The high-quality reservoirs in T_3X^4 are controlled by the development of primary intergranular pores and dissolution pores, mainly developed in underwater distributary channels with strong hydrodynamic conditions, large particle size, high content of brittle minerals, and low content of sedimentary rock debris, matrix, and cements.

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