Micrometer-scale pores and fractures in coals and the effects of tectonic deformation on permeability based on fractal theory

Zhenni Ye, Enke Hou, and Zhonghui Duan
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Zhenni Ye,1,2,a) Enke Hou,1 and Zhonghui Duan2,3

AFFILIATIONS
1 College of Geology and Environment, Xi’an University of Science and Technology, Xi’an 710054, China
2 Key Laboratory of Coal Resources Exploration and Comprehensive Utilization, Ministry of Land and Resources, Xi’an 710054, China
3 Shaanxi Coal Geology Group Co., Ltd., Xi’an 710026, China

a) Author to whom correspondence should be addressed: 58334686@qq.com

ABSTRACT
Micrometer-scale pore and fracture structures of coal seams are the crucial parameters in the case of enhanced coalbed methane (CBM) recovery as they determine permeability and productivity. A significant study has been made in fracture characteristics; however, the detailed structural and fractal characteristics of micro-fractures and micro-pores of tectonically deformed coals are poorly understood. To get deep insight into the variability and heterogeneity of micro-pores and micro-fractures in different tectonically deformed coals collected from the Guojiahe coal mine, the multifractal analysis using the Menger sponge and box-counting model was employed to study deformed coals based on mercury injection porosimetry and scanning electron microscopy. The results show that tectonic deformation changed the structure of the micro-pores by increasing their diameter and that of the micro-fractures by expanding, intersecting, and creating additional micro-fracture networks at any scale. For the coals investigated in this study, permeability was nonlinearly correlated with their structural fractal. For undeformed coals, with the increase in the fractal dimension of micro-pores, the distribution of coal permeability exhibits a U-shape. However, it exhibited an inverted U-shape as the fractal dimension of micro-fractures increased. The distribution of the permeability of deformed coal samples is characterized by a U-shape as the fractal dimension of micro-fractures increased, while the fractal dimension of micro-pores decreased. Thus, the structural proportional odds of micro-pores and micro-fractures are vital in defining the maximum value of permeability. As a whole, deformed coals have a relatively high permeability as local micro-pores and micro-fractures are well connected. We suggest that coal seams with brittle deformation at syncline, anticline, and folded areas are favorable for CBM exploitation.

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I. INTRODUCTION
The coalbed methane (CBM) generated in coal seams is a clean and valuable energy resource that is widely used in China (Shi et al., 2018). However, the low permeability of coal reservoirs hinders CBM commercial production. The low and variable permeability of coal seams is determined by their complicated dual-structure system composed of many pores and fractures at a wide range of scales. Therefore, comprehensively understanding the micrometer-scale pores and fractures of coals could significantly contribute to CBM recovery.

The internal structures of micro-pores and fractures are determined by many factors, including the coal rank, temperature, pressure, and tectonic stress. Tectonic stress forms tectonically deformed coals (TDCs) as it changes their primary structure and physical and chemical texture, and plays a key role in structural evolution. However, there is still little detailed information regarding the structural characteristics of micro-pores and fractures related to the degree of tectonic deformation.

Coal basins in China have experienced complex tectonic evolution, which has resulted in the generation of various types of tectonically deformed coals (Hou et al., 2012; Li et al., 2014). Jiang et al. classified the deformation environments of TDCs as brittle, ductile, and brittle–ductile (Jiang et al., 2010). Coals can be categorized into four classes based on the deformation...
degree: undeformed, cataclastic, granulated, and mylonitized (Ju et al., 2009).

Many studies have revealed the structural characteristics of micro-pores in TDCs and undeformed coals by conducting liquid nitrogen experiments (LNEs), mercury injection porosimetry (MIP), methane isothermal adsorption experiments (MIAEs), and nuclear magnetic resonance (NMR). Meng et al. demonstrated that the methane adsorption ability of TDC is significantly stronger than that of UC using MIAE (Meng et al., 2016; Zhang et al., 2018; and Cai et al., 2018), while Qu et al. found that the types of micro-pores in coals vary depending on their degree of tectonic deformation (Qu et al., 2017). Ju and Li (2009) indicated that the mechanisms of methane adsorption and desorption in TDC greatly differ from those of undeformed coals due to the changes in the micropore structures (Ju and Li, 2009). Several methods have been followed to study the structural characteristics of microfracture networks, including scanning electron microscopy (SEM) and using the X-ray computed tomography scanning experiment. By conducting SEM and MIE, Zou et al. (2013) indicated that the gas adsorption ability is determined by the mineral substance and microfracture volume. Pan et al. (2015) found that the permeability of TDC differs from that of undeformed coal due to differences in the quantity, width, and length of micro-fractures.

The micro-pores and micro-fractures of coal have complex and inhomogeneous structural properties, rendering it difficult to describe the coal by microscopic observation or the traditional geometric method (Wang et al., 2012). However, after it was initially proposed by Mandelbrot et al. (1983), the fractal analysis theory became a scientific and sophisticated tool that could be used to characterize the physical-geometric properties of coals, such as the structure of its micrometer-scale pores and fractures, and permeability (Pape et al., 2006; Zhang and Weller, 2014; Zhao et al., 2017; Chen et al., 2017; and Zhao and Pan, 2018). The fractal dimension (D) has been applied widely to describe the complexity and irregularities of microscale pores and fractures. Various researchers have used the fractal model to describe the structure of micro-pores. Yin et al. (2017) assessed the structure of coals by a combination of fractal analysis and using NMR data sets and concluded that the volume fractal dimension of micro-pores was correlated with the permeability. Zhou et al. (2017) conducted fractal analysis of pore-fractures by mercury injection and found that the fractal method could be an effective analytical tool for estimating the inhomogeneous permeability of coals. However, few reports have conducted the fractal analysis of micro-pores and fractures and determined their effects on the permeability of different types of deformed coals. In this paper, the detailed characteristics of the micro-pores and fractures in different types of deformed coals collected from Guojiahe Colliery were analyzed through MIE, SEM, and fractal theory. The effects of the degree of deformation on micropore and microfracture properties were identified, and correlations between the fractal features of micrascale pores/fractures and the permeability of TDCs and undeformed coals were revealed.

II. GEOLOGICAL SETTING

Guojiahe Colliery in the Yonglong Mining Area, China, is selected as the study site. The colliery is located in the northern Weibei flexure belt tectonic unit and western Miaobin depression. The regional strata in Guojiahe Colliery include the Tongchuan, Fuxian, Yanan, Zhiluo, Anding, Yijun, Luohe, and Huachi Formations, and Neogene, Middle-Late Pleistocene, and Holocene units in chronological order. The Mid-Jurassic Yanan Formation is the coal-bearing stratum. The main mineable coal seam in this area is No. 3. The thickness of coal seam No. 3 ranges from 0.55 m to 26.83 m, with an average thickness of 11.88 m. The coal is bituminous, with R0 values ranging from 0.527% to 0.585%. The folded strata dip gently to the NW–NNW and strike NE–NEE, and their characteristics are controlled by the paleostructure created by the Indosinian movement (Ye et al., 2019a). The EW-trending Caizigou syncline is located in the north of the area, while the NE-trending Liangting anticline is distributed in the southwestern area. Secondary folds and tensile faults developed on these folds, which caused changes in the coal thickness distribution. The coal seam in the folded and faulted area exhibits weak-brittle deformation as a result of tectonic events. Thus, primary and cataclastic coals are present in Guojiahe Colliery (Ye et al., 2019b).

III. EXPERIMENTS AND MODELING

A. Coal samples and experiments

According to the three-dimensional analysis, 20 folds and 43 normal faults are present in panel I, which resulted in the development of TDCs. Two to three coal samples were collected at one of ten coal sampling locations, and a total of 25 coal samples were selected from the different tectonic parts of panel I. According to the structure-genetic classification system of TDCs proposed by Ju and Li (2009), ten groups of experimental samples were selected and divided into four sets of undeformed coals (G01, G02, G03, and G04) and six sets of cataclastic coals (GF01, GF02, GF03, GF04, GX01, and GX02) in Fig. 1.

Mercury injection porosimetry (MIP) analysis was conducted for ten samples using a YG-97A instrument. The experimental coals weighed approximately 9 g and had a block size of 20–25 mm. Prior to the experiment, ten samples were dried at 105 °C for 8 h. The Washburn equation was used to calculate the pore diameter, assuming that the pores are cylindrical. The contact angle between the mercury and pore surface is 140°, and the surface tension force is 0.48 N/m. The maximum pressure applied to the samples was 50.1 MPa, indicating that a pore diameter smaller than 75 μm can be penetrated by mercury.

Ten samples were dried at 105 °C for 2 h and then underwent SEM analysis using a JSM-7610F plus field emission scanning electron microscope. The samples selected for SEM observation had a block size of 1 mm3 and a relatively flat surface. Samples were fixed to the sample plate using a conductive adhesive, and their surfaces were then sputter-coated with gold-palladium for SEM observation. The SEM instrument offers true 1 000 000 × magnification with a resolution of 0.8 nm at 15 kV (1.0 nm at 1 kV) and unmatched beam stability, allowing the fine surface morphology of the nanostructures to be observed.

B. Fractal model

1. Menger fractal model

The coal with a complicated dual-structure system exhibits heterogeneous characteristics. Fractal theory is typically applied to
study the nonlinear and irregular characteristics of objects, and the fractal dimension is the main tool used to characterize the complexity and irregularities of shapes (Niu et al., 2019; Zhou et al., 2018; Yao et al., 2008; and Ye et al., 2019c). Various fractal models have been used to determine the fractal dimension of coal materials, including the Sierpinski, BET, and Langmuir models. The fractal dimension of a polyporous material can be calculated using the Menger model combined with the Washburn equation (Washburn, 1921),

\[ P = -2\sigma \cos \theta / d, \]

where \( P \) is the mercury intrusion pressure, MPa; \( d \) is the pore radius; \( \sigma \) is the tension of mercury (0.48 J/m\(^2\)); and \( \theta \) is the contact angle (143°).

Equation (1) can be simplified as

\[ P = 0.735 / d. \]

Based on the definition of the Menger model (Friesen and Mikula, 1987), the fractal dimension formula is expressed as

\[ \ln \left( -\frac{dV_p}{dp} \right) = (4 - D) \ln(P) + \ln(\alpha), \]

where \( V_p \) is the corrected pore volume associated with the intrusion pressure, cm\(^3\)/g; \( D \) is the fractal dimension; and \( \alpha \) is a constant ratio,

\[ D = 4 + \left[ \ln \left( -\frac{dV_p}{dp} \right) - \ln(\alpha) \right] / \ln(P). \]

Thus, \( D \) can be calculated through the slope of the \( \ln(-dV_p/dP) \) and the \( \ln(P) \) curve based on Eq. (4).

Micro-pores with different scales in the coal matrix exhibit heterogeneous characteristics. The integrated fractal dimension is a tool to quantitatively characterize the heterogeneity and complexity of micro-pores at any scale. The weighted method is used to obtain the integrated fractal dimension, which can be expressed as

\[ D_p = \sum_{i=1}^{n} D_i T_i, \]

where \( D_p \) is the integrated fractal dimension, \( D_i \) is the fractal dimension of micro-pores with a range of apertures, and \( T_i \) is the pore volume ratio associated with the aperture.

2. Box-counting model

Various approaches have been developed to estimate the fractal dimensions of micro-fractures. Of the various methods, the box-counting method is most widely used as it is simple and exhibits high computability (Fernández-Martínez and Sánchez-Granero, 2016). The microfracture images obtained by SEM are converted to binary images before the box-counting method is used, which consists of partitioning the image space into square boxes of equal sizes \( r_i \) (Fig. 2). The number \( N_i \) of non-empty boxes of size \( r_i \) required to cover the fractal structure depends on \( r_i \),

\[ \frac{N_i+1}{N_i} = \left( \frac{r_i}{r_{i+1}} \right)^D. \]

Hence, the box-counting algorithm counts the number \( N(r) \) for different values of \( r \) and plots the log of \( N(r) \) against the log of \( r \). The fractal dimension \( D_f \) is estimated from the best-fitting curve slope of the Richardson plot,

\[ D_f = -\lim_{r \to 0} \frac{\ln N(r)}{\ln r}. \]
IV. RESULTS AND DISCUSSION

A. Micro-pores and micro-fractures in coal

1. Structural characteristics of micro-pores

There are several types of classes of micro-pores. The B. B. Walkot classification method is widely used for classifying micro-pores, and Lu et al. followed the method to classify such pores as adsorption (diameter < 0.1 μm) or seepage pores (diameter ≥ 0.1 μm) (Lu et al., 2018). However, the classification is not sufficiently detailed as large micro-pores (diameter > 5 μm) play a key role in methane migration through diffusion from micro-pores and micro-fractures (Gamson et al., 1993). Therefore, in this study, the micro-pores are classified into three types: fracture (diameter > 5 μm), seepage (0.1 μm ≤ diameter ≤ 5 μm), and adsorption pores (diameter < 0.1 μm). The characteristic micropore structural parameters were obtained by the MIP analysis. As shown in Table I, the coal samples exhibit a wide range of mercury saturation values, sorting coefficients, and specific surface area ratios. The sorting coefficient exceeded 3 and ranged from 4.0 to 10.8, indicating that all experimental samples exhibit poor sorting. The measured mercury saturation values ranged from 50.56% to 68.64%, with an average of 59.09%, indicating that all coal samples mostly consisted of one-end pores and have relatively low connectivity. The pore connectivity of cataclastic coals is higher than that of undeformed coals as their mercury saturation values are relatively high. The specific surface area ratio of adsorption pores in undeformed and cataclastic coals is 84.02% and 82.43%, respectively, which is larger than that of the other types of pores, indicating that adsorption pores are predominant in coal samples. The characteristic parameters of micro-pores indicate that the tectonic force brittlely deformed the coals by expanding the diameter of micrometer-scale pores and improve their connectivity.

2. Structural parameters of micro-fractures

The structure of micro-fractures in coals plays a significant role in the CBM’s permeability (Sun et al., 2020). Micro-scale images of the structures of undeformed and cataclastic coals were obtained by the SEM experiment. The structural images of select coal samples are shown in Fig. 3. G01 and G02 are undeformed coal samples with a group of clear, regular, and sparse fractures. Cataclastic coals endure

| Table I | Characteristic structural micropore parameters. The letter “F” in the coal sample numbers represents the fault area and X represents the syncline area. Sorting coefficients of <0.35, ranging from 0.84 to 1.4, and >3 represent fine, moderate, and poor sorting, respectively. |
|---|---|---|---|---|---|
| Number | Coal structure | Sorting coefficient | Mercury saturation (%) | Fracture pores | Seepage pores | Adsorption pores |
|---|---|---|---|---|---|---|
| G01 | Undeformed | 4.0 | 50.56 | 1.04 | 24.45 | 74.51 |
| G02 | Undeformed | 7.2 | 63.03 | 0.16 | 16.39 | 83.45 |
| G03 | Undeformed | 6.3 | 52.48 | 0.03 | 2.18 | 97.79 |
| G04 | Undeformed | 7.6 | 68.26 | 0.17 | 19.52 | 80.31 |
| GF01 | Cataclastic | 8.9 | 66.25 | 0.11 | 7.06 | 92.83 |
| GF02 | Cataclastic | 4.7 | 57.42 | 0.17 | 6.26 | 93.57 |
| GF03 | Cataclastic | 5.2 | 68.64 | 0.11 | 10.02 | 89.87 |
| GF04 | Cataclastic | 4.8 | 61.94 | 0.36 | 63.70 | 35.94 |
| GX01 | Cataclastic | 10.8 | 52.06 | 0.01 | 11.44 | 88.55 |
| GX02 | Cataclastic | 4.9 | 50.30 | 0.06 | 6.14 | 93.81 |
weak tectonic stress; thus, their structure preserves part of their primary structure. Samples GX01, GF03, and GF04 exhibit multiple groups of fractures with irregular curves. Thus, tectonic deformation has a significant influence on the structure of micro-fractures.

As the structure of the micro-fractures in the coal samples varies by the degree of deformation, it is important that their characteristics are quantitatively analyzed by identifying their structural parameters. Image Processing software (Image-Pro) can detect the edges and identify the parameters of micro-fractures. This method requires a binary image; therefore, the digital images obtained through the SEM analysis should be preprocessed before use. Image-Pro was used to analyze 10 experimental samples. Parameters, including the length, width, and area, were selected to measure the identified micro-fractures by the image software, which was then automatically followed by checking the spatial calibration. The parameters are measured by the software, as shown in Fig. 4, and the characteristics of the micro-fractures can be expressed as $C_i$ and $S_i$.

The equation for $C_i$ is as follows:

$$C_i = \frac{W_{\text{max}}}{L},$$  \hspace{1cm} (8)

where $W_{\text{max}}$ (mm) is the maximum gap between the micro-fractures in a plane projection, $L$ (mm) is the length of the micro-fractures in a plane projection, and $i$ is the number of micro-fractures.

The equation for $S_i$ is as follows:

$$S_i = 100 \times \sum_{\mu=1}^{u} \frac{a_{\mu}}{A},$$  \hspace{1cm} (9)

where $a$ ($\mu m^2$) is the area of a microfracture, $u$ is the number of micro-fractures, $A$ ($\mu m^2$) is the image area, and $i$ is the number of micro-fractures.

Structural parameters $C_i$ and $S_i$ were calculated according to the equations, and the results are shown in Table II. According to the classification of micro-pores, micro-fractures smaller than 5 $\mu m$ are classed as fracture pores; thus, the microfracture parameters of coal samples G03, G04, and GF01 are not listed in Table II. $C_i$ represents the scale of micro-fractures. For undeformed and cataclastic coal samples, $C_i$ varies from 0.00207 to 0.00888, with an average of 0.00507, and from 0.00531 to 0.03871, with an average of
0.023 31, respectively. The C value of cataclastic coals is larger than that of undeformed samples, indicating that the micro-fractures in cataclastic coals contain large gaps and exhibit poor extension. The Si value of undeformed coals ranges from 0.0992 to 0.1811, with an average of 0.14, while that of cataclastic samples varies from 0.3741 to 1.7149, with an average of 0.7727. The Si value of undeformed and coal samples differed greatly, indicating that the number of micro-fractures and their areas in cataclastic coals are larger than those in undeformed coals. Thus, tectonic deformation significantly contributes to the changes in the structure of micro-fractures as they extend the gap and induce the development of additional micro-fractures. This result was consistent with the findings for high-rank coal samples obtained from different coal mines in China.

### TABLE II. Parameters of the micro-fractures.

| Number | Coal structure | L (µm) | Wmax (µm) | Ci | Si (%) |
|--------|----------------|--------|-----------|----|--------|
| G01    | Undeformed     | 38.63  | 0.08      | 0.00207 | 0.0992 |
| G01    | Undeformed     | 38.64  | 0.34      | 0.0088  | 0.1811 |
| G03    | Undeformed     | 38.58  | 0.16      | 0.00496 | 0.1366 |
| G04    | Undeformed     | 37.89  | 0.20      | 0.00533 | 0.1438 |
| GF01   | Cataclastic    | 23.32  | 0.54      | 0.02325 | 0.747  |
| GF02   | Cataclastic    | 10.01  | 0.26      | 0.02597 | 0.4623 |
| GF03   | Cataclastic    | 8.03   | 0.24      | 0.02989 | 0.8716 |
| GF04   | Cataclastic    | 101.66 | 0.54      | 0.00531 | 0.3741 |
| GX01   |                | 26.33  | 0.44      | 0.01671 | 0.4663 |
| GX02   |                | 21.7   | 0.84      | 0.03871 | 1.7149 |

### B. Fractal dimensions of micro-pores in primary and cataclastic coals

According to fractal theory, the fractal dimension of solid porous media varies from 2 to 3. However, as the coal matrix is compressively deformed when the pressure exceeds 10 MPa, the slope ε of the curve of Vs against the P curve in double logarithmic coordinates may vary from −1 to 0. Although the fractal dimension exceeds 3, according to Eq. (1), it is still an effective method of evaluating the characteristics of micro-pores (Yu et al., 2018). The fractal dimensions of micro-pores were obtained according to Eq. (4) and are presented in Table III. The fractal dimension of fracture (D1), seepage (D2), and adsorption pores (D3) ranged from 2.05 to 2.79, with an average of 2.52, 2.4–3.3, with an average of 2.89 and 2.1–3.5, with an average of 2.84, respectively. Based on Eq. (5), the integrated fractal dimension (Dp) varied from 2.63 to 2.98, with an average of 2.77. Comparing the average fractal dimensions of different types of pores and the average integrated fractal dimension value, it was observed that the average fractal dimension peaked at 2.99 in seepage pores.

The fractal dimension of micro-pores varies with the degree of tectonic deformation due to the changes in their structural characteristics. As shown in Fig. 5, with an increase in the deformation strength, the average values of D1, D2, and D3 increase, while that of D3 decreases. The increasing trend indicates that the tectonic force plays a positive role in the structural complexity of all micro-pores and particularly that of fracture and seepage pores; thus, the irregularity in the structure of micro-pores is dominated by the structure of fracture and seepage pores. For deformed coals, seepage pores exhibit the most complex structure, while the adsorption pores with complex structures have a high fractal dimension in undeformed coals. The complexity of adsorption pores in undeformed coal samples exhibits a large variation range. The variation range decreases

### TABLE III. Fractal dimensions of coal samples. The letter “d” represents the diameter of the micro-pores. D1, D2, and D3 represent the fractal dimension of fracture, seepage, and adsorption pores, respectively. Dp represents the integrated fractal dimension. Finally, T1, T2, and T3 represent the pore volume ratio of fracture, seepage, and adsorption pores, respectively.

| Sample number | Coal structure | D1 (µm) | T1 (%) Average | D2 (µm) | T2 (%) Average | D3 (µm) | T3 (%) Average | Dp | Average |
|---------------|----------------|---------|----------------|---------|----------------|---------|----------------|-----|---------|
| G01           | Undeformed     |          |                |         |                |         |                |     |         |
| G02           | Undeformed     | 2.58    | 44.9           |         | 2.59           | 49.96   |                |     |         |
| G03           | Undeformed     | 2.32    | 29.1           |         | 3.22           | 43.77   |                |     |         |
| G04           | Undeformed     | 2.05    | 14.9           |         | 2.40           | 32.50   |                |     |         |
| G01           | Undeformed     | 2.72    | 24.7           |         | 2.90           | 45.82   |                |     |         |
| G02           | Undeformed     | 2.71    | 32.9           |         | 3.31           | 26.27   |                |     |         |
| G03           | Undeformed     | 2.73    | 31.3           |         | 3.07           | 34.63   |                |     |         |
| G04           | Undeformed     | 2.80    | 33.3           |         | 2.87           | 62.22   |                |     |         |
| G01           | Undeformed     | 2.61    | 8.9            |         | 2.82           | 56.61   |                |     |         |
| G02           | Undeformed     | 2.28    | 21.9           |         | 2.96           | 28.12   |                |     |         |
| Average       |                |          |                |         |                |         |                |     |         |
|               |                | 2.52    |                |         | 2.89           |         |                |     |         |
|               |                | 2.84    |                |         | 2.84           |         |                |     |         |
|               |                | 2.76    |                |         |                |         |                |     |         |
as the tectonic deformation increases, indicating that the tectonic force greatly contributes to the structural heterogeneity of adsorption pores. This trend has also been observed in brittle and ductile deformed coals, such as fragmented and mylonitic coals (Hou et al., 2012; Qu et al., 2017; and Wang et al., 2012).

C. Fractal dimensions of micro-fractures and their corresponding factors

The structure of micro-fractures in the coal seam is complex and heterogeneous. Fractal theory is an effective method of analyzing micro-fractures as it is simple and easily computable (Wang et al., 2012; Fernández-Martínez and Sánchez-Granero, 2016; and Sun et al., 2019). The calculated fractal dimensions of the micro-fractures of the coal samples varied from 1.37 to 1.7. Parameters $C_i$ and $S_i$ are dominant factors affecting the complexity of micro-fractures, and the MATLAB software was used to calculate their relationship. The relationship of $D_f$, $C_i$, and $S_i$ can be expressed by a binary quadratic equation (10):

$$D_f = 1.748 + 0.017 \ln C_i + 0.164 \ln S_i - 0.114 S_i^2. \quad (10)$$

The three-dimensional surface model is shown in Fig. 6. The fractal dimension of the brittlely deformed coal is higher than that of the undeformed coal, and fractures with a wide gap and high area ratio have a relatively high fractal dimension. Thus, tectonic deformation greatly contributes to the structural complexity as brittle deformation extends, intersects, and causes the development of micro-fractures.

D. Correlation between the fractal dimension and permeability

Permeability is an important index for evaluating the productivity of a reservoir as it can indicate the ability of a fluid to flow through porous media (Pan et al., 2010). Micro-pores and micro-fractures in coals significantly contribute to the overall permeability of a coal reservoir (Gamson et al., 1993; Heriawan and Koike, 2015; and Tariq Janjeh et al., 2018). The permeability of the experimental samples was low, ranging from 0.019 76 to 0.020 26 mD, with an average of 0.019 98 mD. The relationship between the permeability and the fractal dimensions, including $D_p$ and $D_f$, of undeformed and brittlely deformed coals is shown in Fig. 7, which indicates that in undeformed coal samples, $D_p$ and $D_f$ are closely correlated with permeability, with correlation coefficients of 0.9 and 0.85, respectively. This demonstrates that the complexity of micro-fractures and micro-pores greatly affects the permeability. The distribution of the permeability of coal samples is characterized by a U-shape as the...
The relationship between the fractal dimension and permeability of micro-pores and micro-fractures: (a) undeformed coal and (b) brittlely deformed coal.

**FIG. 7.** Relationship between the fractal dimension and permeability of micro-pores and micro-fractures: (a) undeformed coal and (b) brittlely deformed coal.

$D_p$ increased and reaches a minimum value of 0.019 841 mD when $D_f$ is 2.81. However, permeability is characterized by an inverted U-shape with increasing $D_f$ and reaches a peak of 0.020 18 mD when $D_f$ is 1.4. The maximum permeability is defined by the complexity of micro-fractures, while the minimum value is determined by the fractal dimension of micro-pores. However, for brittlely deformed samples, the permeability exhibits a U-shape with an increase in $D_p$, reaching a minimum value of 0.019 75 mD when $D_p$ is 1.61, while the permeability reaches its maximum value of 2.69 mD when $D_p$ is 2.69. The distribution of permeability is contrary to that of $D_f$ and $D_p$ in both undeformed and brittlely deformed coals, indicating that permeability is attributed to the proportional odds of the structural characteristics of micro-pores and micro-fractures. The difference in the permeability values between the maximum and minimum values in undeformed coals is greater than that in cataclastic coals, indicating that brittle deformation maintains the reservoir permeability at a relatively stable and high value by connecting the local micro-pores and micro-fractures of coals. Thus, we suggest that tectonic areas, such as faults, syncline, and anticline deposits with brittle deformed coal seams, could be considered as favorable zones for CBM recovery.

**V. CONCLUSION**

(1) The experimental coals are dominated by adsorption pores. Specifically, the pore size of cataclastic coals investigated in the study is bigger than that of undeformed coals. Additionally, the permeability of cataclastic coals is also higher due to the development of micro-fractures and well connectivity. Thus, brittle tectonic force changes the structure of coals by expanding the pore diameter and improving connectivity.

(2) Tectonic deformation has an influence on the heterogeneity of coal sample structure. According to the fractal dimensions of adsorption, seepage, and fracture pores, the structure of seepage pores determines the complexity of the coal structure. The tectonic deformation complicates the coal sample structure by increasing the heterogeneity of fracture pores and seepage pores. Additionally, the complexity of the micro-fracture structure is determined by their width, length, and density. The fractal dimension of micro-fractures in experimental coals can be expressed by a binary equation related to the ratio of width and length and area proportion. The micro-fractures in deformed coals are more complex in structure as brittle deformation extends, intersects, and induces the development of additional micro-fractures.

(3) The structural complexity of micro-pores and micro-fractures in coals leads to permeability. The distribution of the permeability of undeformed coal samples is characterized by a U-shape with an increase in $D_p$ and decrease in $D_f$. However, that of brittlely deformed coals is an inverted U-shape. The proportional odds of the structural characteristics of micro-pores and micro-fractures determine the permeability. Brittle deformation maintains the permeability of a coal reservoir at a relatively high and stable value. Therefore, we suggest that tectonic areas, such as faults, synclines, and anticline deposits with brittle deformed coal seams, could be favorable zones for CBM recovery.

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