Pore characteristics and its heterogeneity of lignite reservoir in the Erlian Basin of Inner Mongolia, China

Pengfei Jiang¹,²,³, Hao Xu¹,²,³, Heng Wu¹,²,³, Fudong Xin¹,²,³, Tiantian Zhao¹,²,³ and Xiangyang Chen¹,²,³

Abstract
The pore characteristics of coal reservoirs play a very important role in the migration of coalbed methane reservoirs, and its heterogeneity has been studied by a large number of scholars. However, there are few studies on lignite reservoirs. In this paper, three sets of lignite reservoirs in the Jiergalangtu depression are taken as the research object. The scanning electron microscope (SEM) images are converted from time-domain signals to frequency-domain signals through Fourier transformation, which quantitatively characterizes the heterogeneity of coal reservoirs. The variance of the value indicates that the three sets of coal seams NO.4Var<NO.5Var<NO.6Var. Through nitrogen adsorption experiment and fractal analysis, the pore continuity, surface roughness, pore structure, pore type and other aspects are studied. The lignite in the study area has high pore surface roughness and complex pore structure. Affected by various geological factors such as material composition, coal-forming environment, degree of evolution and other geological factors, lignite reservoirs in different layers and different mining areas show obvious heterogeneity.

Keywords
SEM, nitrogen adsorption, low-rank coal, reservoir, heterogeneity

¹School of Energy Resources, China University of Geosciences, Beijing, China
²Coal Reservoir Laboratory of National Engineering Research Center of CBM Development & Utilization, China University of Geosciences, Beijing, China
³Beijing Key Laboratory of Unconventional Natural Gas Geological Evaluation and Development Engineering, Beijing, China

Corresponding author:
Hao Xu, School of Energy Resources, China University of Geosciences, Beijing 100083, China.
Email: xuhao600@163.com

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access page (https://us.sagepub.com/en-us/nam/open-access-at-sage).
Introduction

Coalbed methane (CBM) is a kind of clean energy, and its development and utilization not only benefits coal mine safety but also helps reduce greenhouse gas emissions (Bertoli et al., 2013; Montgomery, 1999; Moore, 2012; Singh et al., 2016; Xu et al., 2012). Low CBM resources are abundant, and in recent years it has become a hot spot for China’s coalbed methane exploration and development (Xin et al., 2019). However, the exploration effect of China’s low-rank coal is not satisfactory (Qin, 2018; Xu et al., 2015a; Yang and Han, 1979). Understanding the properties of lignite reservoirs is essential for CBM exploration and development.

Due to the uneven distribution of material composition and pore-fracture, coal reservoirs usually have strong heterogeneity in the vertical direction (Ward, 2002). The pores of coal reservoirs can be divided into seepage pores with a diameter greater than 100 nm and adsorption pores with a diameter of less than 100 nm. The adsorption pores have a large specific surface area, which mainly affects the adsorption, desorption and diffusion of coalbed methane (Tao et al., 2019). It has been shown that the different surface morphologies in the pores are also important factors in determining the methane adsorption capacity (Kumar et al., 2021). Studies have shown that methane adsorption is proportional to porosity (Kumar et al., 2019a; Kumar et al., 2019b).

The characterization of coal pore structure is mainly carried out by two methods: fluid intrusion and imaging description (Li et al., 2012; Liu et al., 2017; Nie et al., 2015). Due to the strong heterogeneity of the reservoir, the resolution and accuracy of coalbed methane reservoirs have been continuously improved. The fluid intrusion method is used for detection in different aperture ranges, such as adsorption of low-temperature nitrogen and carbon dioxide (Emmett, 1948; Xin et al., 2021). Small-angle neutron scattering and small-angle x-ray scattering are mainly used for small-diameter adsorption pores (Larsen et al., 1995; Sakurovs et al., 2012). Among them, low-temperature nitrogen adsorption is efficient and has the advantages of a wide range of test pore sizes (Xu et al., 2015b; Zhang et al., 2019). Imaging methods include two-dimensional imaging methods, such as scanning electron microscopy (SEM) and broad ion beam scanning electron microscopy (BIB-SEM), as well as three-dimensional imaging methods, such as focusing on ion beam scanning electron microscope (FIB-SEM) and ion beam-Helium ion microscope (FIB-HIM). Among them, scanning electron microscopy is the most widely used image description method because it is cost-effective.

Previous studies separated the pores in SEM images of coal samples by setting appropriate gray thresholds and then analyzed the pore structure characteristics of coal (Liu and Nie, 2016). However, considering that the brightness of different types of pores may be different and the uneven surface of the coal sample will affect the distribution of brightness, and many other factors will affect the distribution of grayscale, it is difficult to accurately identify all the pores in SEM images by a single threshold. Fourier analysis can mine the information in the frequency domain by identifying the degree of change in the brightness of SEM image to achieve effective identification of pores in coal. Fractal theory Fractal theory has been widely used in the analysis of coal reservoir pore structure (Fu et al., 2017; Wang and Li, 1997; Zhao et al., 2016), which can effectively evaluate the properties of pores in porous materials.

In this paper, based on maceral analysis and proximate analysis, the pore structure and its heterogeneity of lignite were analyzed. The composition and pore characteristics of the lignite in the Erlian Basin were analyzed by improved scanning electron microscope images and low-temperature nitrogen adsorption. It was expected to provide a reference for the efficient exploration and development of the CBM.
**Geological setting**

The Erlian Basin is a Mesozoic and Cenozoic intracontinental faulted basin in northern China. It is mainly composed of five subbasins and one uplift, including the Chuanjin subbasin, the Manite subbasin, the Wulanchabu subbasin, the Wunite subbasin, the Tengger subbasin and Sunite uplift (Figure 1(a); Lin et al., 2001). The coal seams in this basin are mainly developed in the Lower-Middle Jurassic and Lower Cretaceous strata. The Lower Cretaceous is composed of the Aershan Formation, the Tengger Formation and the Saihantala Formation (Figure 1(b); Wang et al., 2019). Saihantala Formation is dominated by fluvial facies. Jiergalangtu sag is located in the Wunite subbasin. The Saihantala Formation in this area is rich in coal resources, and a huge thick coal seam is developed. The maximum coal cumulative thickness exceeds 200 m, the coal-bearing area is 342 km², and the coal reserves are 22.4 billion tons.

**Experiments and methods**

**Samples**

The three sets of coal seams (NO.4, NO.5, NO.6) are the main mined coal seams in the area (Figure 2(a)). The thickness of NO.4 coal seam is 19.3 m on average, which is relatively thin compared with other coal seams. The average thickness of NO.5 and NO.6 coal seams is about 70 m, which is widely distributed. The sample collection takes into account the main mining seam, the depth of the sample, the horizontal and vertical spreading of the coal seam and other factors, and the sample has strong representativeness.

13 samples of three sets of coal seams (NO.4, NO.5, NO.6) were collected from Datang Coal Mine, Shenhua Coal Mine, and Zhekuang Coal Mine in Jiergalangtu Sag, Erlian Basin, Inner Mongolia, China.
In this study, samples of different coal seams were collected to reveal the heterogeneity of lignite reservoirs. The distribution and spatial position relationships of the samples are shown in Figure 2(b). Lignite easily loses moisture at room temperature, and then fresh coal samples were collected from the working surface and immediately packed in sealed valve bags. Then the coal samples were quickly measured in the laboratory.

After sample collection, proximate analysis, huminite reflectance measurement and maceral analysis were performed. Maceral analysis is the basis for studying the composition and structure of lignite. In the process of maceral analysis, the lignite classification of the international conformity certification programm is often used to divided coal maceral into the huminite, the liptinite and the inertinite, which respectively correspond to the vitrinite, the exinite and the inertinite in the hard coal.

Huminite reflectance ($R_o$%) measurements and maceral analysis (500 points) were performed, under oil immersion in reflected lignite using a photometer-based microscope. Proximate analysis was performed using a 5E-MAG6700 fully automatic proximate analyzer. By using the 5E-MAG6700 fully automatic proximate analyzer, the moisture content, ash yield and volatile content of the sample are measured.

The maceral composition of the samples is determined. The experimental results show that the coal maturity of the Jiergalangtu Sag is low, and the huminite reflectance between 0.29% and 0.53%, Its maturity has strong heterogeneity between layers and different mining areas. The $R_o$ of coal seams in the same mining area shows a general trend of increasing with the increase of burial depth. The $R_o$ of each mining interval in the sag also changed significantly. The composition of the coal seams differs greatly, and the overall change law is as follows: in the vertical direction, with the increase of the burial depth, the moisture content increases first and then stabilizes. The ash yield is mainly affected by the sedimentary environment, and the volatile content is mainly related to the coal rank. Overall, the material composition of lignite is the result of a combination of various factors, resulting in lignite exhibiting strong heterogeneity.

**Experiments**

**Coal fundamental properties.** To prevent dehydration and oxidation of samples, store them in vacuum bags immediately after sampling. Mean random vitrinite reflectance and microscopic
composition of coal were measured using a Leitz microscope with a photometer as required by ISO 7404-3-1994 (1994) and ISO 7404-5-2009 (2009). According to ISO1171-2010 (2010) and ISO 11722-2013 (2013), the basic material composition of coal was determined by proximate analysis. Basic information can be found in Table 1.

**Nitrogen adsorption.** The specific surface area, pore volume and pore size distribution of the sample can be measured through the low-temperature nitrogen adsorption experiment. The experimental instrument used the Quantachrome NOVA2000e analyzer. The pore size theory test range is 2 to 200 nm, and the specific surface area theory test range is 0.1 to 3,500 m$^2$/g. The test process was carried out following National Petroleum Industry Standard SY/T 6154-1995. The samples were crushed, and 5 g-10 g of samples with a particle size of 40–60 mesh (0.28mm-0.45 mm) were selected, then dried at 105°C for 8 h put it in the desiccator for later use. The nitrogen adsorption-analytical curve with a relative pressure ranging from 0.01 to 0.99 is obtained at a temperature of 77 K. The specific surface area and pore size distribution are calculated using the BET (Brunauer-Emmett-Teller) and BJH (Barrett-Joyner-Halenda) models (Fu et al., 2017; Zhao et al., 2016).

**SEM.** Using FESEM JSM-7500F scanning electron microscopic observation, the maximum resolution of the instrument 1 nm, the range of magnification × 30- × 1000 k. After the sample is evacuated, the pores, cracks, and microstructure and microscopic morphology of the minerals on the cleat surface of the coal sample can be observed under a voltage of 15 kv.

In this paper, the analysis of SEM images is not only limited to the direct response characteristics of the images. Since the images have a binary format stored in the computer, the pictures can be converted into numbers (red, green, and blue [RGB] values) through software processing, and the qualitative analysis can be extended to quantitative analysis. Through direct observation of the image, it is found that the edge color of the pore fissure development has a significant change, which shows a sudden change in the value of the RGB value. Therefore, statistical analysis

### Table 1. Basic information of the samples.

| Sample | Site   | Coal seam | $R_o$ (%) | Proximate analysis (%) | Coal composition (%) |
|--------|--------|-----------|-----------|------------------------|----------------------|
| DT1    | Datang | 4         | 0.34      | 14.04 13.83 40.17      | Exinite 89.8 | 8.2       |
| DT2    | Datang | 6         | 0.37      | 11.61 23.19 37.91      | Huminite 44.6 | 53.8      |
| DT3    | Datang | 5         | 0.38      | 24.11 6.97 43.41       | Inertinite 94.9 | 3.2       |
| SH1    | Shenhua| 5         | 0.32      | 10.34 37.16 45.01      | Exinite 88.6 | 11.2      |
| SH2    | Shenhua| 6         | 0.36      | 21.45 8.11 45.08       | Huminite 77.3 | 20.4      |
| SH3    | Shenhua| 5         | 0.39      | 21.97 10.32 44.07      | Inertinite 54.5 | 45.2      |
| SH4    | Shenhua| 5         | 0.29      | 15.65 16.72 44.6       | Exinite 92.7 | 6         |
| SH5    | Shenhua| 6         | 0.42      | 13.18 13.82 40.3       | Huminite 60.5 | 37.9      |
| SH6    | Shenhua| 5         | 0.44      | 14.31 13.03 34.36      | Inertinite 96.2 | 3.2       |
| ZK2    | Zhekuang| 6        | 0.53      | 29.35 14.97 41.51      | Exinite 92.1 | 7.4       |
| ZK3    | Zhekuang| 6        | 0.43      | 21.25 17.92 38.71      | Huminite 56.7 | 42.6      |
| ZK4    | Zhekuang| 6        | 0.38      | 17.6 14.7 42.33        | Inertinite 89.3 | 10.3      |
| ZK5    | Zhekuang| 6        | 0.35      | 9.97 16.66 35.53       | Exinite 49.9 | 49.3      |

$R_o$: vitrinite reflectance, %; Aad: ash yield; Mad: moisture content (air-dried basis); Vdaf: volatile content (dry, ash-free basis).
of the value can obtain the development status and heterogeneity of the pore fissure in the coal seam.

Fourier transform (FFT) is widely used in digital signal processing. Its logical meaning is that any continuously measured signal can be represented by an infinite superposition of sine wave signals of different frequencies. The formula can be expressed as follows:

\[
F(\omega) = \int_{-\infty}^{+\infty} f(t) e^{-j\omega t} dt \quad (1)
\]

Where \(\omega\) represents frequency, \(t\) represents time, \(e^{-j\omega t}\) is a complex function.

This method can transform the time-domain signal of the digitally processed SEM image into a frequency-domain signal that is easy to analyze. Frequency domain signals are expressed in the form of spectrograms. Filter out the frequency components that are not of interest in the spectrogram, and then keep the frequency components of interest. Finally, the inverse Fourier transform (IFFT) is performed to obtain the SEM image after image processing. The formula can be expressed as follows:

\[
f(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega) e^{j\omega t} d\omega \quad (2)
\]

The process is shown in Figure 3.

**Fraction dimensions from low-temperature \(N_2\) adsorption isotherms.** The Frenkel-Halsey-Hill (FHH) model is the most widely used method for calculating coal reservoir pore fractal dimension based on gas adsorption isotherm (Jiao et al., 2014; Li et al., 2018; Pfeifer et al., 1989). The formula can be expressed as follows:

\[
\ln V = C + A \left[ \ln \left( \ln \left( \frac{P}{P_0} \right) \right) \right] \quad (3)
\]

**Figure 3.** Fourier image processing.
Where, $V$ is the volume of the adsorption equilibrium pressure $P$, cm$^3$/g; $C$ is a constant; $A$ is $\ln V$ and $\ln \left( \ln \left( \frac{P_0}{P} \right) \right)$ of the slope of the curve; $P_0$ is the saturation pressure of methane gas, megapascals.

The fractal dimension $D$ is generally obtained from the slope $A$ of the line. However, at different stages of the adsorption process, there are different calculation formulas. During the early stage of multilayer adsorption, the solid-gas potential controls the adsorption process. The fractal dimension can be calculated by the following formula:

$$D = 3A + 3$$  \hspace{1cm} (4)

When the interface is controlled by the liquid-gas surface tension, the fractal dimension is calculated by the following formula:

$$D = A + 3$$  \hspace{1cm} (5)

**Results and discussion**

**Maceral analysis**

The microscopic components of the coal seam in the study area are dominated by huminite, which are mainly composed of huminite formed by lignin and cellulose. The huminite are brown-yellow to reddish-brown under transmitted light, and gray under oil-immersed reflected light, with high oxygen content. The observation under microscope showed that DT1 distributed microsporinite, cutinite, suberinite and Liptodetrinite in parallel, and occasionally resinite and a small amount of Pollen (Figure 4(a)); fluorinite, microsporinite, liptodetrinite and pollen are distributed in parallel in the SH1 sample; localized in SH3 see the enrichment of fluorescent components, mainly microsporinite, resinite, liptodetrinite, pollen and cutinite (Figure 4(c)); DT2 microsporinite is locally

**Figure 4.** Photomicrographs of macerals. Taken under oil immersion with fluorescent. The identification of macerals is as follows: Ld-Liptodetrinite; Py-Pyrite; Cu-Cutinite; Mis-Microsporinite; Re-Resinite; Po-Pollen; Fl-Fluorinite.
concentrated, the individual is deformed, and even broken into a liptodetrinite, occasionally resinite and pollen are seen, and the shape is small (Figure 4(e)); SH2 lignite is partially seen liptodetrinite Enriched, pollen are easy to see, and microsporinite are occasionally seen, which are mixed with each other randomly (Figure 4(d)); resinite and liptodetrinite are easily seen in ZK5 lignite, and microsporinite are occasionally seen (Figure 4(f)).

The sample test results show that the content of Huminite is between 82% and 98%, and the content of liptinite and inertinite is less, the content of liptinite is 0.5%~0.8%, and the content of inertinite is 1.6%~17.5%. The distribution of maceral components of each coal seam shows that the content of huminite shows a decreasing trend with the increase of burial, and the change of content of inertinite is on the contrary, the content of huminite in the coal samples of No.6 coal seam is the lowest, and the content of inertinite is higher than the rest of coal seam (Figure 5). Therefore, No.6 coal seam mainly contains abundant plant tissue pores; No.5 coal seam has plant tissue pores and mineral pores developed together; No.5 coal seam is mainly dominated by intergranular pores, and the regularity and pore diameter of pores decrease due to the effect of compaction, and the connectivity of pores becomes (Rai et al., 2022).

Improved SEM analysis

The pores of low-rank coal can be divided into three types: plant tissue pores, mineral-related pores and thermogenic pores (Chen et al., 2015; Xin et al., 2019). Scanning electron microscopy results in this study showed that mineral-related pores and plant tissue pores were mainly developed, and no obvious thermogenic pores were found. This may be due to the low maturity (R_o) of the lignite in

![Figure 5. Variation of maceral composition in different coal seams.](image-url)
the study area; It has not yet begun to produce large amounts of natural gas during this geological period.

Scanning electron microscopy results also show that different coal seams have different results of pore cracks. No. 4 and No. 5 coal seams have mainly developed mineral pores and poor fracture connectivity (Figure 6(a)–(d)); No. 6 coal seam has a large number of plant tissue pores, cellular structure is well developed, microfractures are developed, and pore connectivity is good. However, it was damaged during the later compaction, cellular structure is incomplete (Figure 6(e)–(f)).

The Ro (%) and proximate analysis of the three coal seams are not much different, but the coal macerals are quite different (Table 1), which controls the type and development degree of pores. The inertinite of No. 6 coal seam is developed, and the content of inertinite in samples DT2 and SH3 are as high as 53.8% and 45.2% respectively. In comparison, the content of inertinite of No. 4 in sample DT1 is only 8.2%, and the content of inertinite of No. 5 is only 6%. The content of inertinite directly controls the degree of cellular structure and plant tissue pores development. At the same time, it can be found that the samples of the No. 6 coal seam generally have a high inertinite content, which also means that there are a large number of cellular structures and plant tissue pores in the No. 6 coal seam.

Figure 6. Different coal seam SEM images. (a) and (b) from sample No. 4 coal seam: Shows mineral-related pores development; (c) and (d) from No. 5 coal seam: The development of mineral pores is the same as that of visible plant tissue; (e) and (f) from sample No. 6 coal seam: Plant pores are well developed and have good connectivity.
Scanning electron microscope observation can study the morphological characteristics of the sample, but it also causes difficulties for the effective identification of pores. Through image analysis technology, the observation of pores by SEM is expanded from qualitative to quantitative. First, digitize the RGB values based on the SEM images. The changes in the size and distribution of the RGB values reflect the lithology and pore distribution. Generally, the larger the atomic number, the brighter the SEM image, so the lithology can be judged by the RGB value. At the same time, the distribution of pores can be identified based on the same principle.

Then the Fourier transform method is used to filter the color signal of the SEM image in the frequency domain. This is the most critical step for the image processing of the SEM image. The high-frequency component represents a large change in pixel value, which can be expressed as the boundary between the pore and coal rock; the low-frequency component represents a small change in pixel value, representing the pore or the same type of coal rock component developed in the coal rock sample. Therefore, in the filtering process, the low-frequency components are filtered out, and then the filtered components are subjected to inverse Fourier transform (IFFT), and finally filter the Figure 6 to get Figure 7. The dark areas in the figure represent the development of pore and fractures, and the observation results similar to the previous ones can be obtained more intuitively.

**Figure 7.** Improved SEM images.
The improved SEM images obtained by image processing of the SEM images in Figure 5, the dark part in the figure represents the development of pores and fractures in the coal, and the bright part represents the coal-rock matrix. (a) The mineral pores are well developed and the connectivity is poor, and the frequency of light and dark changes in the processed images is low. (e) and (f) plant pores are well developed and have good connectivity. The processed image has a high frequency of light and dark changes.
However, there are some objectivity disturbances in the image processing, and the image processing needs to be adjusted to avoid the impact on the observation results. When observing the filtered SEM images (Figure 7), the mineral pores are easier to identify than the cellular structure and cell pores, which may be due to the higher atomic number of the mineral composition and the stronger secondary electron signal received, so the RGB value of the brightness is also higher. The brightness of the pores is generally the lowest because it receives the least secondary electronic signal. During the filtering process, low-frequency changes are filtered while high-frequency changes are retained, so the contrast between the mineral and the surrounding pores will be more vivid. On the contrary, the cellular structure and plant tissue pores of organic matter are usually developed in the coal rock matrix, and the atomic number of the coal component is relatively low, so the secondary electron signal received is weak, and the contrast with the surrounding pores is not sharp enough. When filtering out low-frequency signals during the filtering process, it may unintentionally reduce the recognition of such plant tissue pores. Therefore, when performing image processing on samples of low-rank coal and high inertinite, the low-frequency filtering range should be controlled to avoid missing identification of plant tissue pores.

At the same time, the surface morphology of the sample will also affect the brightness and darkness of the SEM image, which will also indirectly affect the quality of the image processing results, which may make us miss the identification of the plant tissue pores. For No. 6 coal seam, unprocessed SEM images can identify the plant tissue pores (Figure 6(f)), but when image processing is carried out, the cell pores cannot be well identified (Figure 7(f)). This may be due to the surface morphology of the sample, the location of the plant tissue pores is in the relatively concave part, the secondary electron signal received by the coal rock matrix around the pores is not strong, and the pores will not be well identified when filtered. Therefore, in the process of sample selection and preparation, the sample surface should be as much as possible to avoid fluctuations. Generally, the sample table can be tilted at a certain angle during the scanning electron microscope observation to avoid and reduce the influence of surface morphology on the later image processing.

The image processing method can not only efficiently identify pores and fractures but also further accurately compare the degree of heterogeneity between various coal seams. The analysis and comparison are performed in the form of the spectrum, and the filtered results (Figure 8) are directly compared in the frequency domain rather than in the time domain by inverse Fourier transform (IFFT). Due to different magnifications and different pixel values during the scanning electron microscopy process, try to select images with the same magnification as possible during the image selection process (Figure 6), and then homogenize the pixels, randomly selecting 1,000 samples points for spectrum display. The high-frequency component in Figure 7 represents the boundary between the pore and coal rock; the low-frequency component represents the pore or the same type of coal rock component developed in the coal rock sample. Due to the influence of sensitivity during shooting, the pores are mainly distributed in the medium frequency range. The results show that the pore development degree of the No. 5 coal seam in the study area is weaker than that of No. 4 coal seam and No. 6 coal seam. By calculating the Fourier Transform of three coal seams to obtain the variance (Var), it is found that all three coal seams have strong heterogeneity, of which NO.4Var < NO.5Var < NO.6Var, indicating that the heterogeneity of the No. 4 coal seam is the weakest compared to the others, and the heterogeneity of coal seam No. 6 coal seam is the strongest in the three coal seams.

They are all lignite samples, but there are clear differences in pore development type and reservoir heterogeneity, which shows that lignite reservoirs are highly complicated in actual exploration and development. Comparing the results of maceral analysis and proximate analysis, the main
difference is the content of the inertinite, and the ash content also has a certain difference. Different material compositions and coal-forming environments profoundly affect the heterogeneity of the lignite reservoir.

Low-temperature nitrogen adsorption/desorption (Lt-N$_2$ga) analysis

LT-N$_2$GA isotherms and pore shapes. Low temperature nitrogen adsorption/desorption experiments are widely used to define the complexity and morphology of coal pores. For pores of a specific form, when the relative pressure points corresponding to adsorption condensation and desorption evaporation are different, a hysteresis loop will appear, and the shape of the hysteresis loop can reflect the type of pores. According to the classification of adsorption isotherms by Sing et al. (1985), it is found that the nitrogen adsorption/desorption isotherms of the target coal seams can be divided into two types.

Samples DT2 and SH1 belong to type A (Figure 9). This type of desorption isotherm exhibits a sharp drop when the relative pressure ($P/P_0$) is 0.45–0.5. This significant inflection point indicates relative pressure during condensation in the gas adsorption process is higher than the relative pressure during desorption, indicating that the pore types of coal rocks in this area are mainly connected pores with open ends, such as parallel plate pores with open ends, which is beneficial to the enrichment and exploitation of coalbed methane. Samples DT1, SH2, SH3, and ZK5 belong to type B. There is almost no obvious hysteresis loop or only a narrow hysteresis loop between the adsorption and desorption isotherms of this type, indicating the relative pressures of such pores during adsorption and desorption are almost the same. These kinds of pores are semi-open pores with poor connectivity, such as slit-shaped pores with one closed side, and wedge-shaped pores., which is beneficial to the enrichment of coalbed methane, but not conducive to the exploitation of coalbed methane. The pore morphology of the No. 4 coal seam is type B, but the No. 5 and No. 6 coal seams have developed A-type and B-type pores. The pore structure is complex and the coal seam has strong heterogeneity.

Figure 8. Scanning electron microscope Fourier transform spectrum.
The maximum adsorption capacity of samples DT1 and SH2 is 8 (10^{-3} ml/g), the pores are mainly mesopores and transition pores, and the development of B-type pores is conducive to the seepage of methane. The maximum adsorption capacity of samples Zk5 and SH3 is between 18–25 (10^{-3} ml/g), the average pore size is 22.43 nm and 18.04 nm respectively, the degree of colализation is low, and the pores of plant tissue are the main ones. The maximum adsorption capacity of samples SH1 and DT2 is about 14 (10^{-3} ml/g), and the average pores of BJH are 9.34 nm and 19.48 nm, respectively. Micropores and transition pores are developed. Compared with ZK-5, the crystal particles of plant tissue pores and intercrystalline pores are due to Compaction is tighter, resulting in reduced porosity.

Specific surface area and pore volume. Table 2 shows the analysis of the results of low-temperature nitrogen adsorption/ desorption experiments. The BJH pore volume varies from 11.48 to 48.32 10^{-3} ml/g (avg. 27.39), the BET surface area ranges from 2.83 to 16.90 m²/g (avg. 7.99). The contribution of pore volume mainly comes from the medium pores larger than 10 nm, while the...
contribution of the specific surface area of the pores smaller than 10 nm is significant. BJH pore volume is positively correlated with BET specific surface area (Figure 10a). The average pore diameter varies from 9.34 to 22.43 nm (avg. 15.78). But the average pore diameter of the sample showed an obviously negative correlation with BET specific surface area (Figure 10b). This negative correlation is caused by the geometrical characteristics of the pores. The larger the pore size, the smaller the specific surface area and volume ratio, so the small pores contribute more to the surface area and the larger pores contribute less to the surface area.

Pore size distribution. Crosdale et al. (2008) proposed that matrix porosity in low-rank coal is large and has the potential to store free gas, which may account for 50–70% of the total gas content (Crosdale et al., 2008). Therefore, the relationship between pore distribution and volume in low-rank coal reservoirs is particularly important. The average pore diameter varies from 9.34 to 22.43 nm. The percentage of pore volume at each level was calculated by using Hodot pore size classification scheme, as shown in Figure 11 (Hodot, 1966; Zhao et al., 2016).

The pore size distribution characteristics of samples in the research area are shown in Figure 11. There are 3 peaks at 2–3 nm, 8–10 nm, and 40–50 nm, indicating that the pores in this range increase the volume contribution rate and the number of pores. The peak value is small at 2–3 nm and 8–10 nm, and its volume contribution is limited, but the contribution is huge at 40–50 nm. When the pore diameter is in the range of 50–100 nm, the increased rate of pore volume decreases sharply, and the content of pores in this range is not much. The increased rate of pore volume increased sharply in the range of 100–150 nm, indicating that the pore content in this range was in the majority. According to section 3.1, the genesis types of pores in this region are mainly mineral pores and plant tissue pores. Therefore, the difference in pore development degree in different size intervals may be controlled by mineral particle size and plant type.

### Table 2. Low temperature nitrogen adsorption test results.

| Sample | Average pore diameter (nm) | BJH Pore volume (ml/g) | BJH Pore volume ratio % | BET specific surface area (m²/g) | BET Specific surface area ratio % |
|--------|---------------------------|------------------------|-------------------------|----------------------------------|----------------------------------|
|        |                           |                        |                         |                                  |                                  |
| 4DT1   | 15.9206                   | 0.011476               | 37.1                    | 2.88322                          | 3.6                              |
| 5DT3   | 21.6903                   | 0.015345               | 41                      | 2.82991                          | 5.4                              |
| 5SH1   | 9.3442                    | 0.019699               | 28.1                    | 8.432645                         | 1.5                              |
| 6SH3   | 18.0446                   | 0.018964               | 38.4                    | 2.03739                          | 3.9                              |
| 6DT2   | 19.4845                   | 0.024217               | 41                      | 4.971589                         | 4.7                              |
| 5SH2   | 12.0370                   | 0.034911               | 32.3                    | 11.60117                         | 2.5                              |
| 6ZK2   | 13.5204                   | 0.048318               | 31.7                    | 14.29472                         | 2.2                              |
| 6ZK3   | 20.1490                   | 0.017709               | 41.4                    | 3.515582                         | 5.1                              |
| 6ZK4   | 12.7829                   | 0.030455               | 25.9                    | 9.530043                         | 2.1                              |
| 6ZK5   | 22.4344                   | 0.017818               | 41.2                    | 3.176958                         | 5.7                              |
| 5SH4   | 13.5969                   | 0.046167               | 28                      | 13.58153                         | 2.5                              |
| 6SH5   | 10.3296                   | 0.043645               | 25.3                    | 16.90103                         | 1.6                              |
The performance of heterogeneity in fractal characteristics

Table 3 and Figure 12 show the results of fractal dimensions, the D1 ranges from 2.5512 to 2.7474 (avg. 2.6239), the D2 ranges from 2.5404 to 2.6103 (avg. 2.5695). D1 represents fractals from pore surface area generated by surface irregularity of coals (Yao et al., 2008), high D1 represents high pore surface roughness due to the complex structure of the primary pore of low-rank coal. D2 characterizes fractals related to pore structures, high D2 represents the coal reservoir in this region with complex pore structure.

Meanwhile, both samples SH1 and SH3 belong to the No. 5 coal seam, but the pore surface roughness and pore structure of sample SH1 are much higher than sample SH3, indicating that there is strong heterogeneity in the same coal seam. The above study believes that material composition, coal formation environment, and coal rank mainly control the pore type and reservoir
heterogeneity. In summary, it can be found that there are very large differences between different lignite seams, and even the internal reservoirs of the same brown coal seam have very large heterogeneity.

**Conclusion**

1. In this study, the time domain signal of the SEM image is converted into a frequency-domain signal that is easy to analyze, and the qualitative analysis is extended to the quantitative analysis through statistical analysis of the numerical values, the development status and heterogeneity of the pore-fracture in the coal seam were obtained.

2. The Fourier transform of the three coal seam SEM data shows that the variance of the numerical value indicates that the heterogeneity of the lignite reservoir between different coal seams and different mining areas is significant. Nitrogen adsorption data and fractal analysis indicate that the lignite in the study area has high pore surface roughness and complex pore structure.

3. Affected by various geological factors such as material composition, coal formation environment, evolution degree, etc., lignite reservoirs in different layers and different mining areas show apparent heterogeneity. Therefore, in the actual exploration and development process, it is necessary to conduct a favorable reservoir evaluation and adopt appropriate development technology.

**Acknowledgements**

This work was supported by the National Natural Science Foundation Project, China (Grant No. 42172188, U1703126), and the National Science and Technology Major Project of China (2016ZX05041-002).

**Declaration of Conflicting Interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.
Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the The National Science and Technology Major Project of China, The National Natural Science Foundation Project, China, (grant number 2016ZX05041-002, No. 42172188, U1703126).

ORCID iD
Hao Xu https://orcid.org/0000-0002-7173-5616

References
Bertoli O, Paul A, Casley Z, et al. (2013) Geostatistical drillhole spacing analysis for coal resource classification in the bowen basin, queensland. International Journal of Coal Geology 112: 107–113.
Chen Y, Tang D, Xu H, et al. (2015) Pore and fracture characteristics of different rank coals in the eastern margin of the Ordos Basin, China. Journal of Natural Gas Science and Engineering 26: 1264–1277.
Crosdale PJ, Moore TA and Mares TE (2008) Influence of moisture content and temperature on methane adsorption isotherm analysis for coals from a low-rank, biogenically-sourced gas reservoir. International Journal of Coal Geology 76(1–2): 166–174.
Emmett P H (1948) Adsorption and pore-size measurements on charcoals and whetlerites[J]. Chemical Reviews 43(1): 69–148.
Fu H, Tang D, Xu T, et al. (2017) Characteristics of pore structure and fractal dimension of low-rank coal: A case study of lower jurassic xishanyao coal in the southern Junggar Basin, NW China. Fuel 193: 254–264.
Hodot BB (1966) Outburst of Coal and Coalbed Gas (Chinese Translation). Beijing: China Coal Industry Press.
Jiao K, Yao S, Liu C, et al. (2014) The characterization and quantitative analysis of nanopores in unconventional gas reservoirs utilizing FESEM-FIB and image processing: an example from the lower Silurian Longmaxi Shale, upper Yangtze region, China. International Journal of Coal Geology. https://doi.org/10.1016/j.coal.2014.03.004.
Kumar H, Mishra MK and Mishra S (2019a) Experimental and numerical evaluation of CBM potential in Jharia Coalfield India. Geomechanics and Geophysics for Geo-Energy and Geo-Resources 3: 289–314.
Kumar H, Mishra MK and Mishra S (2019b) Sorption capacity of Indian coal and its variation with rank parameters. Journal of Petroleum Exploration and Production Technology 9: 2175–2184.
Kumar H, Mishra MK, Mishra S, et al. (2021) Determination of methane sorption capacity using microstructural analysis in coal of jharia coalfield. India. Arabian Journal of Geosciences 14: 690.
Larsen JW, Hall P and Wernett PC (1995) Pore structure of the argonne premium coals[J]. Energy & Fuels 9(2): 324–330.
Li K, Zeng F, Cai J, et al. (2018) FRACTAL CHARACTERISTICS of PORES in TAIYUAN FORMATION SHALE from HEDONG COAL FIELD, CHINA. Fractals. https://doi.org/10.1142/S0218348X18400066.
Li S, Tang D, Xu H, et al. (2012) Advanced characterization of physical properties of coals with different coal structures by nuclear magnetic resonance and X-ray computed tomography. Computers and Geosciences 48: 220–227.
Lin C, Kenneth E, Li S, et al. (2001) Sequence architecture, depositional systems, and controls on development of lacustrine basin fills in part of the Erlian Basin, northeast China. AAPG Bulletin 85(11): 2017–2043.
Liu S, Sang S, Wang G, et al. (2017) FIB-SEM and X-ray CT characterization of interconnected pores in high-rank coal formed from regional metamorphism. Journal of Petroleum Science and Engineering 148: 21–31.
Liu X and Nie B (2016) Fractal characteristics of coal samples utilizing image analysis and gas adsorption. Fuel 182: 314–322.
Montgomery SL (1999) Powder river basin, Wyoming: an expanding coalbed methane (CBM) play. AAPG Bulletin 83(8): 1207–1222.
Moore TA (2012) Coalbed methane: A review. International Journal of Coal Geology 101: 36–81.
Nie B, Liu X, Yang L, et al. (2015) Pore structure characterization of different rank coals using gas adsorption and scanning electron microscopy. Fuel 158: 908–917.
Pfeifer P, Wu YJ, Cole MW, et al. (1989) Multilayer adsorption on a fractally rough surface. Physical Review Letters. https://doi.org/10.1103/PhysRevLett.62.1997.
Qin Y (2018) Research progress of symbiotic accumulation of coal measure gas in China. Natural Gas Industry B 5(5): 466–474.
Rai S, Rai A, Kumar K, et al. (2022) Study of micro-structures and their relation with occurrence of mineral matter in Ramagundam Coals, Godavari basin, India: implications on coal and hydrocarbon industries. JOURNAL OF THE GEOLOGICAL SOCIETY OF INDIA 98: 88–92.
Sakurovs R, He L, Melnichenko Y B, et al. (2012) Pore size distribution and accessible pore size distribution in bituminous coals[J]. International Journal of Coal Geology 100: 51–64.
Sing KSW, Everett DH, Haul RAW, et al. (1985) Reporting physisorption data for gas/solid systems with special reference to the determination of surface area and porosity. Pure and Applied Chemistry. https://doi.org/10.1351/pac198557040603.
Singh PK, Singh VK, Rajak PK, et al. (2016) Eocene lignites from Cambay basin, western India: an excellent source of hydrocarbon. Geoscience Frontiers 7: 811–819.
Wang F and Li S (1997) Determination of the surface fractal dimension for porous media by capillary condensation. Industrial & Engineering Chemistry Research 36(5): 1598–1602.
Wang S, Shao L, Wang D, et al. (2019) Sequence stratigraphy and coal accumulation of lower cretaceous coal-bearing series in Erlian basin, northeastern China. AAPG Bulletin 103(7): 1653–1690.
Ward CR (2002) Analysis and significance of mineral matter in coal seams. International Journal of Coal Geology 50(1–4): 135–168.
Tao S, Pan Z, Chen S, et al. (2019) Coal seam porosity and fracture heterogeneity of macrolithotypes in the Fanzhuang block, southern Qinshui basin, China. Journal of Natural Gas Science and Engineering 66(April): 148–158.
Xin F, Xu H, Tang D, et al. (2019) Pore structure evolution of low-rank coal in China. International Journal of Coal Geology 205(August 2018): 126–139.
Xin F, Xu H, Tang D, et al. (2020) Experimental study on the change of reservoir characteristics of different lithotypes of lignite after dehydration and improvement of seepage capacity. FUEL 277: 118196.
Xin F, Xu H, Tang D, et al. (2021) Problems in pore property testing of lignite: analysis and correction[J]. International Journal of Coal Geology 245: 103829.
Xu H, Tang D, Zhao J, et al. (2015a) A precise measurement method for shale porosity with low-field nuclear magnetic resonance: A case study of the Carboniferous-Permian strata in the Linxing area, eastern Ordos basin, China. Fuel 143: 47–54.
Xu H, Tang D, Zhao J, et al. (2015b) Geologic controls of the production of coalbed methane in the Hancheng area, southeastern Ordos basin. Journal of Natural Gas Science and Engineering 26: 156–162.
Xu H, Tang DZ, Liu DM, et al. (2012) Study on coalbed methane accumulation characteristics and favorable areas in the Binchang area, southwestern Ordos basin, China. International Journal of Coal Geology 95: 1–11.
Yang Q and Han D (1979) Coal Geology of China, Vol. 2. Beijing: China Coal Industry Publishing House.
Yao Y, Liu D, Tang D, et al. (2008) Fractal characterization of adsorption-pores of coals from North China: an investigation on CH4 adsorption capacity of coals. International Journal of Coal Geology 73(1): 27–42.
Zhang J, Wei C, Zhao J, et al. (2019) Comparative evaluation of the compressibility of middle and high rank coals by different experimental methods. Fuel 245(December 2018): 39–51.
Zhao J, Xu H, Tang D, et al. (2016) Coal seam porosity and fracture heterogeneity of macrolithotypes in the Hancheng block, eastern margin, Ordos basin, China. International Journal of Coal Geology 159: 18–29.