Abstract
The physical properties of thick coal seams show strong vertical heterogeneity; thus, an accurate characterization of their pore structure is essential for coalbed methane (CBM) exploration and production. A total of 18 coal samples, collected from a thick coal seam in the Yili Basin of NW China, were tested by a series of laboratory experiments to investigate the peat mire evolution and pore structure characteristics. The results show that the No. 4 coal seam has undergone multiple stages of evolution in the peatification stage, and was divided into four water-transgression/water-regression cycles according to the regular cyclic changes of the vitrinite/inertinite ratio, structure preservation index, gelification index, vegetation index, trace element ratios, and stable carbon isotopes of organic matter. The changes of pore structure characteristics with the changes of coal deposition cycles are also analyzed. It is concluded that pore structure characteristics of the four cycles are quite different. In each water-transgression cycle, the vitrinite gradually increased and the inertinite gradually decreased, resulting in a decrease of the porosity, pore volume, specific surface area, and fractal dimension. While in each water-regression cycle, the vitrinite gradually decreased and the inertinite gradually increased, leading to an increase of the porosity, pore volume, specific surface area, and fractal dimension. A strong relationship exists between the porosity, pore volume, specific surface area, fractal dimension,
and submacerals, with fusinite and semifusinite which contained more pores having a positive correlation, desmocollinite and corpovitrinite which contained few pores having a negative correlation.

Keywords
Peat mire, thick coal reservoirs, pore structure, controlled factors, Yili Basin

Introduction
Coal seams whose minable single-thickness layers are 3.5–8.0 m are considered thick coal seams (Yang and Dexin, 1979). There are nine large gas-bearing basins (groups) including the Erlian and Hailar basins in Northeast China, Ordos Basin in North China, Junggar Basin, as well as the Tuha and Tianshan basins in Northwest China, where Jurassic and Cretaceous coal-bearing strata have developed widespread thick coal seams with lower coal ranks; they are rich in coalbed methane resources. Although the gas production and gas content of low-rank coals are low, the significant thickness of the thick coal seams makes up for the lack of low resource abundance caused by low gas content. Therefore, thick coal seams are the main body of CBM resource distribution and the preferred horizon of CBM exploration and development (Jerrett et al., 2011).

According to the widely accepted theory that “thick coal seam[s] represent a succession of stacked mires separated by hiatal surfaces” (Jerrett et al., 2011; Li et al., 2012; Shearer et al., 1994; Wang et al., 1995), we know that thick coal seams have the characteristics of “multiple coal seam superposition and multi-cycle development.” When the long-term accommodation rate (AR) outpaces the peat production rate (PPR), the water table of the mire gradually rises and the coal-forming environment becomes wetter and more reductive. Conversely, if the long-term AR falls below the PPR, the water table of the mire gradually drops and the peat is exposed, oxidized, eroded, and replaced by terrigenous clastic sediments. It is not difficult to find that the physical characteristics have strong vertical heterogeneity and the pore structure parameters even differ by an order of magnitude according to the current situation of describing the characteristics of thick coal reservoirs (Hou et al., 2017; Wang, 2018); this often brings difficulties to the selection of coalbed methane exploitation interval. However, there are still relatively few studies related to the vertical pore structure characteristics of thick coal reservoirs at present, which hinders further understanding the heterogeneity of thick coal reservoirs and their effect on the development of coalbed methane.

It is believed that macerals directly control the development of pore structure characteristics (Pan and Wood, 2015). Unsworth et al. (1988), Berbesi et al. (2009), Adeboye and Bustin (2013), Shan et al. (2015), Teng et al. (2017), Wang et al. (2017), and Keshavarz et al. (2017) concluded that inertinite has more macropores and that the porosity, pore volume, and specific surface area increase with the increase of inertinite. Kedzior and Jelonek (2013) and Gurdal and Yalcin (2001) have argued that there is no obvious relationship between macerals and coal porosity, pore volume, or specific surface area. However, variation in composition is imparted at the local scale by water table and vegetation variations within the mire, regionally by the depositional setting of the mire and vertically by the interplay of accommodation and vegetation supply over time (Zhang et al., 2010). Shao et al. (2003),
Turner and Richardson (2004), Davies et al. (2005), and Izart et al. (2006) found that the difference in the equilibrium relationship between the increased AR and PPR leads to large differences in coal macerals and coal qualities, which can guide the identification of various types of sedimentary hiatus and water-transgression/water-regression cycles in peat mires. Thus, studies on the influence of coal compositions on the pore structure and identification of various types of sedimentary hiatus and cycles in thick coal seams guided by coal macerals and coal qualities have made certain progress. However, there are still few studies on the heterogeneities and controlling factors of the vertical pore structure of thick coal seams.

Thick coal seams have largely developed in the Yining mining area of the Yili Basin in Xinjiang province, and the No.4 coal seam of the Xishanyao formation of the Middle Jurassic in this mining area was selected as the research object. First, the methods of maceral analysis and trace element and organic carbon stable carbon isotope analyses are used to divide the water-transgression/water-regression cycles in the thick coal seam. Then, the pore structure characteristics of each cycle were studied by mercury intrusion porosimetry (MIP), N$_2$ adsorption/desorption, and scanning electron microscope (SEM). Then, the change law of the vertical pore structure of the thick coal seam reservoir with the evolution of vertical macerals was analyzed to reveal the change law of the vertical pore structure of thick coal seam with the evolution of coal-bearing cycles. This not only provides theoretical support for the selection of favorable mining horizon of the thick coal reservoirs in this area but also guides the study of the vertical heterogeneity of the thick coal reservoirs with low rank in northern China.

**Geological setting of study area**

The Yili Basin is a large Mesozoic and Cenozoic intermountain superimposed basin that straddles China and Kazakhstan (the main body is in Kazakhstan). Its formation and development are controlled by basin marginal faults and belong to the Yili-Zhongtianshan microplate in the Tianshan orogen (Charvet et al., 2011). Its present vertical structure is a three-layer structure that consists of metamorphic basements from the Middle and Neoproterozoic, deformation basements of the Carboniferous Rift Volcanic Rock Series and sedimentary rock series since the Permian. The overall shape of the north-south profile is the hedged structural pattern caused by the thrusting of the orogenic belt on both sides into the basin. The northern and southern margins of the basin is bounded by the Keguqin-Boloholo orogenic belt and the Hark-Nalati orogenic belt, and is subdivided into the Yining depression, Gongnaisi depression, Nileke depression and Zhaosu depression (Figure 1) (Zhang et al., 1999).

Jurassic coal-bearing formations in the Yili Basin include the early Jurassic Badaowan Formation, Sangonghe Formation, and the Middle Jurassic Xishanyao Formation, of which the Badaowan and Xishanyao formations are the main coal-bearing formations.

The Badaowan formation is mainly distributed in the Yining, Nileke, and Gongnaisi sags. The grain size of the sediments ranges from coarse to fine from bottom to top and is mainly composed of conglomerate, sandstone, siltstone, silty mudstone, and mudstone. Regionally distributed coal seams have been deposited in the swamp environments of alluvial fans, braided river deltas, shallow lakes, as well as humid and warm climates (Shi et al., 2011). Coal seams are mainly distributed in the middle and lower sections of the Badaowan formation, with a total thickness of 3.6–130 m and an average thickness of 69.4 m (Li et al., 2014). Thick coal seams have developed in the lower section of the Badaowan formation (J$_1$x$_1$).
The Xishanyao formation is mainly distributed in the Yining, Nileke, Gongnaisi, and Zhaosu sags, consisting of sandstone, siltstone, mudstone, coal seam, and siderite (Li et al., 2014). From the bottom to the top of the Xishanyao Formation, the grain size of the sediments changed from coarse to fine and coarse again; the depth of the corresponding sedimentary water body changed from shallow to deep and shallow again, forming two 3-level sequences (SQ1 and SQ2) with a thickness of approximately 350 m. SQ1 is equivalent to the lower section of the Xishanyao formation and SQ2 is equivalent to the upper section of the Xishanyao formation. Coal seams deposited mainly in delta, shallow lake, and swamp environments with humid and warm weather conditions. The study area is in the northern part of the Yining Depression. Thick coal seams deposited mainly in the Xishanyao formation. The total coal seam thickness is 10–36 m and contains 5–9 layers of coal. The No. 4 coal seam developed in the lower section of the Xishanyao formation (J2x1). In the SQ1 sequence, the sedimentary environment is mainly river-dominated delta; peat mires are formed in lake margins and flood plains. Thick coal seams deposited mainly in the later period of the lowstand and highstand systems tracts. However, during the period of the highstand systems tract, although peat mires were still extensively deposited on the lake-shore plains, the continuity of coal seam worsened due to the occurrence of channel diversion and floods caused by tectonic movement (Ma et al., 2012).

**Samples and methods**

**Samples**

The samples were collected from the No. 4 coal seam of the Xishanyao formation in the Yining mining area of the Yili Basin. A total of 18 coal samples were collected by stratified sampling intensively from the top to the bottom at intervals of 0.2–0.5 m according to

![Figure 1. The location and components of the Yili Basin, as well as the sampling sites (modified from Li et al., 2014).](image)
“GB482-2008” and the changes of macrolithotype in coal. We selected the coal seam profile with low oxidation degree and stripped the surface oxide layer, then collected fresh coal samples (Figure 2). Each stratified sample was packed into the sampling bag, air was squeezed out, and the bag mouth was tightened. Meanwhile, the macroscopic coal-rock characteristics, stratified thickness of each stratified sample and total sampling thickness were described and recorded. As shown in Table 1, the sampling requires each sample to be more than 2 kg and that it be kept as block-like as possible to facilitate the subsequent experiments.

Table 1. Sample information.

| Sample ID | Gross thickness(m) | Macrolithotype | Sample ID | Gross thickness(m) | Macrolithotype |
|-----------|-------------------|----------------|-----------|-------------------|----------------|
| YN-01     | 0.50              | Bright         | YN-10     | 4.60              | Semidull       |
| YN-02     | 0.90              | Dull           | YN-11     | 4.90              | Dull           |
| YN-03     | 1.30              | Dull           | YN-12     | 5.20              | Bright         |
| YN-04     | 1.80              | Dull           | YN-13     | 5.60              | Dull           |
| YN-05     | 2.30              | Semibright     | YN-14     | 6.00              | Dull           |
| YN-06     | 2.70              | Bright         | YN-15     | 6.30              | Bright         |
| YN-07     | 3.10              | Dull           | YN-16     | 6.80              | Dull           |
| YN-08     | 3.60              | Dull           | YN-17     | 7.30              | Semibright     |
| YN-09     | 4.10              | Dull           | YN-18     | 7.80              | Bright         |

Figure 2. Stratified sampling map of No. 4 coal seam in Yining mining area.
**Experimental methods**

The coal samples were crushed to powder. Then, pulverized coal samples of 0.2 mm and 20 g or above were screened by the divisions for the industrial analysis of coal. Screening pulverized coal samples of less than 1 mm and about 20 g to prepare polished grain mounts 60–80 mesh (0.20–0.25 mm) pulverized coal samples were selected for N₂ adsorption/desorption experiments, and pulverized coal samples below 200 mesh were used for inductively coupled plasma mass spectrometry (ICP-MS) measurement of the trace elements in samples. Small samples of approximately 10 cm³ were used for mercury intrusion porosimetry experiments and organic carbon stable carbon isotope tests.

**Maceral and proximate analysis.** To analyze the cycle changes in thick coal reservoirs, the vitrinite reflectance, coal macerals, and industrial analysis were performed according to GB/T6948-1998, GB/T8899-2013, and GB/T 30732-2014.

**Organic matter stable carbon isotope and trace element analysis.** The composition of the trace elements in the samples was determined by ICP-MS. According to China National Standard 18340.2-2010 Part 2, a Thermo Scientific Delta V Advantage isotope ratio mass spectrometer and standard USGS40 L-glutamic acid were used for organic stable carbon Isotope tests.

**Tests and analyses of pore structures.** The selected block and powder coal samples were tested for pore volume, pore specific surface area, pore size distribution, and porosity by mercury intrusion porosimetry experiments and N₂ adsorption/desorption experiments, using the US Core Lab CMS300 and AutoPore IV9505 mercury indenter and American specific surface area analyzer (NOVA200e), respectively. The representative layered debris in the coal sample, whose major axis does not exceed 0.5 cm, were selected and used with a HITACHI S-4800 cold field emission scanning electron microscope to observe the coal sample, distinguish the main submacerals, and analyze the coal pore distribution and morphological characteristics.

**Fractal theory**

Fractal theory has proven to be an effective method for characterizing complex porous media. It can be combined with nitrogen adsorption/desorption and mercury intrusion porosimetry to digitally quantify the complexity and heterogeneity of pores in coal reservoirs (Cai et al., 2013; Garbacz, 1998; Sahouli et al., 1996; Yao et al., 2008; Zhang et al., 2014). According to the fractal theory, the surface fractal dimension (Dₛ) is used to characterize the surface roughness of materials. The larger the fractal dimension, the more complicated the pore space structure of coal reservoirs (Reich et al., 1992). According to the contribution of pores to CBM storage and recoverability, the pores in coal are divided into adsorption pores, including micropores (<10 nm) and transition pores (10–100 nm), as well as seepage pores (>100 nm) (Shi and Durucan, 2005; Yao et al., 2006).

The Frenkel-Halsey-Hill (FHH) model is one of the important methods to calculate the specific surface fractal dimension (Dₛ) of complex fractal porous media based on low-temperature liquid nitrogen experiments. The Frenkel-Halsey-Hill (FHH) model is generally used to calculate the fractal dimension of adsorption pores (<100 nm) (Yao et al., 2008).
According to the theory proposed by Pfeifer and Avnir (1983), the fractal dimension of the pore surface can be calculated by the FHH equation:

$$\ln\left(\frac{V}{V_0}\right) = C + A \times \ln\left[\ln\left(\frac{P_0}{P}\right)\right]$$  \hspace{1cm} (1)

$$D = A + 3$$  \hspace{1cm} (2)

where: $V$ is the volume of gas adsorbed at equilibrium pressure $P$, $V_0$ is the volume of gas adsorbed by the monolayer, $P_0$ is the saturated vapor pressure of gas adsorption, $A$ is the slope of $\ln\left(\frac{V}{V_0}\right)$ and $\ln[\ln(P_0/P)]$ in double logarithmic coordinates, and $C$ is a constant.

According to the mercury intrusion experimental data, the fractal dimension of the seepage pores (>100 nm) is often calculated using the Menger model, Sierpinski model, and thermodynamic model (Jiang et al., 2013; Song et al., 2018; Zhang and Li, 1995; Zhang et al., 2006). This study used a thermodynamic model to calculate the fractal dimension of the surface of the seepage pores. With the increase of pressure in the process of mercury intrusion, the amount of mercury introduced gradually increased, thereby increasing the pore surface energy. Therefore, the power produced by the environment external to the mercury is equal to the increase in the surface energy of the mercury liquid in the pores. The relation between the increment and the pore surface energy is (Rootare and Prenzlow, 1967):

$$dW = -\gamma L \cos \theta \, dS$$  \hspace{1cm} (3)

In the formula: $W$ is the pore surface energy (J), $\gamma L$ is the surface tension between mercury and pore surface (J/m), $\theta$ is the contact angle between mercury and the pore surface (°), and $S$ is the pore surface area (m²).

The expression of the mercury advance $Q_n$ and the corresponding surface energy $W_n$ can be obtained as follows:

$$W_n = \sum_{i=1}^{n} Pi \Delta Vi, \quad Q_n = V_n^{1/3}/r_n$$  \hspace{1cm} (4)

$$\Delta V_{obs} = \Delta V_p + \Delta V_c$$  \hspace{1cm} (5)

Zhang et al. (2006) modified equation (5) and obtained equation (6):

$$\ln\left(\frac{W_n}{r_n^2}\right) = D \ln\left(\frac{V_n^{1/3}}{r_n}\right) + C$$  \hspace{1cm} (6)

In the formula: $V_n$ is the pore volume and the slope is the fractal dimension $D$ of the pore surface.

**Results**

**Proximate and maceral analyses**

Table 2 shows the analysis results of coal macerals in the Yining mining area. The vitrinite reflectance ($R_o$, in oil) ranged from 0.34% to 0.37%, indicating that the samples have
| Sample ID | T | C1 | C2 | C3 | VD | Total | F | Sf | Fu | Ma | Mi | ID | Total | Total | Total | Total |
|-----------|---|----|----|----|----|-------|---|----|----|----|----|----|-------|-------|-------|-------|
| YN-01     | 20.5 | 7.5 | 39.2 | 0 | 0 | 67.2 | 6.1 | 10.8 | 0 | 0.9 | 1.4 | 19.2 | 0.5 | 13.1 | 0.34 |
| YN-02     | 0.9 | 0.3 | 3.8 | 0 | 0 | 4.7 | 4.7 | 63.5 | 0 | 0.5 | 3.8 | 4.7 | 77.2 | 1.9 | 16.2 | 0.34 |
| YN-03     | 0 | 0 | 3.1 | 0 | 0.4 | 3.5 | 11.5 | 71.7 | 0 | 0.9 | 0.4 | 10.3 | 94.8 | 0.8 | 0.9 | 0.35 |
| YN-04     | 1 | 0 | 2.3 | 0 | 0.5 | 3.8 | 8.7 | 73.5 | 0 | 0 | 1.4 | 5.8 | 89.4 | 4.4 | 2.4 | 0.35 |
| YN-05     | 1.43 | 6.67 | 56.2 | 1 | 0 | 65.3 | 3.81 | 8.1 | 0 | 0.48 | 1.9 | 2.86 | 17.2 | 1.4 | 16.2 | 0.35 |
| YN-06     | 18.7 | 11.4 | 50.1 | 1.8 | 0 | 82.0 | 3.6 | 9.6 | 0 | 0 | 1.4 | 0.5 | 15.1 | 1.4 | 1.5 | 0.35 |
| YN-07     | 0 | 2.8 | 17.7 | 0 | 0 | 20.5 | 8.2 | 57.3 | 0 | 0.5 | 9.5 | 75.5 | 1.9 | 2.1 | 0.35 |
| YN-08     | 1.5 | 1.0 | 7.0 | 0 | 0 | 9.5 | 7.5 | 65.9 | 0 | 2.5 | 0.5 | 6 | 82.4 | 2 | 6.1 | 0.36 |
| YN-09     | 1.7 | 0.9 | 8.7 | 0 | 0 | 11.3 | 15.2 | 58.4 | 0 | 0 | 12.1 | 85.7 | 0.8 | 2.2 | 0.36 |
| YN-10     | 5.6 | 0.9 | 26.8 | 0.5 | 0 | 33.8 | 12.7 | 47.9 | 0 | 0.5 | 3.7 | 64.8 | 0.5 | 0.9 | 0.36 |
| YN-11     | 5.5 | 3.7 | 23.1 | 0 | 0 | 32.3 | 10.6 | 49.2 | 0 | 0.5 | 1.8 | 4.1 | 66.2 | 1 | 0.5 | 0.36 |
| YN-12     | 9.7 | 3.1 | 61.5 | 1.3 | 0 | 75.6 | 4.0 | 11.5 | 0 | 0 | 0.9 | 1.3 | 17.7 | 3.1 | 3.6 | 0.36 |
| YN-13     | 6 | 2.2 | 22.1 | 0.5 | 0.5 | 31.3 | 13.8 | 42.9 | 0 | 0.5 | 0.9 | 8.3 | 66.4 | 0.5 | 1.8 | 0.35 |
| YN-14     | 4.7 | 1.4 | 23.0 | 0 | 1.4 | 30.5 | 14.1 | 44.1 | 0 | 0.9 | 0 | 8.5 | 67.6 | 0 | 1.9 | 0.37 |
| YN-15     | 3.8 | 3.0 | 54.9 | 0 | 0 | 61.7 | 6.0 | 14.8 | 0.4 | 0.4 | 0.9 | 11.1 | 33.6 | 2.59 | 2.14 | 0.37 |
| YN-16     | 5.4 | 0.8 | 20.8 | 0 | 0 | 27.0 | 14.9 | 48.6 | 0 | 0.4 | 0 | 7.9 | 71.8 | 0 | 1.2 | 0.37 |
| YN-17     | 15.3 | 3.5 | 51.1 | 0 | 0 | 69.9 | 2.6 | 15.3 | 0 | 0.4 | 0.9 | 7.4 | 26.6 | 2.6 | 0.9 | 0.37 |
| YN-18     | 5.0 | 3.5 | 60.4 | 4 | 0 | 72.9 | 1.5 | 16.1 | 0 | 1.0 | 1.5 | 20.1 | 5.5 | 1.5 | 0.37 |

Note: T denotes telinite; C1 denotes telocollinite; C2 denotes desmocollinite; C3 denotes corpovitrinites; VD denotes vitrodetrinite; F denotes fusinite; Sf denotes semifusinite; Fu denotes funginite; Ma denotes macrosome; Mi denotes microsome; ID denotes inertodetrinite.
experienced the same coalification process in the later stage. All the samples are characterized by high organic matter content (above 90%), and the inertinite content ranges from 15.1% to 94.8%; the vitrinite content accounts for between 3.5% and 82%. The proportion of exinite and mineral is the least, which is less than 2.0%. As Table 2 shows, the inertinite is dominated by semifusinite with proportions ranging from 8.1% to 73.5%, followed by fusinite and inertodetrinite; while the vitrinite is dominated by desmocollinite with proportions between 2.3% and 61.5%, followed by telocollinite and telinite.

**Trace element and organic matter stable carbon isotopes analyses**

The results of the organic carbon isotopic composition and trace element analyses are listed in Table 3. The content of Sr ranges from 68.3 ug/g to 238 ug/g and averages at 159 ug/g, which is higher in the upper part of the vertical coal seam than in the lower part. The content of Ba ranges from 7.45 ug/g to 592 ug/g and averages at 79.5 ug/g. The overall change of Ba content in the vertical direction is small and abnormally high values appear at the bottom of the coal seam. The content of Th is between 0.18 ug/g and 3.24 ug/g, with an average of 0.65 ug/g. The overall change of Th content in the vertical direction is weak; high values appear in the upper and middle coal seams. The content of U ranges from 0.06 ug/g to 1.22 ug/g and averages at 0.32 ug/g. Its content in the vertical direction has almost no changes in the middle and lower parts of the coal seam; the upper and middle parts of the coal seam have an oscillating change. The content of Rb ranges from 0.23 ug/g to 1.41 ug/g and averages at 0.61 ug/g, which is higher in the upper part of the vertical coal seam than in the lower part. The ratios of Sr/Ba, Th/U, and Rb/Sr are 0.14 to 25.4, 0.16 to 4.2, and 0.13 to 0.97, respectively, all of which have large changes. The organic carbon stable carbon isotope is $-24.7$ to $-21.6$, with an average of $-23.3$, which is higher in the middle of the coal seam and slightly smaller in the upper and lower parts.

**Table 3. Results of organic carbon isotopic composition and trace elements in Yining mining area.**

| Sample ID | Sr(μg/g) | Ba(μg/g) | Th(μg/g) | U(μg/g) | Rb(μg/g) | $\delta^{13}C_{\%PDB}$ |
|-----------|----------|----------|----------|---------|----------|-----------------|
| YN-01     | 160      | 21.3     | 0.65     | 0.24    | 1.41     | $-22.5$         |
| YN-02     | 199      | 11.1     | 0.92     | 1.13    | 1.30     | $-22.9$         |
| YN-03     | 181      | 29.2     | 0.51     | 0.27    | 0.37     | $-23.3$         |
| YN-04     | 238      | 9.37     | 0.84     | 0.22    | 0.76     | $-23.2$         |
| YN-05     | 119      | 12.3     | 3.24     | 1.05    | 0.90     | $-23.7$         |
| YN-06     | 68.3     | 72.5     | 0.55     | 0.20    | 0.66     | $-23.2$         |
| YN-07     | 202      | 137      | 1.08     | 0.27    | 0.58     | $-22.6$         |
| YN-08     | 212      | 19.6     | 0.35     | 0.12    | 0.48     | $-21.6$         |
| YN-09     | 184      | 10.1     | 0.31     | 0.09    | 0.24     | $-22.4$         |
| YN-10     | 151      | 17.7     | 0.35     | 0.14    | 1.00     | $-23.2$         |
| YN-11     | 105      | 79.5     | 0.29     | 0.07    | 0.36     | $-24.3$         |
| YN-12     | 124      | 216      | 0.18     | 0.06    | 0.28     | $-24.3$         |
| YN-13     | 189      | 39.9     | 0.24     | 0.06    | 0.30     | $-24.7$         |
| YN-14     | 155      | 7.90     | 0.19     | 0.06    | 0.32     | $-23.8$         |
| YN-15     | 172      | 7.45     | 0.37     | 0.18    | 0.35     | $-23.8$         |
| YN-16     | 147      | 7.90     | 0.74     | 0.22    | 0.61     | $-23.3$         |
| YN-17     | 165      | 140      | 0.60     | 0.15    | 0.75     | $-24.3$         |
| YN-18     | 83.5     | 592      | 0.20     | 1.22    | 0.23     | $-22.6$         |
**Pore structures by MIP**

The results of the MIP experiments are shown in Table 4 and Figure 3. The porosity ranges from 10.6% to 30.5%, with an average of 21.2%. The total pore volume is between $7.7 \times 10^{-2} \text{cm}^3/\text{g}$ and $28.4 \times 10^{-2} \text{cm}^3/\text{g}$, with an average of $17.0 \times 10^{-2} \text{cm}^3/\text{g}$. There are some differences in the distribution of pore volume of different pore sizes. The pore volume of mesopores and macropores accounts for the largest proportion, followed by transition pores; micropores account for the smallest proportion. The pore volume distribution of macropores ($>1000\text{ nm}$) is $1.05-14.4 \times 10^{-2} \text{cm}^3/\text{g}$, with an average of $6.07 \times 10^{-2} \text{cm}^3/\text{g}$. The pore volume of the mesopores (with pore diameters of 100–1000 nm) is $0.93-12.47 \times 10^{-2} \text{cm}^3/\text{g}$, with an average of $6.12 \times 10^{-2} \text{cm}^3/\text{g}$. The pore volume of the transition pores (with pore diameters of 10–100 nm) is $2.32-6.19 \times 10^{-2} \text{cm}^3/\text{g}$, with an average of $3.73 \times 10^{-2} \text{cm}^3/\text{g}$. The pore volume of micropores (pore diameter $<10\text{ nm}$) is $0.8-1.49 \times 10^{-2} \text{cm}^3/\text{g}$, with an average value of $1.05 \times 10^{-2} \text{cm}^3/\text{g}$. The maximum mercury saturation is 86.5–97.2%, with an average of 94.8% and the efficiency of mercury withdrawal is 13.2–49.9%, with an average of 26.8%. It can be concluded from the maximum mercury saturation and mercury withdrawal efficiency that the samples have relatively poor pore connectivity.

**Pore structures by N$_2$ adsorption/desorption**

The adsorption/desorption curve contains pore structure information such as specific surface area, pore size distribution, pore volume, pore shape, and fractal characteristics. It is mainly used to test the micropore and transition pore characteristics (Brunauer et al., 1938; Gan et al., 1972; Groen et al., 2003; Khalili et al., 2000; Mastalerz et al., 2012; Nie et al., 2015; Pyun and Rhee, 2004; Rouquerol et al., 1994; Tang et al., 2016; Wang et al., 2020; Xu et al., 2010).

This study adopts the classification of pores in coal proposed by Chen and Tang (2001) and divides coal pores into three types: one-side-closed (Type I), two-sides-opened (Type II), and bottleneck pores (Type III). One-side-closed pores include the cylindrically shaped pores (type I-1), parallel plate-shaped pores (type I-2), wedge-shaped pores (type I-3), tapered pores (type I-4), and slit-shaped pores (type I-5). The two-sides-opened pores include cylindrical-shaped pores with open ends (type II-1) and parallel plate-shaped pores with four open sides (type II-2). Chen and Tang (2001) suggested that two-sides-opened and bottleneck pores cause hysteresis in the isotherms mentioned above; in which a sharp decrease in desorption isotherms indicated the existence of bottleneck pores, while the overlapping isotherms were caused by one-side-closed pore. The adsorption/desorption isotherms are shown in Figure 4. According to Figure 4, there are three adsorption/desorption isotherms. The adsorption isotherms of type A (YN-04, YN-07–YN-11, YN-13-14, and YN-16) are horizontal and parallel to the desorption isotherms. The isotherms of adsorption and desorption are reversible in the whole relative pressure range, indicating that there are mainly type-I pores in the range of small apertures, and in addition to the type-I pores, there are also a small number of type II pores in the mesopores and macropores. The difference between type B (YN-02, YN-03) and type A of the hysteresis loop is that the adsorption and desorption curves are only parallel to each other and do not overlap between a relative pressure of 0 and 0.5. These three samples show a lack of total closure of the low-pressure hysteresis loop, which has been interpreted as being due to swelling or adsorption in
Table 4. Results of mercury porosimetry experiments.

| Sample ID | Porosity (%) | Mercury saturation (%) | Withdrawal efficiency (%) | Volume of different pore sizes ($10^{-2} \text{cm}^3/\text{g}$) | Pore volume ratio (%) |
|-----------|--------------|------------------------|---------------------------|-------------------------------------------------|----------------------|
|           |              |                        |                           | $V_1$ | $V_2$ | $V_3$ | $V_4$ | $V_1$ | $V_2$ | $V_3$ | $V_4$ |
| YN-01     | 10.6         | 90.6                   | 39.3                      | 7.70  | 1.37  | 2.54  | 1.54  | 2.22  | 17.9 | 33.1 | 20.1 | 28.9 |
| YN-02     | 25.0         | 96.3                   | 19.7                      | 20.6  | 0.81  | 3.03  | 12.47 | 4.27  | 3.94 | 14.7 | 60.6 | 20.7 |
| YN-03     | 29.2         | 97.2                   | 18.6                      | 17.0  | 0.80  | 2.32  | 8.15  | 5.69  | 4.72 | 13.7 | 48.1 | 33.5 |
| YN-04     | 19.2         | 95.3                   | 24.7                      | 14.3  | 0.92  | 4.36  | 6.77  | 2.22  | 6.45 | 30.6 | 47.4 | 15.6 |
| YN-05     | 15.4         | 94.2                   | 37.4                      | 11.4  | 1.07  | 3.88  | 1.71  | 4.69  | 9.43 | 34.2 | 15.1 | 41.3 |
| YN-06     | 10.7         | 91.1                   | 37.5                      | 7.80  | 1.03  | 2.95  | 1.58  | 2.27  | 13.2 | 37.7 | 20.2 | 29.0 |
| YN-07     | 29.5         | 97.0                   | 14.5                      | 25.4  | 0.92  | 2.93  | 11.3  | 10.3  | 3.62 | 11.5 | 44.2 | 40.6 |
| YN-08     | 26.0         | 96.5                   | 19.8                      | 17.9  | 0.84  | 3.13  | 8.16  | 5.80  | 4.68 | 17.5 | 45.5 | 32.3 |
| YN-09     | 24.0         | 96.4                   | 20.2                      | 23.6  | 1.14  | 3.72  | 11.2  | 7.51  | 4.84 | 15.8 | 47.5 | 31.9 |
| YN-10     | 27.7         | 96.8                   | 16.9                      | 23.9  | 1.07  | 3.93  | 10.2  | 8.68  | 4.48 | 16.5 | 42.7 | 36.3 |
| YN-11     | 28.2         | 96.8                   | 13.2                      | 24.2  | 0.94  | 3.11  | 6.62  | 13.5  | 3.89 | 12.9 | 27.4 | 55.9 |
| YN-12     | 14.0         | 93.6                   | 46.9                      | 10.4  | 1.05  | 6.19  | 0.93  | 2.20  | 10.1 | 59.7 | 8.97 | 21.2 |
| YN-13     | 23.1         | 96.1                   | 18.4                      | 19.4  | 1.02  | 3.77  | 5.84  | 8.72  | 5.27 | 19.5 | 30.2 | 45.1 |
| YN-14     | 30.5         | 97.2                   | 16.1                      | 28.4  | 1.05  | 3.60  | 9.36  | 14.4  | 3.70 | 12.7 | 33.0 | 50.7 |
| YN-15     | 15.3         | 94.2                   | 37.2                      | 11.5  | 1.13  | 5.62  | 2.35  | 2.41  | 9.82 | 48.8 | 20.4 | 20.9 |
| YN-16     | 25.9         | 96.5                   | 17.1                      | 21.5  | 1.10  | 3.57  | 7.56  | 9.25  | 5.12 | 16.6 | 35.2 | 43.1 |
| YN-17     | 16.4         | 94.7                   | 34.8                      | 12.5  | 1.16  | 4.37  | 2.97  | 3.99  | 9.29 | 35.0 | 23.8 | 31.9 |
| YN-18     | 11.6         | 86.5                   | 49.9                      | 8.30  | 1.49  | 4.18  | 1.53  | 1.05  | 18.1 | 50.7 | 18.5 | 12.7 |
| Averages  | 21.2         | 94.8                   | 26.8                      | 17.0  | 1.05  | 3.73  | 6.12  | 6.07  | 6.19 | 22.0 | 36.07 | 35.74 |

Note: $V_1$, micropore volume (<10 nm); $V_2$, transition pore volume (10–100 nm); $V_3$, mesopore volume (100–1000 nm); $V_4$, macropore volume (>1000 nm); $V_t$, total volume.
micropores (Cai et al., 2013). The shape of the hysteresis loop in these samples reflects that the pore shape types are mainly one-side-closed pores, and there is a small number of two-sides-opened pores. The adsorption isotherms of type C mainly exist in samples YN-01, YN-05, YN-06, YN-12, YN-15, YN-17 and YN-18. In these samples, apertures less than 4 nm mainly consist of one-side-closed pores, while apertures greater than 4 nm mainly consist of two-sides-opened pores and bottleneck pores, and contain a small number of one-side-closed pores. In summary, the three types of pores are developed (Figure 4).

Most of the samples mainly include type I and II pores, however, some samples contain type III pores (Table 5).

Table 5 shows the specific surface area and pore volume results obtained by using the Brunauer, Emmett, and Teller (BET) and Barrett, Joyner, and Halenda (BJH) methods,
Table 5. Results of N$_2$ adsorption/desorption experiments.

| Sample ID | BET specific surface area (m$^2$/g) | BJH specific surface area of different pore sizes (m$^2$/g) | BJH total pore volume ($10^{-3}$cm$^3$/g) | Volume of different pore sizes ($10^{-3}$cm$^3$/g) | Maximum monolayer adsorption capacity (cm$^3$/g) | Total adsorption capacity (cm$^3$/g) | Main pore shape types |
|-----------|-----------------------------------|-------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------|
| YN-01     | 0.50                              | 0.43 0.35 0.02                                 | 4.23                            | 0.52 2.59 1.07                   | 0.05                            | 2.61                            | I + II + III        |
| YN-02     | 2.21                              | 0.16 0.68 0.06                                 | 0.27 6.21 2.58                   | 0.05                            | 6.31                            | I                               |
| YN-03     | 2.89                              | 0.95 0.88 0.05                                 | 1.36 6.72 2.01                   | 0.42                            | 7.00                            | I                               |
| YN-04     | 2.29                              | 0.38 1.20 0.06                                 | 1.61 10.4 2.51                   | 0.13                            | 8.78                            | I                               |
| YN-05     | 0.76                              | 0.46 0.45 0.04                                 | 0.61 3.73 1.95                   | 0.05                            | 6.31                            | I + II + III                   |
| YN-06     | 0.36                              | 0.33 0.35 0.02                                 | 0.47 2.64 1.02                    | 0.46                            | 7.46                            | I                               |
| YN-07     | 1.38                              | 0.98 0.69 0.11                                 | 1.37 6.98 5.39                   | 0.29                            | 7.46                            | I                               |
| YN-08     | 1.62                              | 0.30 0.83 0.09                                 | 0.44 7.55 3.71                   | 0.19                            | 8.46                            | I                               |
| YN-09     | 1.73                              | 0.35 0.72 0.08                                 | 0.50 6.87 3.31                   | 0.29                            | 7.07                            | I                               |
| YN-10     | 1.48                              | 0.26 0.55 0.05                                 | 0.38 4.88 2.22                   | 0.25                            | 5.01                            | I                               |
| YN-11     | 1.54                              | 0.97 0.63 0.06                                 | 1.31 5.02 2.49                   | 0.24                            | 5.74                            | I                               |
| YN-12     | 1.04                              | 0.35 0.49 0.07                                 | 0.49 4.45 2.96                   | 0.17                            | 5.16                            | I + II + III                   |
| YN-13     | 1.24                              | 0.63 0.52 0.07                                 | 0.82 4.52 3.02                   | 0.20                            | 5.41                            | I                               |
| YN-14     | 1.77                              | 0.28 0.65 0.07                                 | 0.43 5.87 2.87                   | 0.31                            | 6.18                            | I                               |
| YN-15     | 0.50                              | 0.98 0.21 0.02                                 | 1.16 1.36 0.94                   | 0.07                            | 2.12                            | I + II + III                   |
| YN-16     | 1.07                              | 0.25 0.44 0.04                                 | 0.36 3.79 1.52                   | 0.16                            | 3.76                            | I                               |
| YN-17     | 0.77                              | 0.92 0.37 0.04                                 | 1.14 2.78 1.72                   | 0.13                            | 4.16                            | I + II + III                   |
| YN-18     | 0.43                              | 0.12 0.59 0.05                                 | 0.23 4.40 2.18                   | 0.05                            | 3.46                            | I + II + III                   |
respectively. The BET specific surface area of the samples ranges from 0.36 m$^2$/g to 2.89 m$^2$/g, with an average of 1.31 m$^2$/g. The micropore specific surface area ranges from 0.12 m$^2$/g to 0.98 m$^2$/g, with an average of 0.55 m$^2$/g, and the transition pore specific surface area ranges from 0.21 m$^2$/g to 1.2 m$^2$/g, with an average of 0.59 m$^2$/g. The total pore volume ranges from 3.52 cm$^3$/g to 13.5 \times 10^{-3}$ cm$^3$/g, with an average of 8.14 \times 10^{-3}$ cm$^3$/g. The micropore volume of the samples ranges from 0.23 \times 10^{-3}$ cm$^3$/g to 1.36 \times 10^{-3}$ cm$^3$/g, and the transition pore volume between 1.36 \times 10^{-3}$ cm$^3$/g and 10.4 \times 10^{-3}$ cm$^3$/g, with an average of 5.04 \times 10^{-3}$ cm$^3$/g. The corresponding total adsorption capacity at the maximum relative pressure ranges from 2.12 cm$^3$/g to 8.78 cm$^3$/g, with an average of 5.29 cm$^3$/g; the maximum monolayer adsorption capacity is 0.05 cm$^3$/g to 0.52 cm$^3$/g, with an average of 0.22 cm$^3$/g.

**Pore genetic types from SEM**

There are many kinds of classification based on pore formation. Gan et al. (1972) divided the pores in coal into intermolecular, plant, thermogenic, and fracture pores. Hao (1987) divided the pores in coal into plant tissue pores, blowholes, intraparticle pores, intergranular pores, mold pores, and erosion pores. Zhang et al. (2003) divided the genetic types of coal pores into primary pores, epigenetic pores, exogenous pores and mineral pores based on the texture, structure, metamorphism, and deformation theory and process of coal. The surface morphology of coal is observed by SEM in this paper, as shown in Figure 5.

It mainly develops tissue pores, followed by clastic pores and blowholes, while exogenous pores and mineral pores are almost invisible in the coal of the Yining mining area. Tissue pores are visible in all coal samples and are more common in coal with higher inertinite content (Figure 5(a) to (e) and (h)). This is because tissue pores are mostly developed in fusinites and semifusinites, which are the main components of the inertinite. The diameters of tissue pores are relatively large, ranging from 2 μm to 10 μm, and usually develop in one direction. The pore shape types are mainly the pores with one end open, including wedge-shaped pores, cylindrical pores, tapered pores, and a small number of pores that are open at both ends, however, there is little connectivity between them. Tissue pores are generally found in telinites and telinites which are less developed in vitrinites, therefore, Tissue pores are rare in vitrinites. As shown in Figure 5(f), the cell structure has been deformed. The pore shapes are mainly those with one end open, including wedge-shaped pores, cylindrical pores, tapered pores, and a small number of ink bottle pores with one end open.

Clastic pores are the fractures that accumulate between organic fragments such as vitrodetrinite, inertodetrinite, and exodetrinite in the coal. They are mainly closed at one end. The content of inertodetrinite is more than vitrodetrinite, so clastic pores are more easily observed in inertinite (Figure 5(g) and (h)). Blowholes are mainly developed in the desmocollinites (Figures 5(m), (o), and (p) and (i)) and corpovitrinites (Figures 5(k), (l), and (n) and 5(j)) in vitrinite; they are unevenly distributed. The shapes of blowholes are mainly oval and circular, followed by droplet and harbor shapes. The pore sizes of a single blowhole are mainly 0.01–5 μm, and longitudinal lengths up to 10 μm and 25 μm can be occasionally observed. The pore combination is dominated by stomata pits (Figure 5(j) to (n)), scattered blowholes (Figure 5(i)), and stomata bands (Figure 5(p)), however, the stomata groups (Figure 5(o)) are rarely observed. Stomatal pits are mainly round and oval, with diameters of 10 μm to 30 μm. The shape of blowholes in stomatal pits is mainly circular and some stomata are connected by ruptures. The diameter of these blowholes is 0.5–4 μm, mainly...
The scattered blowholes are mainly oval and circular, with diameters of 0.5 μm to 10 μm; rupture and connectivity, in this case, are less observed. In general, the blowholes are mostly open at both ends and the connectivity is good. Mineral intergranular pores are also observed (Figure 5(r) and (s)), mainly including intergranular pores between kaolinite mineral particles and nodular pyrite mineral particles. Broken pores are occasionally observed in inertinite (Figure 5(q)), in which the particles are round, sub-circular, and flaky. The size of the particles is less than 2 μm and the pore diameter ranges from 0.1 to 0.5 μm. Breccia pores are occasionally observed in vitrinite (Figure 5(t)). The shapes of the breccia are straight and pointed, and their size is greater than 15 μm; the size of the breccia pores is approximately 0.5 μm.

**Fractal dimension**

The logarithmic curve of the volume and relative pressure of N₂ adsorption/desorption is made based on the formulas (1) and (2). It can be seen from Figure 6 that the fractal characteristics of the adsorption pores are divided into three distinct linear segments based on the relative pressure and they all show good fits. The P/P₀ of the first segment...
is 0–0.05 and the corresponding apertures range from 0.37 nm to 0.64 nm, calculated according to the Kelvin equation. The fractal dimension of this segment is \( D_1 \). The \( P/P_0 \) of the second segment is 0.05–0.5 with a corresponding aperture range from 0.64 nm to 2.02 nm; the fractal dimension of this segment is \( D_2 \). The \( P/P_0 \) of the third segment is 0.5–1.0 with the corresponding apertures ranging from 2.02 nm to 100 nm; the fractal dimension of this segment is \( D_3 \). The fractal model of the adsorption pores of No. 4 coal in the Yining mining area was established using FHH fractal theory; the fractal dimension is calculated as shown in Table 6. According to the fractal geometry theory, the fractal dimension of porous materials in Euclidean space should be between 2.0 and 3.0. From Table 6 it is evident that the fractal dimensions \( D_1 \) are all less than 2, indicating that the pores in this section do not have fractal features. The fractal dimensions \( D_2 \) and \( D_3 \) of the pores in the second and third sections are between 2–3, which have good fractal characteristics. It can be observed from Figure 6 that the double logarithmic curve of the coal sample has a good fit. The pore fractal dimension \( D_2 \) with pore diameter ranging from 0.64 to 2.02 nm is 2.51 to 2.87, with an average of 2.70, and the pore fractal dimension \( D_3 \) with pore diameter ranging from 2.02 nm to 100 nm is 2.33 to 2.56 with an average of 2.43.

Figure 7 shows the relationship curve of \( \ln (W_n/r_n^2) - \ln (V_n^{1/3}/r_n) \) obtained from the mercury intrusion porosimetry experiment. The thermodynamic curves of the coal samples all show good fits, and correlation coefficients are all 0.99. The fractal dimension of the seepage pores is 2.75–2.95, with an average of 2.86. It was concluded that the pore structure of micropores is more complicated than that of transition pores; the pore structures of mesopores and macropores are the most complicated and their homogeneity is poor.

**Discussion**

**Division of the cyclicity of thick coal seam**

The transition surface (i.e. the transition surface where the water level begins to decrease) that changes from the water-transgression cycle to the water-regression cycle during the deposition process of the thick coal seam is called “transgressive hiatal surface,” and is conversely called “regressive hiatal surface”. In this paper, a method based on macerals,
Table 6. Results of fractal dimension calculation.

| Sample ID | 0.37~0.64nm (N2 adsorption) | 0.64~2.02nm (N2 adsorption) | 2.02~100nm (N2 adsorption) | 100~210901nm (mercury injection) |
|-----------|-----------------------------|-----------------------------|----------------------------|---------------------------------|
|           | $A_1$, $R_1^2$, $D_1 = A_1 + R_1^2$ | $A_2$, $R_2^2$, $D_2 = A_2 + R_2^2$ | $A_3$, $R_3^2$, $D_3 = A_3 + R_3^2$ | $D_{12} = A_1$, $R_2^2$ |
| YN-01     | -2.79, 0.92, 0.21           | -0.49, 0.99, 2.51           | -0.61, 0.99, 2.39           | 2.77, 0.99                     |
| YN-02     | -1.00, 0.93, 2.00           | -0.13, 0.95, 2.87           | -0.51, 0.99, 2.49           | 2.93, 0.99                     |
| YN-03     | -1.67, 0.95, 1.33           | -0.29, 0.99, 2.71           | -0.44, 0.99, 2.56           | 2.93, 0.99                     |
| YN-04     | -1.24, 0.92, 1.76           | -0.17, 0.98, 2.83           | -0.60, 0.99, 2.40           | 2.95, 0.99                     |
| YN-05     | -1.35, 0.94, 1.66           | -0.36, 0.96, 2.64           | -0.67, 0.99, 2.33           | 2.75, 0.99                     |
| YN-06     | -2.47, 0.91, 0.53           | -0.41, 0.99, 2.59           | -0.66, 0.99, 2.34           | 2.76, 0.99                     |
| YN-07     | -1.58, 0.95, 1.42           | -0.30, 0.99, 2.70           | -0.55, 0.99, 2.45           | 2.91, 0.99                     |
| YN-08     | -1.46, 0.90, 1.54           | -0.15, 0.95, 2.85           | -0.64, 0.99, 2.36           | 2.92, 0.99                     |
| YN-09     | -1.67, 0.84, 1.33           | -0.30, 1.00, 2.70           | -0.54, 0.99, 2.46           | 2.92, 0.99                     |
| YN-10     | -1.29, 0.94, 1.71           | -0.25, 0.99, 2.76           | -0.53, 0.99, 2.47           | 2.89, 0.99                     |
| YN-11     | -1.52, 0.92, 1.48           | -0.29, 0.99, 2.71           | -0.49, 0.99, 2.51           | 2.84, 0.99                     |
| YN-12     | -1.45, 0.94, 1.55           | -0.32, 0.99, 2.68           | -0.58, 0.99, 2.42           | 2.80, 0.99                     |
| YN-13     | -1.41, 0.94, 1.59           | -0.30, 1.00, 2.70           | -0.53, 0.99, 2.47           | 2.86, 0.99                     |
| YN-14     | -1.50, 0.87, 1.50           | -0.20, 0.98, 2.80           | -0.54, 0.99, 2.46           | 2.90, 0.99                     |
| YN-15     | -1.87, 0.96, 1.13           | -0.43, 0.93, 2.57           | -0.61, 0.99, 2.39           | 2.78, 0.99                     |
| YN-16     | -1.87, 0.92, 1.14           | -0.30, 0.98, 2.70           | -0.53, 0.99, 2.47           | 2.92, 0.99                     |
| YN-17     | -1.44, 0.94, 1.56           | -0.35, 0.99, 2.65           | -0.55, 0.99, 2.45           | 2.77, 0.99                     |
| YN-18     | -2.10, 0.90, 0.91           | -0.43, 0.99, 2.57           | -0.60, 0.99, 2.40           | 2.82, 0.99                     |

Note: $A_1$, $R_1^2$, and $D_1$ are slope, correlation coefficient and fractal dimension in the aperture range of 0.37~0.64nm; $A_2$, $R_2^2$, and $D_2$ are slope, correlation coefficient and fractal dimension in the aperture range of 0.64~2.02nm; $A_3$, $R_3^2$, and $D_3$ is the slope, correlation coefficient and fractal dimension in the aperture range of 2.02~100nm.
supplemented by characteristic trace elements and stable carbon isotopes of organic matter, is used to reflect the coal-forming plants and marsh medium conditions during peat accumulation, to identify the sedimentary hiatal surfaces, and to divide the cycles of thick coal seam.

Basis of division.

1. Division of the cycles of thick coal seam based on maceral analyses

According to previous research results, vitrinite is formed by gelification in the conditions of which water is deep and reductive, and inertinite is formed by fusinization in dry and hot oxidizing environments. In a moist peat swamp environment with deep water cover, peatification is dominated by gelification and the content of vitrinite in the coal is higher. Otherwise, in dry peat swamp environments with shallow water cover, peatification is dominated by fusinization and has a higher content of inertinite (Han et al., 1996; Yang and Dexin, 1979). Therefore, the inertinite content is higher at water-transgression hiatal surfaces. The content of the vitrinite is higher and inertinite content lower at regressive hiatal surfaces (Jerrett et al., 2011; Shearer et al., 1994; Wang et al., 2018). There is no necessary correspondence between inorganic mineral content and sedimentary hiatal surface types; however, it usually shows relatively high or low value in hiatal surfaces. Therefore, mineral content serves as an auxiliary reference for the classification of water-transgression and water-regression cycles (Singh et al., 2015).

The structure preservation index (TPI), gelification index (GI), vitrinite/inertinite ratio index (V/I), and vegetation index (VI) are also used to analyze the vertical sedimentary evolution of coal seams (Calder et al., 1991; Diessel, 1992b; Harvey and Dillon, 1985; Li et al., 2018; Rajak et al., 2019; Singh et al., 2017). The TPI indicates tissue degradation and the proportion of woody plants in coal-forming plants; the larger the TPI value, the lower the peat swamp water level, the weaker the gelification of the plant remains, and the lower the degree of plant tissue degradation. A high TPI value indicates that the proportion of woody plants in coal-forming plants is higher than that of herbaceous plants. The GI is the ratio of gelification components to non-gelatinized components, which reflects the wet degree and duration of peat mire; it represents the water level change characteristics of ancient peat swamps in the early stages of peat formation and the degree of gelification of
plant remains. The higher the GI value, the deeper the swamp water and the stronger the reducibility of the medium. Otherwise, the medium is more oxidative (Diessel, 1992a; Singh et al., 2019). The VI also can reflect the proportion of woody plants and herbaceous plants in coal-forming plants; the larger the VI value, the more woody plants contained in coal-forming plants (Calder et al., 1991; Prakash et al., 2017). The V/I can reflect the level of marsh water near the river. Higher values of V/I usually reflects that the swamp environment is humid and reductive, while lower values of V/I reflects that the swamp environment is dry and oxidative (Harvey and Dillon, 1985). Therefore, the TPI and VI values of water-transgression hiatal surfaces are low and the GI and V/I values are high. In contrast, the above indexes have opposite characteristics for regressive hiatal surfaces.

Based on the above theory, 4 water-transgression hiatal surfaces (T1, T2, T3, and T4) and 4 regressive hiatal surfaces (R1, R2, R3, and R4) were identified in the No. 4 coal seam of the Xishanyao formation in the Yining mining area. They are roughly divided into 4 water-transgression/water-regression cycles from bottom to top (Figure 8(a)).

2. Division of the cycles of thick coal seam based on trace elements

The contents and ratios of trace elements in sediments can also be used to indicate changes in sedimentary environments (Hatch et al., 1992; Reinhardt et al., 1998; Tao et al., 2009; Tribovillard et al., 2006). Sensitive paleoclimate trace element parameters such as the Rb/Sr ratio, Th/U ratio, and Sr/Ba ratio are good indicators of climatic wetness or drought and oxidation or reduction conditions. Rb/Sr, Th/U, and Sr/Ba ratios are relatively low at warm, wet, and reductive conditions (deeper water), and relatively high at hot, dry, and oxidic conditions (shallow water) (Chang et al., 2009; Liu et al., 1984). Therefore, the three ratios at regressive hiatal surfaces are characterized by high values, while at water-transgression hiatal surfaces, they are characterized by low values. Based on these, 4 water-transgression hiatal surfaces (T1, T2, T3, and T4) and 3 regressive hiatal surfaces (R1, R2, and R3) were identified in the No. 4 coal seam of the Xishanyao formation in the Yining mining area. They are roughly divided into 3 water-transgression/water-regression cycles and 1 water-transgression cycle from bottom to top (Figure 8(a)).
3. Division of the cycles of thick coal seam based on organic carbon stable carbon isotope

Humidity and temperature have an important effect on the carbon isotope composition of plants. Humidity has a negative correlation with the carbon isotope composition of plants. In arid climates, plant leaves adapt to the environment by adjusting surface stomatal conductance to change water use efficiency, thereby increasing the $\delta^{13}C$ value. As such, the $\delta^{13}C$ value of the organic carbon stable isotope in the coal seam can represent the temperature and humidity of the peat deposit. Therefore, as the temperature rises and the climate becomes dry, peat swamp environments become more oxidative and $\delta^{13}C$ becomes heavier. Conversely, as the temperature decreases and the climate becomes wet, peat swamp environments become more reductive and $\delta^{13}C$ becomes lighter (Stuiver and Braziunas, 1987; Wilson and Grinsted, 1977). The $\delta^{13}C$ value at transgressive hiatal surfaces becomes smaller, while at regressive hiatal surfaces it becomes larger. Based on the change of $\delta^{13}C$ value, 3 transgressive hiatal surfaces (T1, T2, and T3) and 4 regressive hiatal surfaces (R1, R2, R3, and R4) were identified in the No. 4 coal seam of the Xishanyao formation in the Yining mining area. They are roughly divided into 3 water-transgression/water-regression cycles and 1 water-regression cycle from bottom to top (Figure 8(a)).

Cycle division of No. 4 coal seam in the study area. Based on these methods, the sedimentary hiatal surfaces of the thick coal seam in the Yining mining area have been identified, and 4 water-transgression/water-regression cycles have been divided (Figure 8(a)). Figure 8(b) shows the evolution process of the peat mire in cycle I. With accommodation spaces gradually decreasing and the accumulation of peat increasing in the water-regression process, the peat is gradually oxidized, and the inertinite content increasing, resulting in the formation of regressive hiatal surfaces. While as accommodation spaces and the accumulation of peat gradually increasing in the water-transgression process, peatland moves toward land, the reducibility of the peat mire gradually enhancing, and the vitrinite content increasing, resulting in the formation of transgressive hiatal surfaces. The peat mire evolution of the other three cycles is similar to that of Cycle I, and the peat layers formed in the four-cycle stages are gradually stacked to form the No.4 thick coal seam.

Different identification methods have different sensitivities to sedimentary hiatal surfaces. To ensure the reliability of hiatal surfaces, weights are assigned to various methods. For the sedimentary hiatal surfaces, the method that can identify the sedimentary discontinuity is scored as 1 point, and unrecognizable as 0 points. The scores of various methods are multiplied by weights and summed up to 100 points. The higher the score, the more reliable the existence of the sedimentary hiatal surfaces (Wang et al., 2018). Table 7 shows the identification results of the sedimentary hiatal surfaces of the No. 4 thick coal seam in the Yining mining area. The scores of all sedimentary hiatal surfaces except T4 and R4 are high, indicating that the overall credibility of the cycle division of this coal seam is high (Table 7).

Control of cyclic changes of thick coal reservoir on the pore structure

Relationships between cyclic changes of thick coal seam and evolution of pore structure. Based on the division of water-transgression /water-regression cycles and the testing of pore structure, the porosity, total mercury injection pore volume, adsorption pore volume, seepage pore volume, maximum mercury saturation, mercury withdrawal efficiency, specific surface
area, total adsorption capacity, maximum monolayer adsorption capacity, and fractal dimension were compared vertically with the cycle changes (Figure 9). The parameters of the pore structure in the figure match well with the changes of the water-transgression/water-regression cycles. The porosity, total mercury pore volume, adsorption pore volume, seepage pore volume, maximum mercury saturation, specific surface area, total adsorption capacity, maximum monolayer adsorption capacity, and fractal dimension in cycles I and II gradually increased during the water-regression process and gradually decreased during the water-transgression process. However, mercury withdrawal efficiency decreased during the water-regression process and increased during the water-transgression process. The overall changes of the pore structure characteristics in cycles III and IV during the water-transgression and water-regression processes are similar to those of cycles I and II.

Table 7. Discriminant results of No. 4 coal’ hiatal surface in Xishanyao Formation of Yining Mining Area.

| Discriminated method | Macerals and coal quality | Microelement | Stable carbon isotope of organic matter | Total points |
|----------------------|---------------------------|--------------|----------------------------------------|--------------|
| Weight               |                           | Sr/Ba        | Th/U                                   | Rb/Sr        |              |
| T4                   | 1                         | 10           | 10                                     | 10           | 20           | 70           |
| R4                   | 1                         | 0            | 0                                      | 0            | 20           | 50           |
| T3                   | 1                         | 10           | 0                                      | 0            | 20           | 80           |
| R3                   | 1                         | 1            | 1                                      | 0            | 20           | 90           |
| T2                   | 1                         | 1            | 1                                      | 1            | 20           | 100          |
| R2                   | 1                         | 0            | 1                                      | 1            | 20           | 90           |
| T1                   | 1                         | 0            | 1                                      | 1            | 20           | 90           |
| R1                   | 1                         | 0            | 0                                      | 1            | 20           | 90           |

Figure 9. Changes of pore structure controlled by water-transgression and water-regression process: \( V_t \) is the total pore volume by the mercury injection test; \( V_a \) is the pore volume of the adsorption pores (<100nm) tested by nitrogen adsorption; MS is mercury saturation; MWE is mercury withdrawal efficiency; SSA is BET specific surface area; TAC is total adsorption capacity tested by nitrogen adsorption; MAC is the maximum monolayer adsorption capacity tested by nitrogen adsorption.
In cycle III, the adsorption pore volume, specific surface area, total adsorption capacity, maximum monolayer adsorption capacity, and fractal dimensions $D_2$ and $D_t$ are highly correlated with cycle changes; other parameters have local oscillation changes. The trend of the pore structure parameters in cycle IV is strongly correlated with the water-transgression/water-regression cycles, with only local small oscillatory changes at the top.

Table 8 shows the statistical results of the pore structure parameters in the four cycles. The pore volume of the mesopores and macropores in the four cycles changes greatly. The mesopore and macropore volumes in cycle III are the largest, followed by cycle II, and they decrease firstly and then increase from cycle I to cycle IV. The micropore and transition pore volume in the four cycles change relatively little, gradually increasing from cycle I to cycle IV. It can be concluded from the changes of pore volume that the distribution of porosity is as follows: cycle III > cycle II > cycle I > cycle IV. The distribution of the BET specific surface area in the four cycles is consistent with the change in the pore volume of the adsorption pores, which gradually increases from bottom to top. Mercury withdrawal efficiency reflects the connectivity of the pores. The mercury withdrawal efficiency gradually decreases from cycle I to cycle III and increases from cycle III to cycle IV. As such, the pore connectivity of cycle III is the worst. The fractal dimension distribution of the mesopore and macropore (100–1000 nm and >1000 nm) is cycle III > cycle II > cycle I > cycle IV, showing that the uniformity of seepage pore structure of cycle III is the worst and the uniformity of seepage pore structure of cycle IV is the best. Similarly, there are few differences in the uniformity of the pore structure of the adsorption pores (<100 nm); the uniformity of cycle II is the worst.

Control mechanism of cyclic changes on pore structure. When the degree of metamorphism is similar, the coal-forming environment becomes the main controlling factor of coal macerals and mineral development characteristics (Zhang et al., 2010). Different coal-forming environments have different plant combinations, hydrogeological conditions, and supply sources that control the coal compositions and affect the development of pore characteristics in coal reservoirs. When the long-term AR outpaces the PPR, the water table of the mire gradually rises and the coal forming environment becomes wetter and more reductive, which leads to the gelification gradually being strengthened. Conversely, when the long-term AR falls below the PPR, the water table of the mire gradually drop and the peat is exposed, oxidized, eroded and replaced by terrigenous clastic sediments, which leads to the fusinization gradually being strengthened.

It can be concluded by SEM observation that the pore types mainly include tissue pores, clastic pores, and blowholes. Tissue pores are mainly developed in telinites (T), fusinites (F), and semifusinite (SF). From ‘Trace element and organic matter stable carbon isotopes analyses’ section it is evident that the inertinite in the study area is dominated by fusinites and semifusinites (11.9%~83.2%, with an average of 47.7%). The total contents of $T+F+SF$ have a good positive correlation with porosity, seepage pore volume, and fractal dimension (Figure 10(a) to (e) and (g) to (i)), which indicates that there are more tissue pores. However, the total content of $T+F+SF$ has a strong negative correlation with the mercury withdrawal efficiency (Figure 10(f)), showing that the connectivity of tissue pores is poor. This is also corroborated by the fact that the tissue pores observed by the SEM usually develop in one direction and have less connection with each other. The $N_2$ adsorption/desorption experiments also confirm that the pore shape of coals rich in fusinites (F) and semifusinite (SF) is dominated by one-side-closed (Type I), and the connectivity is
### Table 8. The statistics of pore structure parameters in each cycle.

| Cycle | Porosity (%) | Volume of different pore sizes (cm$^3$/g) (>1000 nm is the result of mercury intrusion test, <100 nm is the result of nitrogen adsorption) | Seepage pore volume ($10^{-3}$ ml/g) | Adsorption pore volume ($10^{-3}$ ml/g) | BJH total pore volume (m$^2$/g) |
|-------|--------------|-------------------------------------------------|-----------------------------------|---------------------------------|------------------------|
|       |              | >1000 nm | 100–1000 nm | 10–100 nm | <10 nm |                                |                      |                   |                    |
| I     |              |          |             |            |          |                                |                      |                   |                    |
|       |              | 11.6–25.9 | 10.5–92.5   | 15.3–75.6  | 1.36–4.4 | 0.23–1.16 | 25.8–168.1 | 2.52–4.63 | 0.50–1.07 |
|       |              | 17.3     | 41.7        | 36.0       | 3.08     | 0.72      | 77.8      | 3.8      | 0.78     |
| II    |              | 14.0–30.5 | 22.0–144    | 9.29–93.6  | 4.45–5.87| 0.43–0.82 | 31.3–237  | 4.93–6.3 | 1.04–1.77 |
|       |              | 22.5     | 84.4        | 53.8       | 4.95     | 0.58      | 138       | 5.53     | 1.35     |
| III   |              | 10.7–29.5 | 22.7–135    | 15.8–113   | 2.64–7.55| 0.38–1.31 | 38.5–216  | 3.11–7.99 | 0.73–1.73 |
|       |              | 23.3     | 80.1        | 81.7       | 5.66     | 0.66      | 162       | 6.32     | 1.41     |
| IV    |              | 10.6–29.2 | 22.2–56.9   | 15.4–125   | 2.59–10.4| 0.27–1.36 | 37.6–167  | 3.11–11.0 | 0.76–2.89 |
|       |              | 19.9     | 38.2        | 61.3       | 5.92     | 0.68      | 99.5      | 6.6      | 1.82     |

| Fractal dimension | Cycle | D2 (0.64–2.02 nm) | D3 (2.02–100 nm) | Mercury saturation (%) | Withdrawal Efficiency (%) | Total adsorption capacity (cm$^3$/g) | Maximum monolayer adsorption capacity (cm$^3$/g) | Dt (> 100 nm) |
|------------------|-------|-------------------|-----------------|------------------------|--------------------------|-----------------------------------|------------------------------------------|-------------|
|                  | I     | 2.57–2.70         | 2.39–2.47       | 2.77–2.92              | 86.5–96.5                | 17.1–49.9                        | 2.12–4.16                               | 0.049–8.783 |
|                  | II    | 2.68–2.80         | 2.42–2.47       | 2.80–2.90              | 93.6–97.2                | 16.1–46.9                        | 2.16–6.18                               | 0.174–0.311 |
|                  | III   | 2.59–2.85         | 2.34–2.51       | 2.76–2.92              | 91.1–97.0                | 13.2–37.5                        | 2.54–8.46                               | 0.045–0.294 |
|                  | IV    | 2.51–2.87         | 2.33–2.56       | 2.75–2.95              | 90.6–97.2                | 18.6–39.3                        | 2.61–8.78                               | 0.049–0.163 |
|                  |       | 2.71              | 2.43            | 2.43                   | 94.7                     | 27.9                              | 5.73                                    | 0.102       |

Note: Above "–" is the interval value, and below "–" is the average value.
poor. It can be concluded that these three submacerals have a great effect on pore structures. Blowholes are developed in desmocollinites (C2) and corpovitrinites (C3). Vitrinite is mainly desmocollinite (2.3%–61.5%, average 30.4%), with a small amount of corpovitrinite (0%–2.2%, average 0.59%). The total of these two has a strong negative correlation with porosity, pore volume, BET specific surface area, and fractal dimension (Figure 10(a) to (e) and (g) to (i)), which shows that there are fewer blowholes and that it has less effect on the pore structure. C2+C3 has a strong positive correlation with the mercury withdrawal efficiency (Figure 10(f)), which indicates that the blowholes are well connected. This is also corroborated by the fact that the blowholes are connected by ruptures observed by the SEM. The N2 adsorption/desorption experiments also confirm that the pore shapes of coals rich in desmocollinites (C2) and corpovitrinites (C3) in addition to type I with one-side-closed, also includes more type II pores with two-sides-opened, and connectivity is good. Clastic pores are mainly developed in vitrodetrinite (VD), and inertodetrinite (ID). These two total contents have a weak positive correlation with porosity, adsorption pore volume, seepage pore volume, BET specific surface area, and fractal dimension (Figure 10), as well as a weak negative correlation with the mercury withdrawal efficiency, indicating that clastic pores are less development and have less influence on the above pore structure characteristics.

Compared with woody plants, herbaceous plants have less lignin, so their degree of lignification and structural preservation are lower (Diessel, 1992b). With the weakening of fusinization in water-transgression cycles, coal-forming aquatic herbs gradually increase and preservation of plant structure decreases (Figure 8). Therefore, the fusinite, semifusinite, and telinite gradually decrease, and the gelatinized components such as the desmocollinite gradually increase at the same time. Conversely, with the reinforcing of fusinization in water-regression cycles, coal-forming woody plants gradually increase, and the preservation

**Figure 10.** Relationship between submacerals contents and pore structure.
degree of plant structure increases (Figure 8), leading to the fusinite, semifusinite, and telinite gradually increasing; the gelatinized components such as the desmocollinite gradually decrease. Therefore, in the process of transgression, the plant tissue pores with diameters greater than 100 nm, which were the main pore types before, are gradually destroyed in large quantities and the blowholes generated in the process of coalification gradually increase in small quantities, leading to the gradual reduction of porosity, seepage pore volume, and fractal dimension. On the contrary, the porosity, pore volume, and fractal dimension increase gradually with the increase of tissue pores and the decrease of blowholes.

In addition, the pore volume and specific surface area of adsorption pores became smaller with the rise of mire water tables. This is because when the coal ranks are similar, the physical and chemical changes of inertinite are significantly smaller than those of vitrinite (Stach, 1990). Furthermore, the inertinite is rich in carbon and depleted in hydrogen, which results in a much lower ability to generate hydrocarbons, especially liquid hydrocarbons, than vitrinite. As such, when the coal rank is low, vitrinite has not yet shown its ability to form micropores and transition pores. The generated liquid hydrocarbon has a filling effect on pores, so micropores and transition pores are less than those of inertinite (Zhang et al., 2008). It was concluded that when the clay mineral content in the Yining mining area is low (average 2.2%) and the coal rank is similar, the specific surface area of pores is mainly controlled by the content of macerals. With the reinforcing of gelification in water-transgression cycles, the content of vitrinite increases, micropores decrease, and the volume and specific surface area of adsorption pores decrease accordingly. In contrast, with the increasing of inertinite content controlled by water-regression processes, micropores increase, resulting in increases in the pore volume and specific surface area of the adsorption pores.

In conclusion, the water-transgression process is characterized by many plant tissue mesopores and macropores decreasing, a small number of blowholes increasing, and a slight decrease in clastic pores. These changes lead to a decrease in total pore volume, macropore volume, and porosity. In addition, pores with good connectivity increase slightly and tissue pores with poor connectivity decrease significantly resulting in reinforcement in the connectivity of the pores and an increase in mercury withdrawal efficiency. The water-regression process is characterized by many plant tissue mesopores and macropores increasing, a small number of blowholes decreasing, and a slight increase in clastic pores. Consequently, the total pore volume, seepage pore volume, and porosity gradually increase. Pores with good connectivity decrease and tissue pores with poor connectivity increase, resulting in a gradual weakening of the pore connectivity and a decrease in the mercury withdrawal efficiency. At the same time, with the enhancement of gelification during the water-transgression process, the plant cell structure gradually disappears and becomes the gelatinous components. The surface of the pore structure gradually becomes uniform and the fractal dimensions decrease. With the enhancement of fusinization during the water-regression process, the degree of preservation of a plant cell structure increases, the pore structure gradually becomes rough, and the fractal dimension gradually increases.

**Inspiration for exploration and development of thick coal reservoirs**

The strong vertical heterogeneity of thick coal seams has severely restricted the exploration and development of China’s CBM in thick coal seams. In particular, the pore structure characteristics of thick coal seams are very different, and they should be regarded as a
superimposed seam of “multiple coal seams with different physical properties” and discussed in layers.

It is considered that it is an effective research method to divide the thick coal reservoir into several water-transgression/water-regression cycles, and then to discuss the physical properties of each cycle. It can provide a theoretical basis for the exploration and development of CBM of thick coal seams. If the thick coal seam is simply divided into several layers on average, and the reservoir evaluation is conducted based on each layer, it will lead to problems such as the inaccuracy of layer thickness and layer basis. However, according to the multi-peat superposition genetic theory to divide the thick coal seam can avoid this problem. The physical properties of coal reservoirs in a water-transgression/water-regression cycle must have obvious change rules. Stratification based on cyclicity can further improve our understanding of the control mechanism of the physical property evolution of thick coal reservoirs. On this basis, it is more reasonable to compare the reservoir physical properties of each cycle vertically and comprehensively evaluate the reservoir. From the perspective of development, taking each cycle as a unit, longitudinally comparing the merits of the reservoir physical properties of each cycle can provide effective theoretical support for the selection of the target horizons for the fracturing and mining of thick coal reserves (Guo et al., 2018).

Conclusions

In this paper, the relationship between the cyclic changes of thick coal seams and evolution of pore structure has been studied by a series of laboratory experiments, particularly relating to their significant impact on CBM development in the Northwest coal-bearing region. Our conclusions are as follows:

1. The No. 4 coal seam has been divided into 4 water-transgression/water-regression cycles by maceral analysis, proximate analysis, trace element analysis, and organic stable carbon isotope analysis. The reliability of the method is evaluated and the result shows that the reliability is relatively high.
2. The distribution of porosity is cycle III > cycle II > cycle I > cycle IV, which is consistent with the seepage pore volume. The distribution of BET specific surface area is cycle IV > cycle III > cycle II > cycle I, which is consistent with the adsorption pore volume. The connectivity distribution is cycle I > cycle IV > cycle II > cycle III. The fractal dimension distribution of the seepage pores is cycle III > cycle II > cycle I > cycle IV, which indicates that the uniformity of the seepage pore (>100 nm) structure of cycle III is the worst. Similarly, the uniformity of the pore structure of adsorption pores (<100 nm) differs little and the uniformity of cycle II is the worst.
3. With the reduction of the preservation of plant structure controlled by water-transgression processes, the main plant tissue pores are gradually destroyed; the porosity, pore volume, specific surface area, and adsorption capacity gradually decrease; and the connectivity between pores improves. Moreover, the surface of the pore structure gradually becomes consistent and the fractal dimension gradually decreases. In contrast, the characteristics of the above pore structures show an opposite trend in water-regression processes.
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