Study on the Applicability of Reservoir Fractal Characterization in Middle−High Rank Coals with NMR: Implications for Pore-Fracture Structure Evolution within the Coalification Process

Haihai Hou,* Qiuhong Qin, Longyi Shao, Guodong Liang, Yue Tang, Huajie Zhang, Qiangqiang Li, and Shujun Liu

ABSTRACT: In order to evaluate the applicability of the pore-fracture structure fractal characterizations in coal reservoirs and confirm the internal relationships between the porosity, permeability, coal metamorphic grade, and pore-fracture structure, the pore-fracture features of 21 middle−high rank coal samples from Anhe, Jiaozuo, and Huaibei coalfields in northern China were investigated using a low-field nuclear magnetic resonance (NMR). All the coal samples are characterized by low moisture content (M<sub>ad</sub>), low and medium ash yield (A<sub>ad</sub>), and high vitrinite (V) in coal maceral. The adsorption space fractal dimension (D<sub>A</sub>) is positively correlated with the Langmuir volume (V<sub>L</sub>) under the three-peak transverse relaxation time (T<sub>2</sub>) spectrum. The fractal dimension of all effective T<sub>2</sub> points under saturated water (D<sub>NMR</sub>) is positively correlated with V<sub>L</sub> and the adsorption pore volume, but negatively correlated with the volume ratio of seepage pores and fractures. The free flow space fractal dimension (D<sub>M</sub>) is negatively correlated with the porosity of full saturated water (Φ<sub>F</sub>) and the porosity of movable water (Φ<sub>M</sub>). There is a negative correlation between Φ<sub>F</sub> and the seepage space fractal dimension (D<sub>S</sub>) in the coal samples with one-peak and two-peak T<sub>2</sub> spectra, but a positive correlation can be found with the three-peak T<sub>2</sub> spectrum. Therefore, it is necessary to consider the types of T<sub>2</sub> spectral peak as a prerequisite to analyze the correlations between pore-fracture parameters and NMR fractal dimensions. With the increase of coal rank, the adsorption pore content, Φ<sub>F</sub>, and bulk volume immovable (BVI) fraction first increase and then decrease, whereas the seepage pore content, fracture development, bulk volume movable (BVM) fraction, and BVM/BVI first decrease and then increase. The inflection points of these changes correspond to the maximum vitrinite reflectance (R<sub>0,max</sub>) at 2.6−2.8%, which would be attributed to the third coalification jump. Generally, D<sub>A</sub> is the fractal dimension representing the coal pore surface, and D<sub>S</sub> and D<sub>M</sub> are closely related to the pore structure. Furthermore, D<sub>NMR</sub> not only represents the roughness of the pore surface but also the complexity of the pore structure.

1. INTRODUCTION

The double pore (pores and fractures) structure in coals is not only an important feature of reservoir structure, but also closely related with the coalbed methane (CBM) storage and migration. The quantitative characterization of the pore-fracture system is of great significance to CBM exploration and development. The experimental methods for characterizing the pore-fracture structure of coals mainly include the following categories: (1) carbon dioxide (CO<sub>2</sub>) adsorption: it can
effectively detect the micropores and ultra-micropores smaller than 2 nm; (2) low temperature nitrogen (N₂) adsorption: it can detect the distribution and fractal characteristics of adsorption pores (pore size ≤100 nm) in coals; and (3) mercury intrusion porosimetry: it can be used to characterize the distribution and fractal characteristics of pores (3.5 nm < pore size < 10 000 nm) by the relationship between mercury injection pressure and pore size combined with classic geometry models. The above three experiments belong to fluid intrusion detection methods, which can partially destroy the coal structures. In addition, the range of pore size in coals detected by each experiment is different; therefore, the pore structure and fractal characteristics of coals cannot be fully and accurately determined. In general, traditional methods have limitations in characterizing the primariness and integrity of pore-fracture, but nuclear magnetic resonance (NMR) with its speediness and non-destructive inspection can effectively resolve these shortcomings.

The low-field NMR can provide useful information about the pore-fracture structure, porosity, and permeability parameters of coals, which has the advantages of rapidity, accuracy, and high resolution in the analysis of the physical properties of coal.
view of these advantages, this method is widely used to study the pore/fracture size, shape, and porosity of coals.12–14 Coals with different coal ranks are characterized by various pore structures, which can be expressed in different NMR spectra.15,16 Thus, it is a basis for analyzing the influence of the metamorphic grade of coal on pore-fracture structure based on NMR. The adsorption space fractal dimension ($D_A$), seepage space fractal dimension ($D_S$), fractal dimension of all effective transverse relaxation time ($T_2$) points under saturated water ($D_{NMR}$), and the free flow space fractal dimension ($D_M$) are calculated through the relationship between the NMR $T_2$ spectra and the corresponding amplitude components.4,17,18 Due to the comprehensive influences of the bulk volume movable (BVM) and the bulk volume immovable (BVI), the permeability in coals is positively correlated with BVM/BVI in seepage pores, but negatively correlated with BVM/BVI in adsorption pores.14 With the increase of $D_A$, the adsorption capacity of coals is enhanced.4 $D_S$ and $D_M$ decrease with increasing distribution areas of $T_2 > 2.5$ ms and the sorting coefficient.4

Previous studies have shown that the fractal characterizations of pore-fracture based on NMR can effectively reflect the heterogeneity of coal reservoirs and quantitatively characterize the adsorption and seepage capacity of coals.4,17,18 However, there are few studies on the applicability evaluation of the pore-fracture structure fractal characterizations using low-field NMR experiments. In this study, the middle–high rank coal samples were selected in typical coal mines and the different pore-fracture fractal dimensions were calculated based on NMR. Besides, the variations of pore-fracture structure parameters and coal material composition were emphatically analyzed with the increase of coal rank, which can further explain the influence of the coalification jump on pore-fracture structure from a micro perspective.

## 2. GEOLOGICAL SETTINGS

The three areas concerned in this study cover the Anhe, Jiaozuo, and Huabei coalfields in northern China (Figure 1). The Carboniferous and Permian coal-bearing strata in these areas are the object horizons. Anhe and Jiaozuo coalfields are situated in the northwestern Henan province, which structurally belong to the Taihang tectonic subregion in southern North China plate. Among them, the no. 21 coal seam in the Permian Shansi Formation is widely developed, which is the main horizon of coal and CBM exploration. The lithology of Shansi Formation is mainly composed of gray/dark-gray mudstone and sandy mudstone, coal, and carbonaceous mudstone (Figure 1). The sedimentary environment was changed from deltaic plain in Anhe coalfield to tidal-flat in Jiaozuo coalfield.20,21 The metamorphic degree of no. 21 coal seam in Shansi Formation is transited from middle–high metamorphic coals (average $R_{max} = 1.96\%$) in Anhe coalfield to high metamorphic coals (average $R_{max} = 2.88\%$) in Jiaozuo coalfield.20 The Huabei coalfield is located in northern Anhui province, and its coal-bearing stratum mainly includes the Permian Shansi Formation and Lower Shizhezi Formation. Among them, the thickness of Shansi Formation ranges from 96 to 143 m, with the lithology of gray/gray-white medium sandstone and siltstone, gray-black mudstone, and coal seams (nos. 10 and 11). The thickness of Lower Shizhezi Formation is between 115 and 135 m. The lithology is mainly light-grey medium sandstone, gray siltstone, dark gray sandy mudstone and mudstone, and coal seams (nos. 6, 7, 8, and 9).22 Tidal flat-lagoon is the dominant sedimentary environment for Shansi Formation and Lower Shizhezi Formation in Huabei coalfield.23
3. SAMPLING AND RESEARCH METHODS

3.1. Coal Sampling. According to the distribution of coal mines and CBM wells, a total of 21 coal samples were collected from the underground working faces and CBM wells in Anhe, Jiaozuo, and Huaibei coalfields (Table 1). Among them, 6 samples were obtained from Anhe Coalfield, 11 from Jiaozuo coalfield, and 4 from Huaibei coalfield. The samples of Anhe and Jiaozuo coalfields were taken from no. 2 coal seam in the Permian Shanxi Formation. Besides, the samples of Huaibei coalfield were taken from no. 8 coal seam in the Permian Low Shihezi Formation. All the coal samples were well packed prior to performing a series of experiments.

3.2. Research Methods. In order to better characterize the physical properties of middle–high rank coals in detail, the research methods and experiments in this paper consist of the macroscopic description of coals, proximate analysis, vitrinite reflectance measurement, coal maceral observation, methane (CH$_4$) isothermal adsorption, NMR testing, and fractal theories of pore-fracture.  

3.2.1. Macroscopic Description ofCoal Samples. The macroscopic description of coal samples is carried out according to the China National Standard GB/T 18023-2000. Based on this standard, the coal samples can be classified into four types including bright, semi-bright, semi-dull, and dull coals, with the bright composition at a proportion of >80, 50–80, 20–50, and <20%, respectively. The classification and determination of macroscopic description should be performed on the fresh and vertical section of coal seam, coal core, or coal specimen. First, the coal sample is divided into different layers according to the overall gloss intensity and then the contents of bright composition are estimated layer by layer to finally determine the macroscopic type of coal sample.

3.2.2. Proximate Analysis, Vitrinite Reflectance Measurement, and Coal Maceral Observation. The proximate analysis of coal samples is carried out according to China National Standard GB/T 30732-2014, and the parameters are obtained from this testing including the moisture content (M$_w$), ash yield (A$_ad$), volatile matter (V$_ad$), and fixed carbon content (FC$_ad$). M$_w$ and A$_ad$ can be acquired using the methods of air seasoning and rapid ashing, respectively. The proximate analysis not only can understand the coal quality characteristics but also is the basis for evaluating the pore structure. According to the relevant results of proximate analysis, the properties, types, processing effects, and the industrial utilization of coals can be preliminarily evaluated. The vitrinite reflectance measurement and maceral analysis (500 points) are performed based on China National Standards GB/T 6948-1998 and GB/T 8899-1998 under oil immersion in reflected light using a Leitz MPV-3 photometer-based microscope. The volumes of vitrinite (V), inertinite (I), and exinite (E) in coal samples can be obtained.

3.2.3. Methane Isothermal Adsorption. Each coal sample (90–120 g) was crushed and sieved to gain a particle size ranging from 0.18 to 0.25 mm (60–80 mesh). After the moisture equilibrium of each coal sample was treated, the methane isothermal adsorption can be carried out based on China National Standard GB/T 19560-2008. The Langmuir volume (V$_l$) and Langmuir pressure (P$_l$) in equilibrium water condition can be determined by an IS-100 high pressure isothermal adsorption apparatus at 30°C at a maximum equilibrium pressure of 10 MPa.

3.2.4. Nuclear Magnetic Resonance. NMR measurements were performed by using a MesoMR23-60H-I medium size NMR analyzer following the Industrial Standard of SY/T 6490-2007. Several parameters were set with a resonance frequency of 23.406 MHz, magnet strength of 0.5 T, coil diameter of 25 mm, magnet temperature of 32 ± 0.02°C, waiting time (TW) of 1500 ms, scanning numbers of 64, and echo spacing (NECH) of 3000. First, the samples were vacuumed for 5 h and injected with distilled water. Then, they were filled with water for 24 h under a pressure of 10 Pa. Moreover, all the samples were subjected to low-field NMR experiments with 100% water saturation to obtain the T$_2$ spectrum. Next, they were put into the centrifuge at a speed of 8000 rpm to make sure that the weights of samples were no longer reduced. All the coal samples were subjected to low-field NMR experiments again to obtain the T$_2$ spectrum under bound water. Both the coal porosity and permeability were measured using the NMR geometric mean T$_2$ and producible porosity models, respectively.

3.3. Fractal Theory of Pore-Fracture with NMR. $D_A$, $D_o$, $D_{NMR}$, and $D_M$ are calculated by NMR results. Among them, $D_M$ and $D_{NMR}$ are the fractal dimensions under saturated water, and $D_M$ is the fractal dimension of pore-fracture space fluid under the combination condition of saturated water and bound water.

4. RESULTS

4.1. Coal Petrology and Proximate Analysis. The results of macroscopic description, vitrinite reflectance, proximate analysis, and maceral observation of coal samples are shown in Table 1. Among the 21 coal samples, most of them are semi-bright and semi-dull coals, with only a small amount of bright coals. The ranges of V, I, and E contents of the coal samples are 62.06–98.22% (84.62% on average), 1.78–37.94% (12.82% on average), and 0–9.14% (2.37% on average), respectively (Table 1). Therefore, the macerals of middle–high rank coals in this study region are dominated by V, followed by I, and the contents of E are the lowest. $R_{o,max}$ of the coal samples ranges from 1.08 to 3.32%, with an average of 2.36%. Among them, $R_{o,max}$ of Jiaozuo coalfield is between 2.45 and 3.32% (2.88% on average), with that of Anhe coalfield ranging from 1.27 to 2.32% (1.96% on average), and that of Huaibei coalfield ranging from 1.08 to 2.12% (1.53% on average), indicating that Jiaozuo coalfield...
belongs to high metamorphic anthracite, and Anhe and Huaibei coalfields belong to middle−high metamorphic coals.

Mad of all the samples is in the range from 0.54 to 3.69% with an average value of 1.54% (Table 1), which suggests that all the samples belong to low moisture coals. Among them, the ranges of Mad in Jiaozuo, Anhe, and Huaibei coalfields are 1.06−3.69% (1.75% on average), 0.84−2.88% (1.71% on average), and 0.54−0.99% (0.69% on average), respectively. The moisture content in coals has an increasing trend with the rise of metamorphic grade (Figure 2a) and R_{max} corresponding to the lowest moisture content is 1.08% (Wugou coal mine). At this point, the dehydration process has been completed, and the content of structural water in coals increases gradually with the increase of coal rank.28 It should be noted that a jump change is

![Figure 2](http://pubs.acs.org/journal/acsodf)

Figure 2. Variation characteristics of Mad, Ad, Vd, and FCd with coal rank of coal samples in Anhe, Jiaozuo, and Huaibei coalfields. (a) Mad vs. R_{max}. (b) Ad vs. R_{max}. (c) Vd vs. R_{max}. (d) FCd vs. R_{max}.

Table 2. Parameters of NMR Experiments and Methane Isothermal Adsorption of Coal Samples in Anhe, Jiaozuo, and Huaibei Coalfields

| sample no. | types of T2 spectral peaks | porosity of full saturated water (%) | permeability (mD) | T2 cutoff value (ms) | BVI (%) | BVM (%) | BVM/BVI | porosity of movable water (%) | V_L (mL/g) | P_L (MPa) |
|------------|-----------------------------|-------------------------------------|------------------|---------------------|---------|---------|---------|-------------------------------|-----------|-----------|
| 2403-2     | two-peak                    | 6.94                                | 0.0882           | 2.6                 | 91.02   | 8.98    | 0.09866  | 0.625                         |           |           |
| 2403-4     | two-peak                    | 5.73                                | 0.0047           | 2.91                | 96.77   | 3.23    | 0.033378 | 0.156                         |           |           |
| 4001-1     | two-peak                    | 5.95                                | 0.1321           | 2.12                | 85.89   | 14.11   | 0.16428  | 0.594                         |           |           |
| 11601-1    | two-peak                    | 8.96                                | 0.3925           | 3.35                | 88.9    | 11.1    | 0.124659 | 1.11                          |           |           |
| 11601-2    | two-peak                    | 7.53                                | 0.2582           | 2.02                | 87.46   | 12.54   | 0.14338  | 1.03                          |           |           |
| 7601-2     | two-peak                    | 5.51                                | 0.2               | 1.42                | 80.9    | 19.1    | 0.236094 | 1.01                          |           |           |
| 7601-3     | two-peak                    | 5.63                                | 0.037            | 1.65                | 91.2    | 8.8     | 0.096491 | 0.68                          |           |           |
| 7601-6     | two-peak                    | 5.33                                | 0.053            | 1.46                | 88.56   | 11.44   | 0.129178 | 0.82                          |           |           |
| 7601-9     | two-peak                    | 7.48                                | 0.21             | 2.12                | 88.42   | 11.58   | 0.130966 | 1.27                          |           |           |
| ZG-1       | one-peak                    | 6.89                                | 0.0024           | 3.04                | 98.36   | 1.64    | 0.016673 | 0.15                          | 32.12     | 32.12     |
| ZG-2       | one-peak                    | 8.68                                | 0.17             | 3.27                | 91.98   | 8.02    | 0.087193 | 1.01                          | 33.87     | 3.5       |
| LS         | one-peak                    | 5.69                                | 0.032            | 1.44                | 91.83   | 8.17    | 0.088969 | 0.67                          |           |           |
| DZ         | three-peak                  | 3.3                                 | 0.0038           | 0.99                | 91.66   | 8.34    | 0.090988 | 0.23                          |           |           |
| ZJ         | three-peak                  | 1.01                                | 0.025            | 7.71                | 28.55   | 71.45   | 2.502627 | 0.73                          |           |           |
| AL         | three-peak                  | 4.35                                | 0.19             | 0.97                | 73.26   | 26.74   | 0.365001 | 1.14                          | 25.75     | 2.22      |
| HB-9       | three-peak                  | 2.67                                | 0.034            | 0.52                | 70.83   | 29.17   | 0.411831 | 0.83                          | 21.59     | 1.95      |
| HB-6       | three-peak                  | 3.2                                 | 0.68             | 0.33                | 43.67   | 56.33   | 1.289902 | 1.92                          | 22.6      | 1.94      |
| GB         | three-peak                  | 2.04                                | 0.49             | 0.32                | 27.14   | 72.86   | 2.684598 | 1.49                          | 14.52     | 2.9       |
| HZ         | three-peak                  | 0.63                                | 0.13             | 0.4                 | 6.46    | 93.54   | 14.47988 | 0.59                          | 17.65     | 3.43      |
| WG         | three-peak                  | 2.23                                | 8.31             | 0.31                | 9.73    | 90.27   | 9.277492 | 2.02                          |           |           |
| YZ         | two-peak                    | 1.08                                | 0.00005          | 0.65                | 91.2    | 8.8     | 0.096491 | 0.11                          | 25.03     | 2.6       |

\(^{a/}\) no data.
found at 2.6−2.8% of $R_{o,max}$ (Figure 2a), which might be attributed to the third coalification transition. Previous studies show that when $R_{o,max}$ is less than 1.1%, the coals are mainly filled with free water, and the moisture content decreases with increasing coal rank. When $R_{o,max}$ is greater than 1.1%, the coals are mainly filled with structural water, and the moisture content increases gradually with the augment of coal rank. Therefore, the changes of moisture content in coals are closely related to coal rank.

$A_{ad}$ of all the samples under air-dried basis is between 5.76 and 15.13% with an average of 10.22% (Table 1), indicating that all the samples belong to low-medium ash coals. Specifically, the ranges of $A_{ad}$ in Jiaozuo, Anhe, and Huaibei coals are 6.43−14.49% (9.16% on average), 6.34−15.13% (11.66% on average), and 5.76−14.40% (10.97% on average), respectively. The ash in coals mainly comes from the terrigenous clastic filling and groundwater circulation in peat swamps, which has little relationship with the metamorphic grade of coals (Figure 2b).

$V_{ad}$ of all the samples varies from 5.28 to 28.78%, with an average value of 10.75% (Table 1). Among them, the ranges of $V_{ad}$ in Jiaozuo, Anhe, and Huaibei coals are 5.28−8.02% (6.14% on average), 6.45−21.33% (13.25% on average), and 8.18−28.78% (19.65% on average), respectively. $V_{ad}$ is closely related to the metamorphic degree of coals, which shows a negative correlation between them (Figure 2c). $F_{Ca}$ of all the samples is within a range from 56.87 to 86.75%, with an average of 77.50% (Table 1). Among them, the ranges of $F_{Ca}$ in Jiaozuo, Anhe, and Huaibei coals are 75.69−86.75% (82.94% on average), 65.68−80.39% (73.39% on average), and 56.87−80.94% (68.69% on average), respectively. $F_{Ca}$ can reflect the metamorphic degree of coals to a certain extent, so it has a good linear positive correlation with $R_{o,max}$ (Figure 2d).

4.2. Isothermal Adsorption Experiment of Methane.

Based on the methane isothermal adsorption experiment, both $V_L$ and $P_L$ of the eight coal samples were measured (Table 2). The eight samples were collected from no. 1 of Zhaogu coal mine (ZG-1), no. 2 of Zhaogu coal mine (ZG-2), Anlin coal mine (AL), no. 9 of Hebi coal mine (HB-9), no. 6 of Hebi coal mine (HB-6), Gubei coal mine (GB), Haizi coal mine (HZ), and Yuanzhuang coal mine (YZ). The physical meaning of $V_L$ is the maximum volume of methane in coals. The experimental results show that $V_L$ ranges from 14.52 to 33.87 mL/g, with an average of 21.33% (13.25% on average), and 8.18−28.78% (19.65% on average), respectively. $V_L$ is closely related to the metamorphic degree of coals, which shows a negative correlation between them (Figure 2c). $F_{Ca}$ of all the samples is within a range from 56.87 to 86.75%, with an average of 77.50% (Table 1). Among them, the ranges of $F_{Ca}$ in Jiaozuo, Anhe, and Huaibei coals are 75.69−86.75% (82.94% on average), 65.68−80.39% (73.39% on average), and 56.87−80.94% (68.69% on average), respectively. $F_{Ca}$ can reflect the metamorphic degree of coals to a certain extent, so it has a good linear positive correlation with $R_{o,max}$ (Figure 2d).

Figure 3. Correlations of $V_L$, $P_L$, and coal rank of coal samples in Anhe, Jiaozuo, and Huaibei coalfields. (a) $V_L$ vs. $R_{o,max}$ (b) $P_L$ vs. $R_{o,max}$.

Figure 4. Types of NMR $T_2$ spectra in Anhe, Jiaozuo, and Huaibei coals (a, one-peak; b, two-peak; and c,d, three-peak).
of 24.14 mL/g. $P_L$ is between 1.94 and 3.5 MPa with an average of 2.71 MPa. In addition, the methane adsorption capacity of ZG-2 in Jiaozuo coalfield is the strongest with $V_1$ of 33.87 mL/g, whereas that of GB in Huaibei coalfield is the weakest with $V_1$ of 14.52 mL/g.

It is found that $V_L$ increases with increasing $R_{\text{r, max}}$ values, and the correlation coefficient ($R^2$) is 0.9486 (Figure 3a), which suggests that the coal rank has a dominant control on the adsorption capacity. Previous investigations show that large pores gradually decrease, whereas small pores and micropores gradually increase with the increase of coal rank. Plenty of small pores and micropores provide more adsorption spaces for methane adsorption, thus enhancing the adsorption capacity of coal. Large micropores and small pores provide more adsorption spaces for methane adsorption, thus enhancing the adsorption capacity of coal. Large micropores and small pores provide more adsorption spaces for methane adsorption, thus enhancing the adsorption capacity of coal.

### 4.3. Parameter Analysis of NMR Experiment

There are three types of NMR $T_2$ spectra of the coal samples under saturated water including one-peak, two-peak, and three-peak (Figure 4), which mainly represent the adsorption pores, adsorption and seepage pores, whole pores and fractures, respectively. Specifically, the peak of NMR $T_2$ spectrum of the adsorption pores (micropores and small pores) is located at 0.5−2.5 ms, the seepage pores (medium-large pores) at 2.5−50 ms, and the fractures at >100 ms.10

Taking the Wugou coal sample as an example (Figure 4d), it can be said that: (1) the three spectrum peaks of this sample reflect three pore-fracture types, respectively, among which the spectrum peak of medium-large pores is higher and wider, indicating that the medium-large pores are the most developed; (2) the spectrum peak of the micropores and small pores is lower, and the change of spectrum form is the smallest after centrifugation, showing that the micropores and small pores are moderately developed with poor connectivity; (3) most of the spectrum peak of the medium-large pores disappear after centrifugation, suggesting that the medium-large pores have a better connectivity; (4) the spectrum peak of the fractures basically disappears after centrifugation, illustrating that the connectivity of fractures is the best; and (5) before centrifugation, the $T_2$ spectra of the micropores, small pores, and medium-large pores, as well as medium-large pores and fractures are continuous, indicating that there are certain connectivities among them.

Several parameters including the porosity of full saturated water ($\Phi_{M}$), permeability, BVI, BVM, and porosity of movable water ($\Phi_{W}$) in coal samples were measured by NMR experiments (Table 2). $\Phi_{M}$ of Jiaozuo, Anhe, and Huaibei coals ranges from 5.33 to 8.96% (6.78% on average), from 1.01 to 5.69% (3.37% on average), and from 0.63 to 2.23% (1.50% on average), respectively. The coal porosities in the three coalfields are quite different, among which Jiaozuo coals are the highest, whereas Huaibei coals are the lowest. The permeabilities of the Jiaozuo, Anhe, and Huaibei coals are from 0.0024 to 0.3925 mD (0.14 mD on average), from 0.0038 to 0.68 mD (0.16 mD on average), and from 0.0005 to 8.31 mD (2.23 mD on average), respectively. BVI of all samples is in the range from 6.46 to 98.36% with an average value of 72.56%, and the range of BVM is 1.64−93.54% with an average value of 27.44%. $\Phi_{W}$ of all the samples is within a range from 0.11 to 2.02% (0.87% on average) with the greatest value in the Huaibei coals, followed by the Anhe and Jiaozuo coals.

### 4.4. Fractal Dimensions of Pore-Fracture Based on NMR Experiments

The pore-fracture fractal dimensions including $D_A$, $D_M$, $D_{\text{NMR}}$, and $D_M$ can be obtained by the results of NMR experiments and the previous calculation formulas (Table 3). $D_A$ values of the Jiaozuo, Anhe, and Huaibei coals range from −0.1047 to 1.3686 (0.7169 on average), from 0.1811 to 1.2893 (1.1456 on average), and from 0.1712 to 2.8288 (1.50% on average). $D_M$ values of the Jiaozuo, Anhe, and Huaibei coals range from −0.1047 to 1.3686 (0.7169 on average), from 0.1811 to 1.2893 (1.1456 on average), and from 0.1712 to 2.8288 (1.50% on average) respectively.
samples. Bound water layer existing in the pore-fracture space of coal which would be related to the proportion of free water layer and complex surface and morphology usually corresponding to high morphological characteristics of pore fracture in coals, with the rougher the surface of coal particles is and the stronger the adsorption capacity of coals is;4,32 and (3) it is necessary to consider different types of $T_2$ spectrum when analyzing the relationship between $D_A$ and $V_L$.

Compared with seepage pores, the proportion and specific surface area of adsorption pores are more closely related to the methane adsorption capacity. Specifically, $V_L$ is positively correlated with the volume proportion of adsorption pores (Figure 6b). The contents of micropores and small pores gradually increase with increasing volume proportion of adsorption pores, providing more adsorption spaces for methane, which enhances the adsorption capacity and $V_L$ values of coals. In addition, the larger the volume proportion of adsorption pores is, the more uneven the pore distribution is, resulting in a more complex pore structure and larger $D_{NMR}$. Therefore, the coals with complex pore structure usually have high adsorption capacity of methane, which is beneficial to the adsorption of CBM but not conducive to desorption and the seepage of CBM. If the NMR experiment was performed with filling $CH_4$ in coals, the significant swelling amount could result in the changes of coal porosity and permeability, which significantly determines the pore surface area and pore size distribution.34

5.2. Influences of NMR Fractal Dimensions on Porosity and Permeability. $D_A$ has some internal relationships with $\Phi_6$ of the coal samples (Figure 7a), but it is worth noting that the trends between $D_3$ and $\Phi_6$ are different with different $T_2$ spectral peaks. Specifically, $D_3$ is negatively correlated with $\Phi_6$ of the coals under one-peak and two-peak $T_2$ spectra; however, $D_3$ is positively correlated with $\Phi_6$ under the three-peak $T_2$ spectrum. This indicates that $D_A$ can reflect the pore structure characteristics of coals, and it is necessary to take the $T_2$ spectral peak type as a prerequisite for the analysis of pore-fracture through $D_A$ (Figure 7a). When the $T_2$ spectra are one-peak or two-peak, the changes of porosity are mainly controlled by the volume proportions of various pores due to less-developed fractures and poor pore connectivity. Thus, the more complex the pore structure is, the lower the porosity is, which is consistent with the previous research results. When the $T_2$ spectrum is three-peak, the rougher the surface of coal particles is and the stronger the adsorption capacity of coals is;4,32 and (3) it is necessary to consider different types of $T_2$ spectrum when analyzing the relationship between $D_A$ and $V_L$. Compared with seepage pores, the proportion and specific surface area of adsorption pores are more closely related to the methane adsorption capacity. Specifically, $V_L$ is positively correlated with the volume proportion of adsorption pores (Figure 6b). The contents of micropores and small pores gradually increase with increasing volume proportion of adsorption pores, providing more adsorption spaces for methane, which enhances the adsorption capacity and $V_L$ values of coals. In addition, the larger the volume proportion of adsorption pores is, the more uneven the pore distribution is, resulting in a more complex pore structure and larger $D_{NMR}$. Therefore, the coals with complex pore structure usually have high adsorption capacity of methane, which is beneficial to the adsorption of CBM but not conducive to desorption and the seepage of CBM. If the NMR experiment was performed with filling $CH_4$ in coals, the significant swelling amount could result in the changes of coal porosity and permeability, which significantly determines the pore surface area and pore size distribution.34

5.2. Influences of NMR Fractal Dimensions on Porosity and Permeability. $D_A$ has some internal relationships with $\Phi_6$ of the coal samples (Figure 7a), but it is worth noting that the trends between $D_3$ and $\Phi_6$ are different with different $T_2$ spectral peaks. Specifically, $D_3$ is negatively correlated with $\Phi_6$ of the coals under one-peak and two-peak $T_2$ spectra; however, $D_3$ is positively correlated with $\Phi_6$ under the three-peak $T_2$ spectrum. This indicates that $D_A$ can reflect the pore structure characteristics of coals, and it is necessary to take the $T_2$ spectral peak type as a prerequisite for the analysis of pore-fracture through $D_A$ (Figure 7a). When the $T_2$ spectra are one-peak or two-peak, the changes of porosity are mainly controlled by the volume proportions of various pores due to less-developed fractures and poor pore connectivity. Thus, the more complex the pore structure is, the lower the porosity is, which is consistent with the previous research results. When the $T_2$ spectrum is three-peak,
the changes of porosity might be related to the complexity of pore shape as the pore connectivity is good and the volume proportion of each pore section is relatively balance-distributed. Besides, when the $T_2$ spectra are one-peak and two-peak, the porosity of coals is greatly influenced by the various pore volume proportions and connectivities. When the $T_2$ spectrum is three-peak, the morphological complexity of pores might play a major role in controlling the porosity of coals.

In order to analyze the physical meaning represented by $D_M$, the internal relationships between $D_M$ and $\Phi_F$, $\Phi_M$ of coals are analyzed (Figure 7b,c). The results show that $D_M$ is inversely proportional to $\Phi_F$ when $D_M$ is divided into two parts by 2.675 (Figure 7b), which means that the negative correlation would be

**Figure 7.** Relationships between NMR fractal dimensions and porosity/permeability parameters (a, b—$\Phi_F$ vs. $D_S$, $D_M$; c—$\Phi_M$ vs. $D_M$; and d—permeability vs. $\Phi_M$) of coal samples in Anhe, Jiaozuo, and Huaihei coalfields.

**Figure 8.** Relationships between $D_{NMR}$ and the volume proportions of adsorption pores, seepage pores, and fractures in Anhe, Jiaozuo, and Huaihei coalfields. (a) Adsorption pore volume percentage vs. $D_{NMR}$. (b) Seepage pore volume percentage vs. $D_{NMR}$. (c) Fracture volume percentage vs. $D_{NMR}$.
stronger in a certain \( D_M \) range. Besides, \( D_M \) is negatively correlated with \( \Phi_M \) of coal samples (Figure 7c), but this negative correlation would be more obvious if the \( T_2 \) spectra are classified based on different types. Generally, \( D_M \) is negatively correlated with \( \Phi_F \) and \( \Phi_M \), indicating that \( D_M \) represents the fractal dimension of the coal pore structure, which is generally consistent with the results of previous studies.\(^4\) However, the classifications of \( D_M \) and \( T_2 \) spectrum are not considered in previous studies. In this study, when analyzing the porosity and permeability of coals through \( D_M \) it is necessary to refer to the distribution characteristics of the NMR \( T_2 \) spectrum to establish a prediction model applicable to different \( T_2 \) spectrum distributions. This is because the different \( T_2 \) spectra generally determine the volume proportions of various pores and fractures, on which basis the fractal characterizations of the pore-fracture structure will be more statistically significant.

There is an obvious positive correlation between \( \Phi_M \) and permeability (Figure 7d), which suggests that the samples with high porosity also have high permeability. The porosity of coals is composed of the pore space with relatively poor connectivity and the free space volume occupied by the fractures with good connectivity. Although the pore space occupied by coal fractures is limited, it is the main channel of CBM seepage.\(^{28}\) In general, the coals with higher \( \Phi_F \) usually correspond to more proportion of fractures and stronger permeability (Figure 7d). Both \( D_S \) and \( D_M \) are related to the porosity of coals (Figure 7a–c), and the porosity is significantly positively correlated with the permeability (Figure 7d). Therefore, \( D_S \) and \( D_M \) are also related to the permeability,\(^{35,36}\) which indicates that \( D_S \) and \( D_M \) are fractal dimensions characterizing the pore structure of coals.

### 5.3. Relationships between NMR Fractal Dimensions and Pore-Fracture Volume

The volumes of adsorption pores (\( T_2 < 2.5 \text{ ms} \)), seepage pores (2.5 ms \( < T_2 < 50 \text{ ms} \)), and fractures (\( T_2 > 100 \text{ ms} \)) of coals can be calculated based on the NMR \( T_2 \) spectrum distribution under saturated water.\(^7\) The correlation analyses are performed between the volume percentages of adsorption pores, seepage pores, fractures of coal samples, and \( D_{\text{NMR}} \) (Figure 8). The results show that \( D_{\text{NMR}} \) is positively correlated with the volume proportion of adsorption pores (Figure 8a), whereas there are negative relationships between \( D_{\text{NMR}} \) and the volume proportions of seepage pores and fractures (Figure 8b,c). It indicates that the coal samples with high \( D_{\text{NMR}} \) have more adsorption pores and less seepage pores and fractures. Due to larger adsorption pores proportion, coals usually have rougher pore surface and greater specific surface area, which results in a bigger \( D_{\text{NMR}} \) (Figure 8a). The coals with great volume proportions of seepage pores and fractures have good pore connectivity and high permeability, which corresponds to a simple pore structure and a small \( D_{\text{NMR}} \) (Figure 8b,c). Therefore, \( D_{\text{NMR}} \) can not only reflect the roughness of coal pore surface but also represent the complexity of coal pore structure to some extent. Generally, the coals with high \( D_{\text{NMR}} \) usually have a rough pore surface and can adsorb more methane. However, the complex pore structure with poor porosity and permeability is not conducive to desorption and the seepage of methane.\(^{33}\)

### 5.4. Pore-Fracture Structure Evolution with the Coalification Process

#### 5.4.1. Variation Characteristics of Different Pore-Fractures in Coals with Coal Rank

The relationships between coal rank and volume proportions of adsorption pores, seepage pores, and fractures are shown in Figure 9. The results indicate that with the increase of \( R_{o,max} \), the volume proportion of adsorption pores in coals increases first and then decreases (Figure 9a). Meanwhile, the volume proportions of seepage pores and fractures rapidly decrease first and then increase slowly (Figure 9b,c). It should be noted that the inflection points of these changes correspond to \( R_{o,max} \) at 2.6–2.8%, which would be closely related with the coalification jump. Almost all the oxygen-containing functional groups fall off and the aromatic
rings gradually add with orderly molecular arrangement in coals between the second and third coalification jumps.\textsuperscript{28}

In this process, the volume proportion of adsorption pores is predominant in the pore system, whereas the content of seepage pores gradually reduces, which leads to a worse pore connectivity and a decrease of fracture development. As the augmenter of adsorption pores is higher than the decrease of seepage pores and fractures,\textsuperscript{28} the porosity increases continually with increasing coal rank (1.1% < $R_{\text{o,max}}$ < 2.8%) before the inflection point (Figure 10a). Although the volume of seepage pores and fractures increase after this inflection point, the augmenter is less than the decrement of adsorption pores, which results in a slow decline with the increase of coal rank (Figure 10a).

5.4.2. Variation Characteristics of NMR Parameters with Coal Rank. The variation characteristics of $\Phi_F$, $T_2$ cutoff value, BVI, BVM, BVM/BVI, and $\Phi_M$ of coal samples with coal rank in Anhe, Jiaozuo, and Huaiabei coals (the red dot in Figure 10b is the outlier). (a) $\Phi_F$ vs. $R_{\text{o,max}}$ (b) $T_2$ cutoff value vs. $R_{\text{o,max}}$ (c) BVI vs. $R_{\text{o,max}}$ (d) BVM vs. $R_{\text{o,max}}$ (e) BVM/BVI vs. $R_{\text{o,max}}$ (f) $\Phi_M$ vs. $R_{\text{o,max}}$.

The porosity increases continually with increasing coal rank (1.1% < $R_{\text{o,max}}$ < 2.8%) before the inflection point (Figure 10a). Although the volume of seepage pores and fractures increase after this inflection point, the augmenter is less than the decrement of adsorption pores, which results in a slow decline with the increase of coal rank (Figure 10a). The variation of coal porosity is essentially controlled by the distributions of adsorption pores, seepage pores, and fracture volume (Figure 9). The $T_2$ cutoff value is the boundary value between BVM and BVI. It is generally considered that the fluid larger than the $T_2$ cutoff value on the $T_2$ spectrum is BVM, whereas the fluid smaller than the $T_2$ cutoff value is BVI.\textsuperscript{28} With the increase of coal rank, the $T_2$ cutoff value increases continuously, and the maximum value can reach 3.35 ms (Figure 10b). It is worth noting that there is an abnormal point (ZJ in Anhe coalfield) with the porosity component of adsorption pores after centrifugation higher than that before centrifugation (Figure 4c), which would be caused by the experimental settings. Due to the complexity of the pore-fracture structure, the $T_2$ cutoff value cannot directly reflect the levels of porosity and permeability.\textsuperscript{12,28} In general, the coals with a higher $T_2$ cutoff value mean that they have more bound fluids (Figure 10b,c). With the augment of coal rank, the bound fluid content increases rapidly first and then reduces slowly (Figure 10c), whereas the movable fluid content decreases rapidly first and then adds slowly (Figure 10d). The changes of bound fluid in

![Figure 10](https://doi.org/10.1021/acsomega.1c03904)

ACS Omega 2021, 6, 32495−32507

32505
coals are consistent with the variation of adsorption pore content (Figure 9a). Because the bound water is mainly stored in the adsorption pores, when $R_{o,max}$ is less than 2.8%, the content of adsorption pores and the bound fluid add with the increase of $R_{o,max}$. When $R_{o,max}$ is greater than 2.8%, the content of adsorption pores reaches the maximum and then decreases slightly (Figure 9a), and so does the content of bound fluid (Figure 10c).

With the increase of coal rank, BVM first reduces and then adds slightly, but the variation trend of BVI is opposite (Figure 10c,d). It is accepted that the movable water is mainly stored in the seepage pores. When $R_{o,max}$ is less than 2.8%, the content of seepage pores decreases with the increase of $R_{o,max}$ (Figure 9b), and the content of movable water reduces at the same time (Figure 10d). When $R_{o,max}$ is greater than 2.8%, the content of seepage pores increases slightly after reaching the minimum value (Figure 10e). Therefore, in the medium metamorphic grade (1.1% $< R_{o,max} < 1.5%$), high connectivity, permeability, and BVM/BVI due to the relatively developed endogenous fractures. In this study, BVM/BVI decreases with the increase of coal rank, which is consistent with the changes of BVM/BVI (Figure 10f). However, the correlation coefficient of $\Phi_M$ with $R_{o,max}$ is low, which would be related to the variation characteristics of $\Phi_M$ under different NMR $T_2$ spectra (Figure 10f).

6. CONCLUSIONS

(1) $D_3$ is the fractal dimension representing the coal pore surface, and $D_{M}$, $D_{V}$ are the fractal dimensions reflecting the pore structure. $D_{NMR}$ can not only reflect the roughness of pore surface but also characterize the complexity of pore structure of coals.

(2) $\Phi_F$ and $\Phi_{Fp}$ are negatively correlated with $D_{M}$, but it is necessary to consider the $T_2$ spectral peak types as a precondition. Under the condition of one-peak and two-peak $T_2$ spectra, there is a negative correlation between $\Phi_F$ and $D_3$, whereas under the condition of three-peak $T_2$ spectrum, $\Phi_F$ is positively correlated with $D_3$.

(3) With the increase of coal rank, the adsorption pore content, $\Phi_{Fp}$, and BVI first increase and then decrease, whereas the seepage pore content, the fracture development, BVM, and BVM/BVI first reduce and then increase. The inflection points of these changes correspond to $R_{o,max}$ at 2.6–2.8%. In addition, the moisture content also shows a jump change with $R_{o,max}$ at 2.6–2.8%, which might be related to the third coalification jump.

# AUTHOR INFORMATION

Corresponding Author

Haihai Hou — Liaoning Technical University, Fuxin 123000, China; orcid.org/0000-0002-9891-979X; Email: houmenshiai@163.com

# ACKNOWLEDGMENTS

This research paper was supported by the China Postdoctoral Science Foundation (2021M693844), the China Geological Survey Scientific Research Project (1212011220794), the discipline innovation team of Liaoning Technical University (LNTU20TD-05; LNTU20TD-14; LNTU20TD-30), the Guiding Program of Liaoning Natural Science Funds (2019-ZD-0046), and the Scientific Research Funding Project of Liaoning Education Department (LJ2019JL004).

# REFERENCES

(1) Moore, T. A. Coalbed methane: a review. Int. J. Coal Geol. 2012, 101, 36–81.

(2) Hou, H.; Shao, L.; Li, Y.; Li, Z.; Wang, S.; Zhang, W.; Wang, X. Influence of coal petrology on methane adsorption capacity of the Middle Jurassic coal in the Yuqiu Coalfield, northern Qaidam Basin, China. J. Petrol. Sci. Eng. 2017, 149, 218–227.

(3) Li, Y.; Tang, D.; Elsworth, D.; Xu, H. Characterization of coalbed methane reservoirs at multiple length scales: a cross-section from southeastern Ordos Basin, China. Energy Fuels 2014, 28, 5587–5595.

(4) Zhou, S.; Liu, D.; Cai, Y.; Yao, Y. Fractal characterization of pore-fracture in low-rank coals using a low-field NMR relaxation method. Fuel 2016, 181, 218–226.

(5) Hou, H.; Shao, L.; Tang, Y.; Zhao, S.; Yuan, Y.; Li, Y.; Mu, G.; Zhou, Y.; Liang, G.; Zhang, J. Quantitative characterization of low-rank coal reservoirs in the southern Junggar Basin, NW China: implications for pore structure evolution around the first coalification jump. Mar. Petrol. Geol. 2020, 113, 104165.
(6) Hou, H.; Liang, G.; Shao, L.; Tang, Y.; Mu, G. Coalbed methane enrichment model of low-rank coals in multi-coals superimposed regions: a case study in the middle section of southern Junggar Basin. Front. Earth Sci. 2021, 15, 256−271.

(7) Spitzer, Z. Mercury porosimetry and its application to the analysis of coal pore structure. Powder Technol. 1981, 29, 177−186.

(8) Suuberg, E.; Deevi, S. C.; Yun, Y. Elastic behaviour of coals studied by mercury porosimetry. Fuel 1995, 74, 1522−1530.

(9) Yao, Y.; Liu, D.; Che, Y.; Tang, D.; Tang, S.; Huang, W. Petrophysical characterization of coals by low-field nuclear magnetic resonance (NMR). Fuel 2010, 89, 1371−1380.

(10) Yao, Y.; Liu, D.; Cai, Y.; Li, J. Advanced characterization of pores and fractures in coals by nuclear magnetic resonance and X-ray computed tomography. Sci. China Earth Sci. 2010, 53, 854−862.

(11) Sun, X. X.; Yao, Y. B.; Liu, D. M.; Elsworth, D.; Fan, Z. J. Interactions and exchange of CO2 and H2O in coals: an investigation by low-field NMR relaxation. Sci. Rep. 2016, 6, 1−9.

(12) Kenyon, W. E. Nuclear magnetic resonance as a petrophysical measurement. Nucl. Geophys. 1992, 6, 153−171.

(13) Hayashi, J.-i.; Norinaga, K.; Kudo, N.; Chiba, T. Estimation of size and shape of pores in moist coal utilizing sorbed water as a molecular probe. Energy Fuels 2001, 15, 903−909.

(14) Ouyang, Z. Q. The characteristics of pore-fractures in middle-high rank coals in Shanxi and its influences on permeability. Master Dissertation, China University of Geosciences, Beijing, 2017.

(15) Xiong, W. H. NMR imaging and changes in pore structure of coal reservoirs of CO2-ECBM process simulation. Master Dissertation, China University of Mining and Technology, Xuzhou, 2018.

(16) Li, S.; Tang, D.; Pan, Z.; Xu, H.; Huang, W. Characterization of the stress sensitivity of pores for different rank coals by nuclear magnetic resonance. Fuel 2013, 111, 746−754.

(17) Ouyang, Z.; Liu, D.; Cai, Y.; Yao, Y. Fractal analysis on heterogeneity of pore-fractures in middle-high rank coals with NMR. Energy Fuels 2016, 30, 5449−5458.

(18) Chen, S.; Tang, D.; Tao, S.; Ji, X.; Xu, H. Fractal analysis of the dynamic variation in pore-fracture systems under the action of stress using a low-field NMR relaxation method: an experimental study of coals from western Guizhou in China. J. Petrol. Sci. Eng. 2019, 173, 617−629.

(19) Cai, Y.; Liu, D.; Yao, Y.; Li, J.; Liu, J. Fractal characteristics of coal pores based on classic geometry and thermodynamics models. Acta Geol. Sin. 2011, 85, 1150−1162.

(20) Hou, H.; Shao, L.; Guo, S.; Li, Z.; Zhang, Z.; Yao, M.; Zhao, S.; Yan, C. Evaluation and genetic analysis of coal structures in deep Jiaozuo Coalfield, northern China: investigation by geophysical logging data. Fuel 2017, 209, 552−566.

(21) Li, Y.; Shao, L.; Fielding, C. R.; Wang, D.; Mu, G.; Luo, H. Sequence stratigraphic analysis of thick coal seams in paralic environments - a case study from the Early Permian Shanxi Formation in the Anhe coalfield, Henan Province, North China. Int. J. Coal Geol. 2020, 222, 103451.

(22) Wang, Y. J.; Pan, J. X.; Liu, X. W. Study on comprehensive evaluation of low permeability sandstone reservoirs of coal-derived gas in Huabei Coalfield. Coal Sci. Technol. 2019, 47, 187−192.

(23) Shao, L.; Xiao, Z.; Lu, J.; He, Z.; Wang, H.; Zhang, P. Carboniferous coal measures in the Qinshui basin: Lithofacies paleogeography and its control on coal accumulation. Front. Earth Sci. 2007, 1, 106−115.

(24) Li, Z. X.; Wei, J. C.; Yu, J. F.; Liu, Y.; Liu, H. Y.; Lyu, D. W. Coal geology. Geological Publishing House: Beijing, 2009; pp 1−301.

(25) Hou, H. H.; Shao, L. Y.; Tang, Y.; Li, Y. N.; Liang, G. D.; Xin, Y. L.; Zhang, J. Q. Coal seam correlation in terrestrial basins by sequence stratigraphy and its implications for palaeoclimate and palaeoenvironment evolution. J. Earth Sci. 2020, 1−25, DOI: 10.1007/s12583-020-1069-4.

(26) Yuan, W.; Pan, Z.; Li, X.; Yang, Y.; Zhao, C.; Connell, L. D.; Li, S.; He, J. Experimental study and modelling of methane adsorption and diffusion in shale. Fuel 2014, 117, 509−519.

(27) Li, S.; Tang, D.; Xu, H.; Yang, Z. Advanced characterization of physical properties of coals with different coal structures by nuclear magnetic resonance and X-ray computed tomography. Comput. Geosci. 2012, 48, 220−227.

(28) Yao, Y. B.; Liu, D. M. Advanced quantitative characterization and comprehensive evaluation model of coalbed methane reservoirs; Geological Publishing House: Beijing, 2013; pp 1−175.

(29) Hou, H.; Shao, L.; Li, Y.; Liu, L.; Liang, G.; Zhang, W.; Wang, X.; Wang, W. Effect of paleoclimate and paleoenvironment on organic matter accumulation in lacustrine shale: Constraints from lithofacies and element geochemistry in the northern Qaidam Basin, NW China. J. Petrol. Sci. Eng. 2022, 208, 109350.

(30) Ramia, M. E.; Martin, C. A. Sedimentary rock porosity studied by electromagnetic techniques: nuclear magnetic resonance and dielectric permittivity. Appl. Phys. A 2015, 118, 769−777.

(31) Zhang, Q.; Yang, X. L. Isothermal adsorption of coals on methane under equilibrium moisture. J. China Coal Soc. 1999, 24, 566−570.

(32) Yao, Y.; Liu, D.; Tang, D.; Tang, S.; Huang, W. Fractal characterization of adsorption-pores of coals from North China: an investigation on CH4 adsorption capacity of coals. Int. J. Coal Geol. 2008, 73, 27−42.

(33) Xu, Y. B.; Zhu, Y. S. Pore structure characteristics of high rank coal and its effect on CBM desorption. Nat. Gas Geosci. 2020, 31, 84−92.

(34) Li, Z.; Yao, J.; Firoozabadi, A. Kerogen swelling in light hydrocarbon gases and liquids and validity of schroeder’s paradox. J. Phys. Chem. C 2021, 125, 8137−8147.

(35) Yao, Y.; Liu, D.; Tang, D.; Tang, S.; Huang, W.; Liu, Z.; Che, Y. Fractal characterization of seepage-pores of coals from China: An investigation on permeability of coals. Comput. Geosci. 2009, 35, 1159−1166.

(36) Weller, A.; Nordsieck, S.; Debschütz, W. Estimating permeability of sandstone samples by nuclear magnetic resonance and spectral-induced polarization. Geophys. 2010, 75, E215−E226.

(37) Tao, S.; Wang, Y. B.; Tang, D. Z.; Xu, H.; He, W.; Li, Y. Pore and fracture systems and their contribution to the permeability of coal reservoirs in southern Qinshui Basin. Geol. J. China Univ. 2012, 18, 522−527.

(38) Xue, X. H.; Ye, J. G. Application of NMR techniques in CBM exploration. Reservoi Eval. Dev. 2013, 3, 72−74.

(39) Cai, Y.; Liu, D.; Pan, Z.; Yao, Y.; Li, J.; Qiu, Y. Pore structure and its impact on CH4 adsorption capacity and flow capability of bituminous and subbituminous coals from Northeast China. Fuel 2013, 103, 258−268.

(40) Chen, Y.; Tang, D. Z.; Tian, L.; Ma, D. M.; Fang, S. Y.; Chen, Q. Coal metamorphism controlling regulation on the development of pores and fractures in low-medium rank coal reservoirs. Nat. Gas Geosci. 2017, 28, 611−621.