

Article

Porosity Characteristics of Coal Seams and the Control Mechanisms of Coal Petrology in the Xishanyao Formation in the Western Part of the Southern Junggar Basin

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Abstract: The porosity characteristics of coal seams serve as a pivotal factor in assessing the development potential of coalbed methane (CBM) resources, significantly influencing the adsorption and permeability capabilities of coal reservoirs, as well as the accumulation, entrapment, and preservation of CBM. In this study, we focused on the coal seams of the Xishanyao Formation in the western part of the southern Junggar Basin (NW China). By leveraging the complementarity of nuclear magnetic resonance (NMR), low-temperature liquid nitrogen experiments, and high-pressure mercury intrusion porosimetry (MIP) in spatial exploration range and precision, we conducted a comprehensive analysis to achieve a fine description of porosity characteristics. Furthermore, we explored the coal petrology factors controlling the pore characteristics of the Xishanyao Formation, aiming to provide geological evidence for the selection of favorable areas and the development potential evaluation of CBM in the study area. The results indicate the following: (1) The total pore volume of the coal samples is $6.318 \times 10^{-3} \text{ cm}^3/\text{g}$ on average, and the micropore volume accounts for a relatively high proportion (averaging 44.17%), followed by the fine pores (averaging 39.41%). The average porosity is approximately 3.87%, indicating good gas storage and connectivity of the coal seams, albeit with some heterogeneity. The coal reservoir is dominated by micropores and fine pores with diameters less than 100 nm, and the pore structure is characterized by low pore volume and high pore area. (2) The pore structure is influenced by both the coalification degree and the coal maceral. Within the range of low coalification, porosity increases with the increase in coalification degree. Building upon this, an increase in the vitrinite content promotes the development of micropores and fine pores, while an increase in the inertinite content promotes the development of meso–macropores. The clay mineral content exhibits a negative correlation with the adsorption pore volume ratio and a positive correlation with the seepage pore volume ratio.

Keywords: coalbed methane; porosity characteristics; petrological control mechanisms; Xishanyao Formation; western part of the southern Junggar Basin



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1. Introduction

The Junggar Basin, located in the northwest of China, as the most typical low coalification sedimentary basin in the country, has the most abundant coalbed methane (CBM) resources [1–3]. Its coal-bearing stratum includes the Lower Jurassic Badaowan Formation and the Middle Jurassic Xishanyao Formation [4–6]. Recently, some significant breakthroughs have been made in CBM exploration and development for the Badaowan Formation in the eastern part of the southern Junggar Basin [7,8]. However, the production effect of CBM single-wells in the Xishanyao Formation remains unsatisfactory [9–11]. While some scholars have conducted macroscopic studies on the CBM gas-bearing characteristics and accumulation conditions of the Xishanyao Formation, concluding that this coal-bearing

stratum is suitable for CBM accumulation [12–16], microscopic studies on the Xishanyao coal reservoirs are still insufficient, which makes it difficult to guide local CBM reservoir evaluations.

In recent years, more researchers have focused on the fact that the scale, distribution, and connectivity of microscopic pores in coal determine the adsorption and permeability capabilities of coal reservoirs, and they also have a significantly influence on the accumulation and later preservation of CBM [17–27]. Chinese and international researchers have primarily used nuclear magnetic resonance (NMR) experiments, low-temperature gas adsorption techniques, and high-pressure mercury intrusion methods (MIP) [28–31]. These methods have a wide measured pore range and high precision, but due to the constraints of their testing principles, different experimental methods have their own limitations and advantages [32–35]. For instance, low-temperature gas adsorption techniques (using N₂ and CO₂) only provide data for pores with diameters less than 50 nm in coal, and high-pressure MIP can cause mechanical damage to coal samples due to the high pressures involved [36,37]. To address these issues, scholars have focused on jointly analyzing pore structure characteristics using multiple experimental techniques recently. Yang Qing et al. characterized the full pore structure of lignite samples by combining scanning electron microscopy (SEM) with low-temperature liquid nitrogen adsorption experiments and high-pressure MIP [38]. Zhai Cheng et al. obtained information on physical properties such as porosity, pore size distribution, and pore connectivity in coal through relaxation spectroscopy analysis of NMR [39]. Li Nana et al. jointly characterized the pore structure of high-rank coal using MIP, low-temperature liquid nitrogen adsorption, and NMR relaxation methods [40].

Drawing upon the current research status and existing problems in the study area, we focused on the coal seams of the Xishanyao Formation in the western part of the southern Junggar Basin and collected coal samples from multiple CBM parameter wells, geological survey wells, and coal mines. Low-temperature liquid nitrogen and high-pressure MIP were used to describe the pore characteristics of the coal seams, complementing each other's advantages. Additionally, NMR was used to explore the characteristics of microcracks in coal. We further discuss the coal petrological control factors of pore characteristics in the Xishanyao Formation, aiming to provide geological basis for selection of favorable CBM areas and the evaluation of their development potential in the future.

2. Geological Setting

The southern Junggar Basin is structurally complex, having undergone multiple tectonic movements, especially the Cenozoic Himalayan orogeny, which resulted in strong folding along the northern margin of the Tianshan Mountains and the formation of many large thrust faults [41–44]. This orogeny played a key role in the subsequent modification of the coal-bearing strata. A series of NWW-, NEE-, and near-EW-trending faults, folds, and intermountain basins in this period have resulted in the coal seams in the study area with large inclinations and deep burial depths [45]. The western part of the southern Junggar Basin is located atop the Qigu fold belt and the Huomatu anticline belt; it stretches from the Manas River in the west to the Urumqi River in the east, bounded by the Changji Depression in the north (Figure 1a). It extends approximately 20 km in width from north to south and 140 km in length from east to west, covering an area of approximately 2800 km². The main structure of the study area is a northward-inclined monocline, with relatively simple tectonic conditions (Figure 1b) [46,47].

The coal-bearing strata are primarily developed within the Qigu fold belt. The overlying strata mainly consist of the Permian, Triassic, and Jurassic formations. The Xishanyao Formation coal seams, which serve as the main gas-producing layer, are stable or relatively stable throughout the entire study area [48,49]. These coal seams are predominantly distributed in the vicinity of Urumqi and Manas, with burial depths ranging from 200 to 1500 m and cumulative thicknesses varying from 30 to 100 m (Figure 1c). These characteristics are highly conducive to the requirements for CBM development. Compared to the Badaowan Formation, the Xishanyao Formation coal seams exhibit lower coalification

degree, a greater number of coal layers, larger single-layer thickness, and better pore permeability and porosity, which can be used as the key target area for CBM exploration and development in the southern Junggar Basin [50–52].

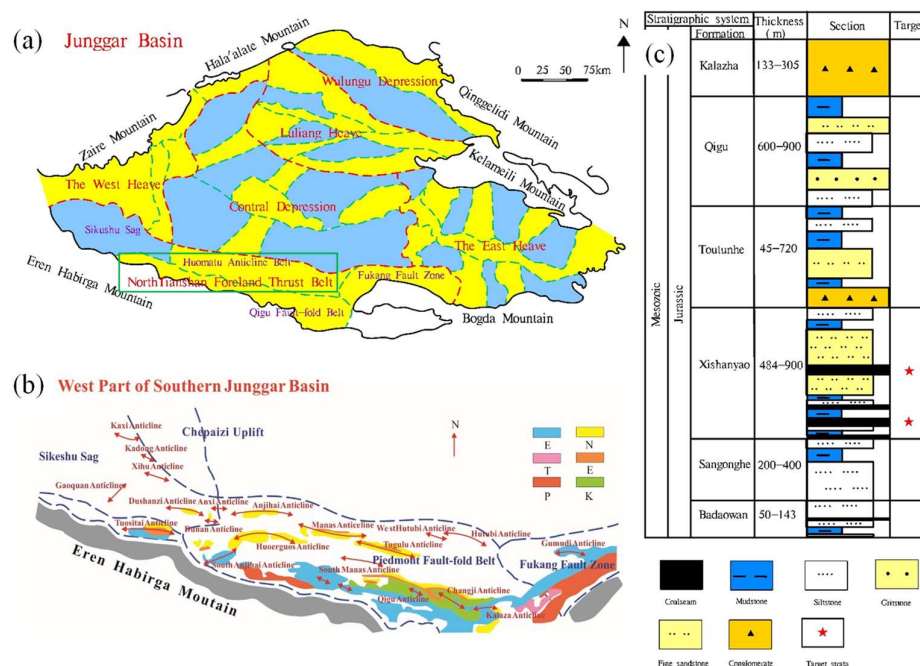


Figure 1. (a) Location of the study area in the Junggar Basin. (b) Structure outline map of the study area. (c) Column of a Jurassic stratigraphic section in the study area; the target strata of CBM in the Xishanyao Formation are presented.

3. Sample and Experiment Method

3.1. Sampling Collection and Experimental Scheme

In line with the progress of CBM exploration in the study area, the sample collection for this study encompassed 10 coal mine sampling sites and 12 CBM wells, including those from Hedong in Urumqi (XWC1 well), Taxi River (MMC1, MMC2, and MMC3 wells), and Queergou in Hutubi (CS1, CS2, XHC1, and XHC2 wells), among others. The exact sampling locations and the significance of their respective identification codes are graphically represented in Figure 2.

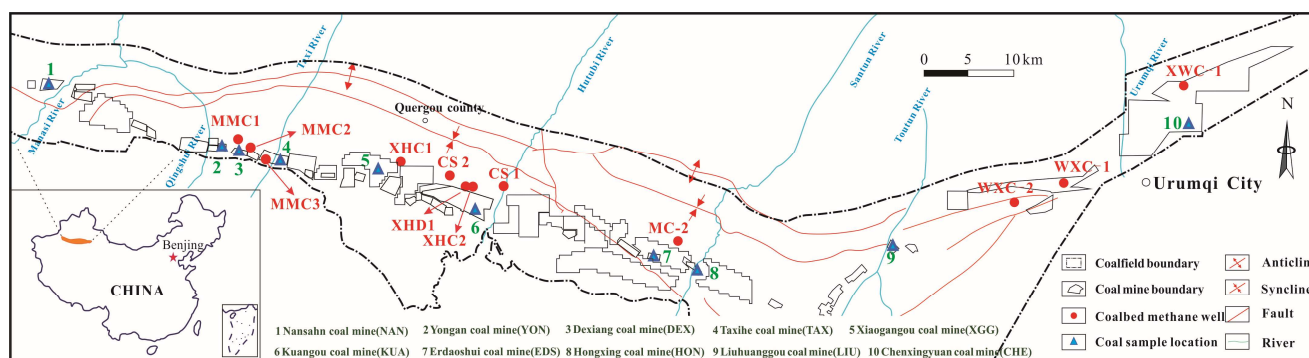


Figure 2. Distribution of coal mines, CBM wells, and sampling locations in the western part of the southern Junggar Basin.

The tiny pores and original fractures in the coal matrix jointly form the dual pores–fractures system of coal [53–55]. Within this system, CBM primarily exists in an adsorbed state within the pores of the coal and migrates outward through the fracture network.

Macro-fractures serve as an indispensable passageway for the migration and output of CBM from the coal reservoir, while microcracks act as the link between the pores and macro-fractures [56–61]. In this study, the vitrinite reflectance, maceral composition, and coal industrial analysis were first measured on the samples. Subsequently, the pore structure data of coal samples were obtained by low-temperature liquid nitrogen adsorption, high-pressure MIP, and NMR. It is believed that these testing methods can complement each other to overcome their respective defects and minimize the final error rate, ultimately leading to more accurate data on the pores and microcracks in coal. Regarding the classification of pore sizes in coal, this study adopts the classification method proposed by B.B. Xohot (1966) [62], which is currently widely used, categorizing coal pores into 4 types: macropores (pore diameter > 1000 nm), mesopores (pore diameter 100–1000 nm), fine pores (pore diameter 10–100 nm), and micropores (pore diameter < 10 nm).

We used the AutoPore IV 9500 mercury injection apparatus manufactured by the US company Micromeritics (Norcross, GA, USA) to analyze the pore size structure and the Quadrasorb 2-SI-KR/MP automatic aperture analyzer manufactured by the US company Quantachrome (Boynton Beac, FL, USA) to acquire more detailed data of the structure and proportion of micropores and fine pores. Additionally, the NMR experiment used a MicroMR12-025V nuclear magnetic resonance analyzer manufactured by the Chinese company NuMai (Suzhou, China), aiming to minimize the secondary destruction of the samples and enable more accurate continuous detection of the structure and distribution of micropores and fine pores, meso–macropores, and microcracks in low-rank coal samples.

3.2. Fundamental Information of the Samples

The coal of the Xishanyao Formation in the study area is mainly primary structural coal and cataclastic coal, with less granitic coal and mylonitic coal. Ro,max ranges from 0.41 to 0.70% (Table 1), and the coalification degree is mainly at a low level, followed by a medium level, collectively indicating that overall, the coal is in the stage of long-flame coal and gas coal. As shown in Table 1, the testing results of the maceral compositions and coal industrial analysis indicate that the coal seams of the Xishanyao Formation have a low ash content, a low water content, and medium-to-high volatile content.

Table 1. Statistics of coal quality and macerals in the study area.

Sample	Ro,max/(%) (avg.)	Macerals (Volume Fraction) (%)				Industrial Analysis (Mass Fraction) (%)		
		Vitrinite	Inertinite	Exinite	Mineral	M _{ad}	A _{ad}	V _{ad}
DAX-1	0.70	72.71	18.22	9.08	0.00	9.64	2.4	21.49
CHE-2	0.57	65.62	32.08	2.31	0.00	4.29	5.7	36.63
CHE-3	0.62	55.61	43.07	1.32	0.00	6.15	8.36	38.15
XGG-1	0.65	62.50	34.05	3.45	0.00	2.24	5.08	34.15
XGG-2	0.64	57.84	37.08	5.08	0.00	2.09	5.72	35.45
TAX-1	0.68	81.93	15.67	2.40	0.00	2.32	24.13	25.20
TAX-2	0.69	61.42	33.71	4.87	0.00	4.06	9.64	34.97
TAX-3	0.69	59.60	37.80	2.60	0.00	4.15	13.88	39.19
LIU-2	0.49	39.58	53.14	7.28	0.00	4.77	6.44	31.99
LIU-3	0.41	41.70	55.32	1.06	1.91	3.69	2.8	32.95
NAN-1	0.62	45.61	48.92	5.47	0.00	3.78	5.48	32.79
NAN-2	0.59	54.61	38.32	7.07	0.00	5.43	2.91	32.8
MMC2-2	0.64	74.32	19.15	3.61	2.92	4.47	6.00	33.94
MMC3-1	0.60	59.50	38.39	0.58	1.54	4.36	8.93	31.50
MMC3-2	0.58	53.80	43.41	1.30	1.48	4.34	9.67	36.00
KUA-1	0.59	58.85	36.21	3.29	1.65	9.64	2.40	21.49
KUA-2	0.64	53.38	42.62	1.48	2.53	4.29	5.70	36.63
KUA-3	0.64	69.75	24.85	2.80	2.60	6.15	8.36	38.15

4. Results and Discussion

4.1. Microcrack Characteristics by NMR

NMR is a fast and non-destructive detection technique, primarily relying on the acquisition of transverse relaxation time T_2 (T_{2C}) and corresponding amplitude to continuously detect the multi-scale physical properties of pores and fractures in coal reservoirs [63–66]. In this study, NMR is used to obtain the structure and distribution of pores and microcracks in coal seams. We conducted NMR experiments on a total of 12 cylindrical samples under saturated water conditions, with a resonant frequency of 11.854 MHz and a temperature of 35.00 ± 0.02 °C. The testing parameters and experimental results of the NMR experiment are shown in Tables 2 and 3. The results show that the NMR porosity ranges from 4.23 to 8.28% with an average of 5.77% (Table 2), T_{2C} ranges from 11.993 to 18.112 ms with an average of 14.423 ms (Table 3), and the NMR permeability ranges from 0.0024 to $0.1347 \times 10^{-3} \mu\text{m}^2$ with an average of $0.0350 \times 10^{-3} \mu\text{m}^2$ (Table 3). The coal samples mainly have micropores, fine pores, macropores, and microcracks, while the mesopores are relatively undeveloped.

Table 2. Experimental sample parameters and porosity test results of NMR in the study area.

Sample	Depth (m)	Oven-Dry Signal Quantity	Saturated Signal Quantity	Oven-Dry Weight (g)	Saturated Weight (g)	Volume (mL)	NMR Porosity (%)	Gravimetric Porosity (%)
MMC2-1	640.75	3129.158	11295.94	13.5735	14.1512	10.99	4.45	5.26
MMC2-2	647.41	8008.744	20425.67	13.897	14.7033	10.92	6.97	7.38
MMC3-1	675.30	3238.128	10874.41	11.9931	12.5652	9.55	4.76	5.99
MMC3-2	730.12	6181.906	2979.59	17.7155	18.5331	13.90	5.86	5.88
MMC3-3	728.66	7041.550	4071.01	18.1116	19.0668	13.62	6.79	7.01
MMC3-4	782.86	3681.808	18371.01	13.4865	14.5027	10.95	8.28	9.28
XHC2-1	793.93	6009.474	16899.78	14.4926	15.2164	11.31	5.86	6.40
XHC2-2	790.65	3888.061	12686.29	15.3458	15.9387	12.01	4.40	4.94
XHC2-3	821.63	4324.343	15592.78	13.4558	14.1940	10.69	6.43	6.91
XWC1-1	883.62	3252.480	11951.41	14.3445	14.9602	11.55	4.53	5.33
XWC1-2	901.82	3649.538	11038.91	13.3186	13.7849	10.38	4.23	4.49
XWC1-3	916.63	3430.437	15266.30	13.3330	14.0405	10.77	6.72	6.57

Table 3. Experimental fluid saturation and permeability test results of NMR in the study area.

Sample	T2 Cutoff Value (ms)	Irreducible Fluid Saturation (%)	Movable Fluid Saturation (%)	NMR Permeability ($10^{-3} \mu\text{m}^2$)
MMC2-1	13.5735	66.66	33.34	0.0098
MMC2-2	13.897	83.23	16.77	0.0096
MMC3-1	11.9931	65.11	34.89	0.0113
MMC3-2	17.7155	48.33	51.67	0.1347
MMC3-3	18.1116	57.71	42.29	0.1144
MMC3-4	13.4865	64.63	35.37	0.0117
XHC2-1	14.4926	80.24	19.76	0.0024
XHC2-2	15.3458	46.37	53.63	0.0501
XHC2-3	13.4558	80.34	19.66	0.0102
XWC1-1	14.3445	74.55	25.45	0.0049
XWC1-2	13.3186	69.68	30.32	0.0060
XWC1-3	13.3330	65.98	34.02	0.0542

According to the research conducted by Yao Yanbin et al., the T_2 relaxation curve in NMR has a certain corresponding relationship with the porosity components of micropores and fine pores (<100 nm), mesopores and macropores (>100 nm), and microcracks (aperture $>1 \mu\text{m}$) [67]. When the T_2 value is less than 10 ms, the porosity distribution is primarily contributed by micropores and fine pores, typically represented as the first peak

of the curve (P1); when the T2 value ranges from 10 ms to 100 ms, the porosity distribution is primarily contributed by mesopores and macropores, which is the second peak of the curve (P2); when the T2 value exceeds 100 ms, the porosity distribution is primarily contributed by microcracks in the coal, which is the third peak of the curve (P3).

In summary, the T2 relaxation curve of NMR often exhibits three peaks at 0.1~1 ms, around 10 ms, and around 100 ms as critical points. When the three peaks are smooth and consecutive without significant fluctuations, it indicates that pores and microcracks across different pore sizes in the coal are well developed and connected, providing efficient channels for diffusion and migration of methane within the coal matrix. Conversely, significant fluctuations or even separation between the three peaks suggests uneven distribution of pores in different pore sizes, and the pores and microcracks are not connected, which cannot provide abundant channels for methane diffusion and migration, thus limiting the production of CBM.

As shown in Figure 3, the NMR T2 spectrum of coal samples from the study area can be classified into three distinct distribution patterns. Treating the dual pores–fractures system in coal seams as a tubular bundle model, the surface relaxation time is approximately equal to the T2, and the surface relaxivity is taken as an empirical value of 10 $\mu\text{m/s}$. The information of different pore sizes in the sample can be obtained by calculation, thus obtaining the pore-crack radius distribution diagrams corresponding to the three distinct distribution patterns. The analysis of these three curve types is as follows:

- (1) Type I: The T2 relaxation curve displays a bimodal structure, with a gradual decrease in porosity contribution rate over the relaxation time. There is a significant weakening of the NMR signal and a large spacing between the two peaks, but P2 and P3 are continuous (Figure 3a). Overall, this type of coal reservoir is dominated by micropores and fine pores, forming excellent adsorption spaces; it also possesses a few seepage conditions. The porosity is relatively high, but the permeability is low. In general, the coal reservoir exhibits good adsorption performance but average physical properties.
- (2) Type II: The T2 relaxation curve also exhibits a bimodal structure but gradually approaching zero after displaying two peaks, P1 and P2, without a peak corresponding to P3 (Figure 3b). Based on this analysis, the pore structure in this type is primarily composed of micropores and fine pores, with the presence of some mesopores and macropores. The microcrack system is scarcely developed, resulting in low permeability and limiting the production of CBM. Overall, the physical properties of this type of coal reservoir are poor.
- (3) Type III: The T2 relaxation curve exhibits a trimodal structure, with three continuous peaks, P1, P2, and P3 (Figure 3c). This suggests that the distribution of pores and endogenous fractures across different pore sizes is continuous, indicating relatively good physical properties of this type of coal reservoir.

Therefore, based on the physical properties of coal reservoirs, it can be inferred that Type III coal samples have the best porosity and permeability conditions while Type II has the worst. The order of porosity and permeability conditions is Type III > Type I > Type II. Among them, Type I dominates over all samples (83.33%), while Type II and Type III samples together account for 16.67%. Based on the NMR experimental results, the coal reservoirs of the Xishanyao Formation are primarily composed of micropores and fine pores, which possess a high capacity for methane adsorption but offer limited pathways for methane migration.

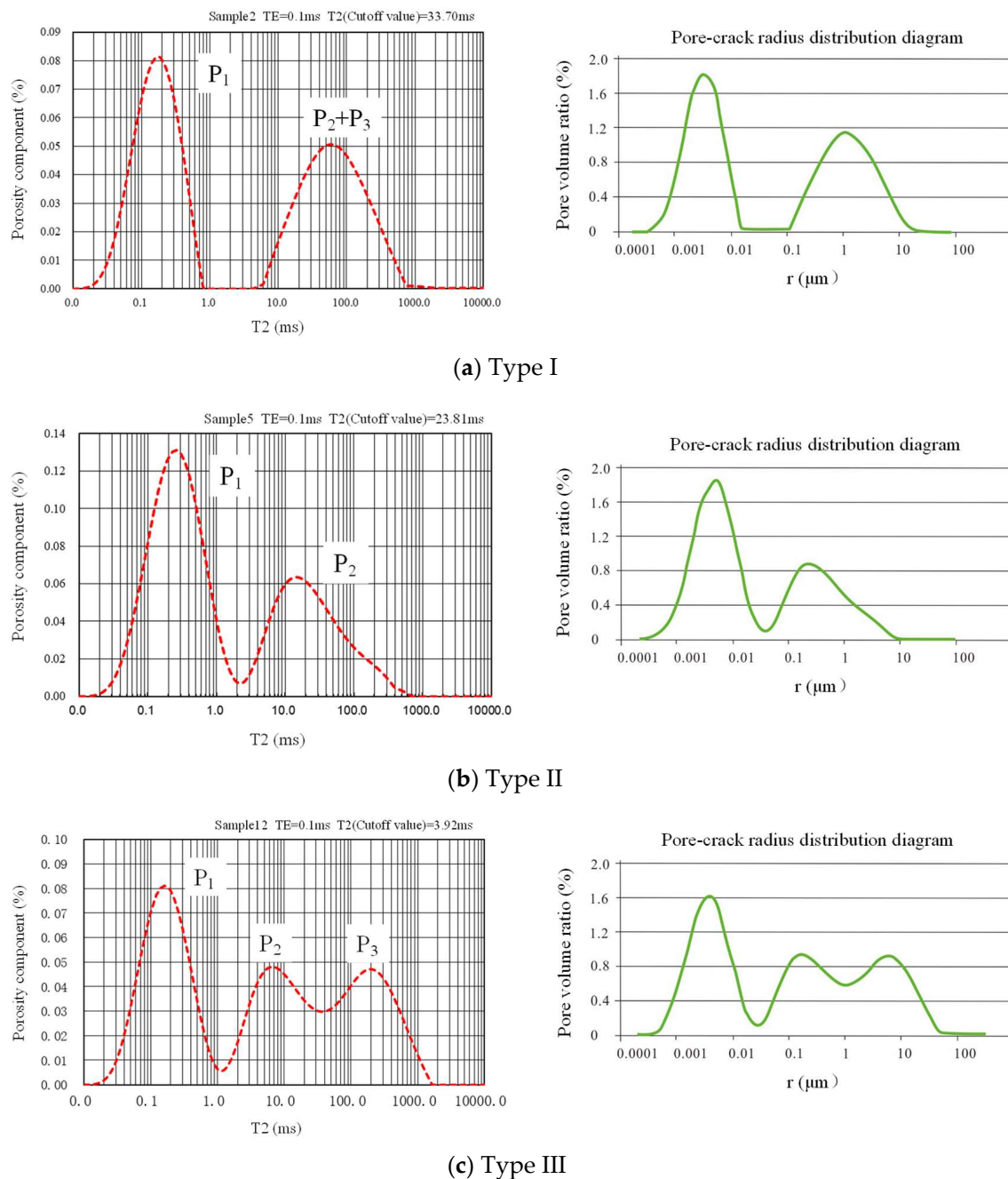


Figure 3. Coal sample T2 curve characteristics of NMR in the study area.

4.2. Pore Characteristics by Low-Temperature Liquid Nitrogen

There were 19 coal samples from the Xishanyao Formation used in this experiment: six from Urumqi, six from Hutubi, and seven from Manas. According to the results of the low-temperature liquid nitrogen experiment, the total pore volume of the coal samples ranges from 0.535 to $17.861 \times 10^{-3} \text{ cm}^3/\text{g}$ with an average of $6.318 \times 10^{-3} \text{ cm}^3/\text{g}$, while the BET specific surface area ranges from 0.258 to $19.247 \text{ m}^2/\text{g}$ with an average value of $4.445 \text{ m}^2/\text{g}$. The experimental data indicate a relatively high proportion of micropore volume in the Xishanyao Formation coal seams, averaging about 44.17%, followed by fine pores with an average of 39.41%, while the proportion of mesopores is the smallest. In terms of specific areas, the Urumqi area demonstrates an average pore diameter and total pore volume of 4.19 nm and $7.006 \times 10^{-3} \text{ cm}^3/\text{g}$, respectively; for the Hutubi area, these values are measured as 11.18 nm and $4.060 \times 10^{-3} \text{ cm}^3/\text{g}$, respectively; finally, for the

Manas area, these values are measured as 11.87 nm and $5.206 \times 10^{-3} \text{ cm}^3/\text{g}$, respectively. It is evident that the adsorption space conditions in the Urumqi area are superior to the other two areas, with Manas being significantly better than Hutubi.

As shown in Figure 4, by comprehensively comparing and analyzing low-temperature liquid nitrogen adsorption–desorption curves of coal samples, three distinct categories can be identified:

- (1) Type I: The curve resembles a slender bamboo leaf shape; it overlaps at the initial value (0) and maximum value (1) of relative pressure and separates between them (Figure 4a). The desorption curve consistently remains above its corresponding adsorption curve throughout its range but experiences a significant rise at a relative pressure approximately equal to 0.5. The adsorption curve shows a steady upward trend, with increasing acceleration when the relative pressure exceeds 0.8. Average pore size distribution curves associated with Type I reveal the distribution of micropores is significantly higher than that of other size pores.
- (2) Type II: The adsorption and desorption curves exhibit the closest proximity, with a nearly parallel trend, but they do not overlap even at a relative pressure of 1 (Figure 4b). The corresponding pore size distribution curve indicates that apart from micropores, fine pores also account for a significant proportion.
- (3) Type III: There is a significant distance between the adsorption and desorption curves at the initial pressures, but they become increasingly closer as the relative pressure increases and approach overlap when the relative pressure reaches 1 (Figure 4c). The corresponding pore size distribution curve is similar to that of Type I, with a significantly higher number of micropores compared to pores of other sizes.

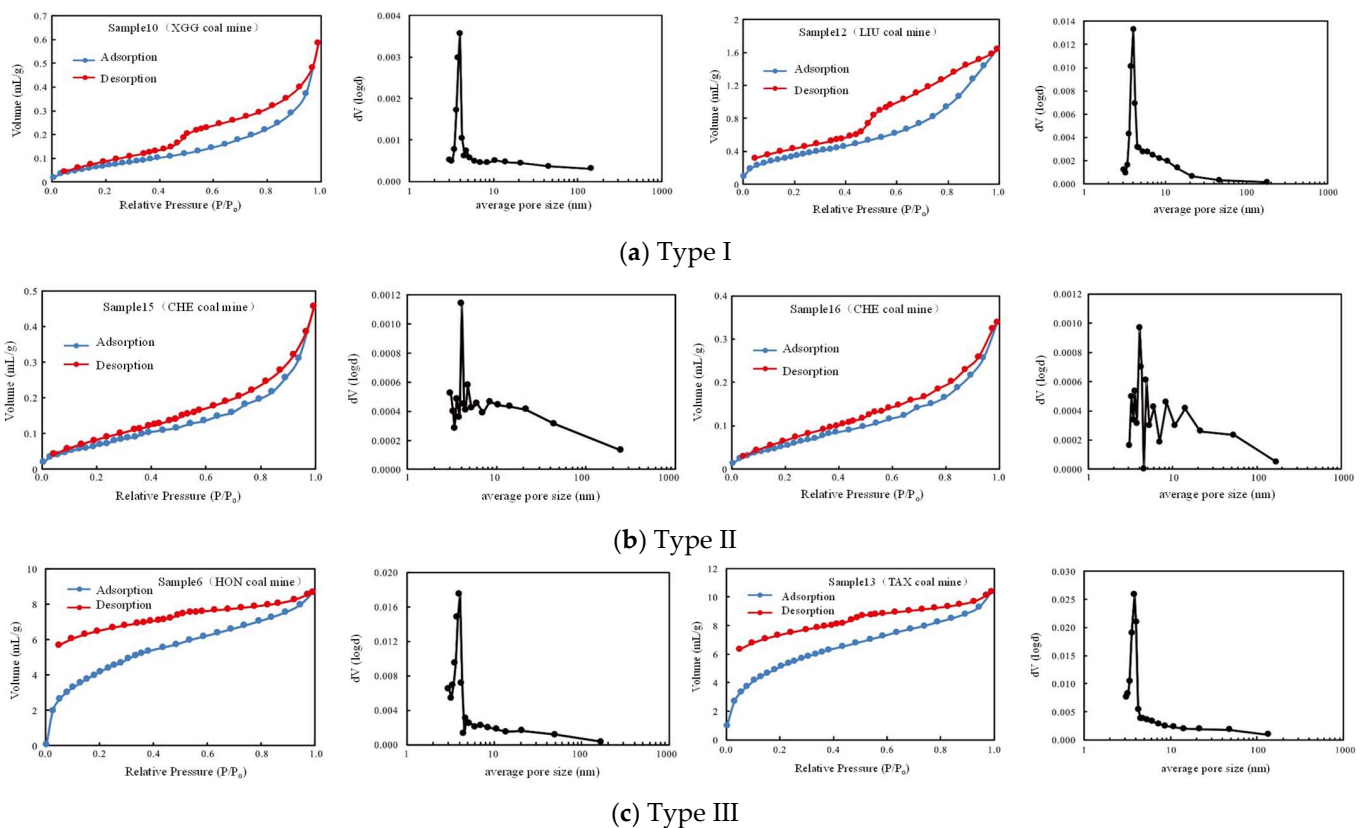


Figure 4. Different types of low-temperature liquid nitrogen adsorption–desorption and pore size distribution curve in the study area.

4.3. Pore Characteristics by MIP

Based on the MIP experiment results, the porosity of the coal samples ranges from 1.49% to 6.71% with an average of 3.87% (Table 4). Overall evaluation suggests good reservoir quality and connectivity for the Xishanyao Formation coal seams. However, permeability data ranges from 0.001 to $1.863 \times 10^{-3} \mu\text{m}^2$ after excluding abnormally high values, indicating noticeable regional variations. Pore volume percentage statistics for different pore sizes reveal that pores in the study area are distributed within the range of 1 to 1000 nm, primarily consisting of micropores and fine pores (<100 nm), followed by mesopores. The average pore volume percentages for micropores–fine pores, mesopores, and macropores are 72.40%, 15.83%, and 11.77%, respectively. Notably, the proportion of micro–fine pores is lower in the Manas–Hutubi area compared to the Urumqi area.

Table 4. Mercury injection data statistics of Xishanyao Formation in the study area.

Sample	Porosity (%)	Permeability ($10^{-3} \mu\text{m}^2$)	Displacement Pressure (MPa)	Mercury Ejection Efficiency (%)	Average Throat Radius (μm)	Average Pore Radius (μm)	Pore Distribution (%)		
							Micro–Fine Pore	Mesopore	Macropore
DAX-1	6.00	0.541	0.025	47.76	5.621	184.981	62.23	17.91	19.86
CHE-2	3.18	8.362	0.018	65.81	10.239	183.945	75.78	15.46	7.57
CHE-3	2.85	0.121	0.105	63.57	4.791	165.269	82.16	10.78	6.35
XGG-1	6.74	0.185	0.050	49.75	5.334	187.163	75.41	9.83	14.76
XGG-2	3.49	0.017	0.020	46.33	4.464	171.084	73.86	18.93	7.21
TAX-1	6.71	1.863	0.025	57.12	5.471	180.421	55.24	27.75	17.01
TAX-2	4.20	0.184	0.021	76.32	5.233	163.788	66.39	24.34	9.27
TAX-3	3.80	0.050	0.021	55.76	5.451	163.561	67.65	23.05	9.30
LIU-2	1.49	0.042	0.066	58.43	6.581	178.870	85.3	9.67	5.47
LIU-3	1.56	0.001	0.353	81.65	2.701	172.677	81.09	11.23	9.02
NAS-1	2.21	0.132	0.059	72.46	4.415	158.612	50.71	27.68	21.61
NAS-2	2.32	0.085	0.090	85.78	5.033	185.663	63.63	13.81	22.56
MMC-2	4.48	0.010	0.141	57.80	4.764	177.563	58.31	9.47	32.22
KUA-1	3.17	0.130	0.261	83.01	5.353	169.862	73.82	10.47	15.71
KUA-2	4.34	1.080	5.503	72.43	5.249	168.201	78.66	14.18	7.16
KUA-3	4.28	0.001	13.655	85.96	5.011	165.566	84.78	8.70	6.52
KUA-4	4.31	0.005	13.532	81.77	5.231	164.450	80.35	11.09	8.57
KUA-5	4.48	0.002	5.485	72.88	5.360	168.668	82.79	10.38	6.82

In this MIP experiment, the displacement pressure of coal samples in the study area ranged from 0.020 to 13.778 MPa. Among these samples, 56% exhibited a displacement pressure of less than 0.1 MPa, 22% had a displacement pressure between 0.1 and 1.0 MPa, and another 22% showed a displacement pressure exceeding 1.0 MPa. Consequently, the overall storage performance of the coal seams in the study area is evaluated as good. As shown in Figure 5, the mercury intrusion curves of coal samples can be broadly classified into two types: Type I curves exhibit a very low displacement pressure and relatively low mercury ejection efficiency, with displacement pressures typically below 0.1 MPa and mercury ejection efficiencies generally not exceeding 70%. On the other hand, Type II curves display higher displacement pressures (>5 MPa) along with greater mercury ejection efficiencies (>70%). Therefore, pore development in Type I coal samples appears more balanced but still predominantly consists of micropores and fine pores, while Type II coal samples are characterized by an absolute dominance of micro–fine pores with a minimal proportion of macropores. Notably, the mercury intrusion curves obtained in this study are primarily of Type I. Since Type I curves indicate a more uniform distribution of pores across different pore sizes, it is inferred that the pore connectivity and permeability of Type I coal samples are superior to those of Type II.

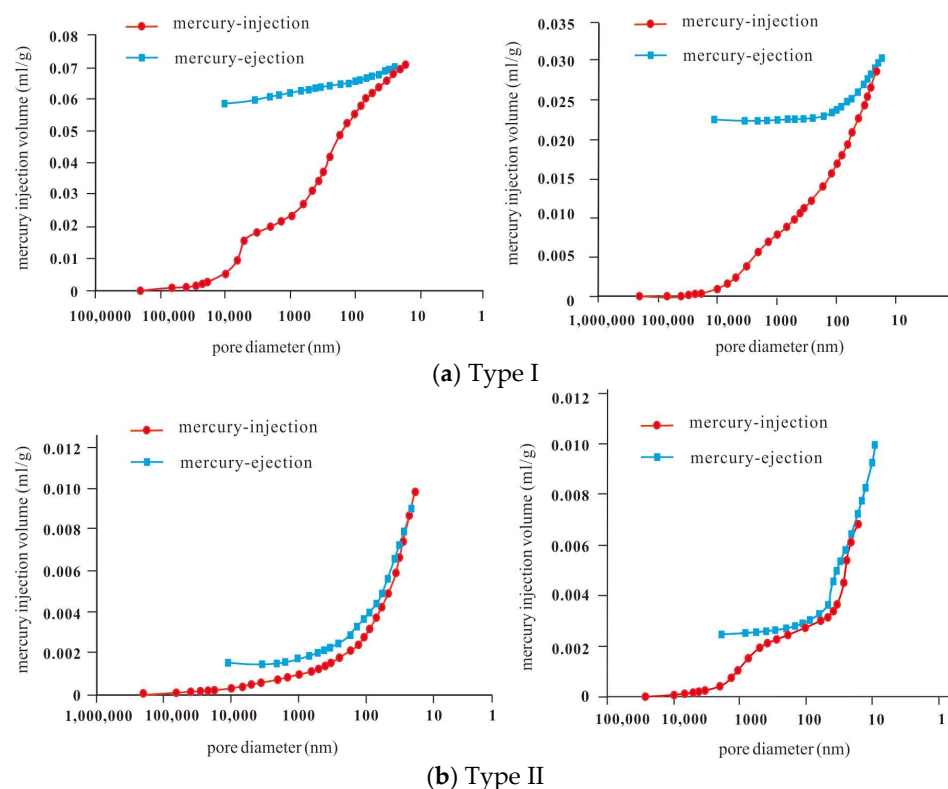


Figure 5. Mercury injection curve of coal samples in the study area.

5. Control Mechanism of Coal Petrology

5.1. Organic Maceral

In the analysis of medium–high-rank coal by previous researchers, it was observed that micropores in the vitrinite component significantly dominate, while both micropores and small pores were present in inertinite with the most abundant pore development, and the pore structure in exinite is the least developed [68,69]. Consequently, it was inferred that inertinite generally possessed higher porosity compared to vitrinite [70–72]. Drawing on these insights and based on mercury intrusion experiments, we analyzed and compared the measured porosity, pore volume percentage of different pore sizes (micropore–fine pore, mesopore, macropore), and coal maceral compositions (Figures 6 and 7).

As shown in Figure 6, the relationship between porosity and Ro is clearly positively correlated in the low-coalification-degree range (Figure 6a). This porosity decreases with increasing vitrinite content, increases with increasing inertinite content, and decreases with increasing exinite content (Figure 6b–d). However, the correlation between porosity and exinite is not obvious, exhibiting considerable scatter in the numerical values. Based on these observations, it can be concluded that the influence of coal organic maceral on the microscopic pore system of coal reservoirs is superimposed on the coal rank. Moreover, the understanding that the pores within vitrinite are primarily micropores, while the pores within inertinite exhibit a uniform distribution across all pore size ranges, holds true not only for high-coalification-degree coal but also for low-coalification-degree coal.

As shown in Figure 7, the increase in coalification degree is observed to result in a decrease in the volume of micro–fine pores and an increase in the volume of meso–macropores (Figure 7a). This indicates that higher coalification degrees correspond to a larger volume of meso–macropores in the coal. Furthermore, an increase in vitrinite and exinite content leads to a higher volume ratio of micro–small pores with diameters less than 100 nm, while reducing the volume ratio of meso–macropores with diameters larger than 100 nm accordingly (Figure 7b,d). Additionally, an increase in the inertinite content favors an elevation in the volume ratio of meso–macropores (Figure 7c). It can be inferred

that an increase in the vitrinite content is conducive to the development of micro-fine pores, whereas an increase in the inertinite content is conducive to the development of meso-macropores.

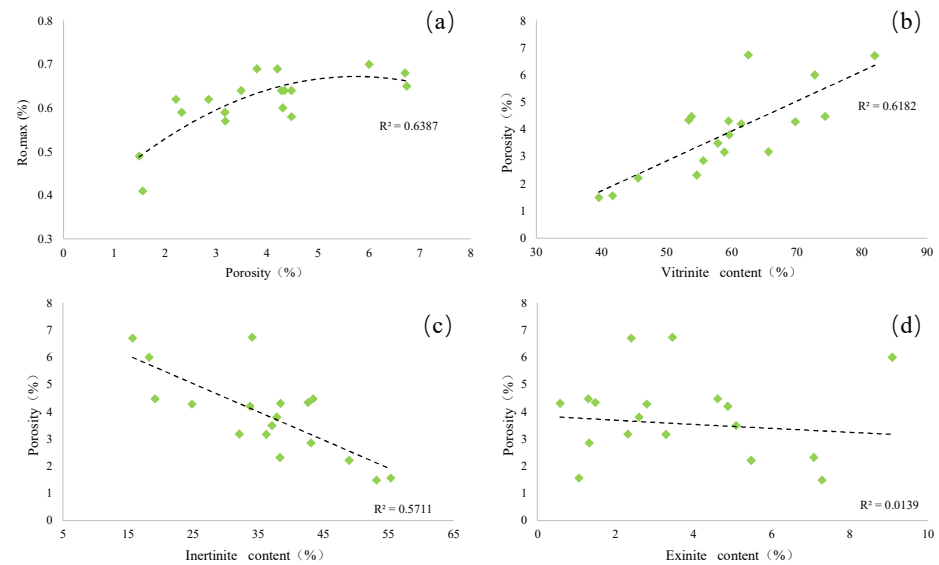


Figure 6. Relation graph of porosity and (a) $R_{o,max}$, (b) vitrinite, (c) inertinite, and (d) exinite.

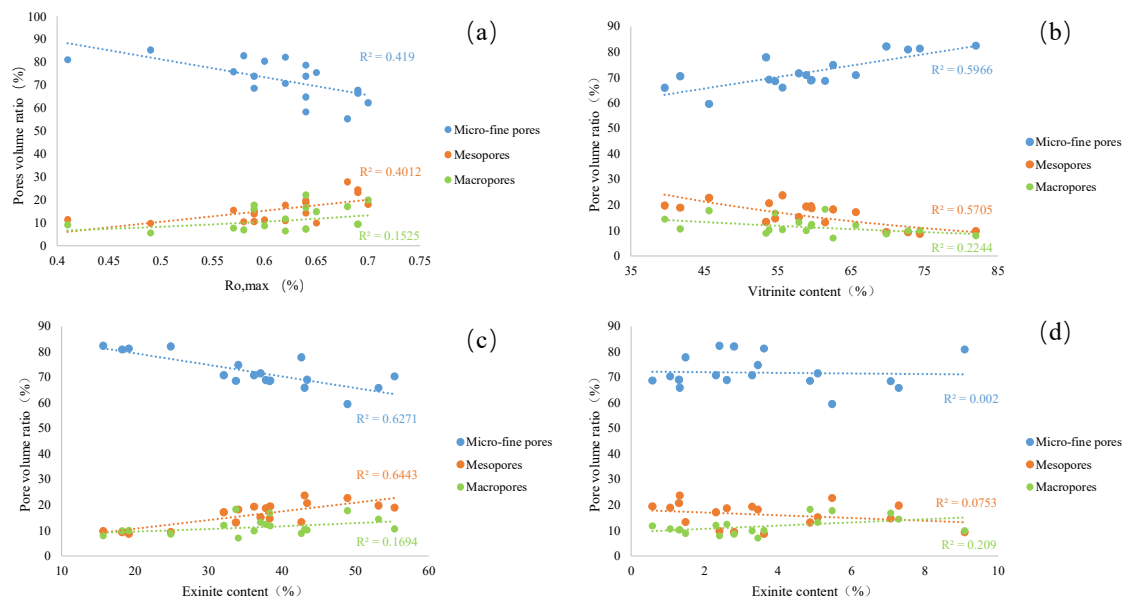


Figure 7. Relation graph of pore characteristics and (a) $R_{o,max}$, (b) vitrinite, (c) inertinite, and (d) exinite.

5.2. Mineral Matter

Generally, coal primarily consists of organic matter with a relatively low content of inorganic minerals; however, the presence of these minerals is closely associated with the pore structure in the coal reservoir [73–75]. The relationship between minerals and pore volume ratio at different pore sizes (micro-fine pores, mesopores, macropores) is shown in Figure 8a, and the relationship between minerals and adsorption pores (<100 nm) and seepage pores (>100 nm) is shown in Figure 8b. It can be observed that there is a generally negative correlation between the mineral content and the volume ratio of adsorption pores, whereas a positive correlation is evident between the mineral content and the volume ratio of seepage pores. This phenomenon may be attributed to the filling of clay minerals,

which is one of the common inorganic minerals in coal, which fills up some of the pores smaller than 100 nm. In addition, other inorganic minerals such as pyrite and carbonate rocks may also fill the pores in coal, further reducing its porosity [76,77]. Consequently, an increase in mineral content leads to a decrease in the pore volume ratio of micro-fine pores along with a relative increase in the pore volume ratio of meso-macropores (>100 nm). Overall, minerals reduce the specific surface area of the coal reservoir, ultimately leading to a reduction in porosity.

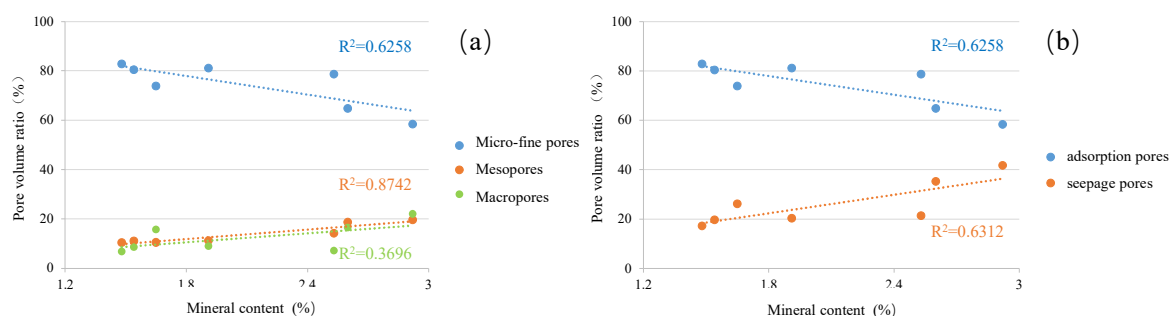


Figure 8. Relation graph of mineral content and the pore volume ratio at different pore sizes. (a) The pores are classified into micro-fine pores, mesopores and macropores. (b) The pores are classified into adsorption pores and seepage pores.

6. Conclusions

- (1) Based on the characteristics of NMR T2 relaxation curves, the NMR T2 spectrum of coal samples can be classified into three distinct types, with the Type I T2 spectrum being the most prominent. The coal reservoirs of the Xishanyao Formation are primarily composed of micropores and fine pores, which possess a high capacity for methane adsorption but offer limited pathways for methane migration, resulting in an overall assessment of good adsorption capacity but low permeability for the coal reservoir.
- (2) Based on low-temperature liquid nitrogen adsorption experiments, it is indicated that the total pore volume of coal samples varies greatly, ranging from 0.535 to $17.861 \times 10^{-3} \text{ cm}^3/\text{g}$ with an average of $6.318 \times 10^{-3} \text{ cm}^3/\text{g}$. Among the pore volumes, micropore volume occupies a relatively high proportion, accounting for an average of 39.41%, followed by fine pores, accounting for an average of 39.41%. According to the low-temperature liquid nitrogen adsorption-desorption curves, the pore structure of coal reservoirs in the study area can be categorized into three distinct types.
- (3) Based on the high-pressure MIP experiments, the porosity in the study area ranges from 1.49% to 6.71%, with an average porosity of 3.87%. The coal seams have good gas storage capacity and connectivity yet display some heterogeneity. The coal reservoirs are dominated by micropores and fine pores throughout the study area. The proportion of micropores in the Manas-Hutubi area is lower than that in the Urumqi area. The displacement pressure of mercury intrusion curves is generally less than 0.1 MPa, indicating a uniform distribution of pores across different pore sizes and excellent gas storage capacity of the coal reservoir.
- (4) Within the range of lower coalification degrees in the study area, porosity increases with the elevation of coalification, accompanied by a gradual increase in the proportion of meso-macropore volumes. Furthermore, an increase in the vitrinite content promotes the development of micro-fine pores, while an increase in inertinite promotes the development of meso-macropores. The mineral content exhibits a negative correlation with the adsorption pore volume ratio and a positive correlation with the seepage pore volume ratio. This may be attributed to the filling of clay minerals or other minerals, which reduces the pore volume ratio of micro-fine pores, overall decreasing the specific surface area of the coal reservoir and ultimately leading to a decrease in porosity.

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