Pore Structure Characteristics of Coal and Their Geological Controlling Factors in Eastern Yunnan and Western Guizhou, China
Zhengguang Zhang, Yong Qin, Tongsheng Yi, Zhenjiang You, and Zhaobiao Yang*

ABSTRACT: Coalbed is the carrier for coalbed methane (CBM) enrichment and migration. The pore structure characteristics of coal and their main geological controlling factors are critical to the exploration and development of CBM. In this paper, 20 coal samples were collected from eastern Yunnan and western Guizhou, China. Based on vitrinite reflectance, proximate analysis, maceral analysis, and low-temperature N₂ adsorption/desorption (LT-N₂,GA) experiments, the hysteresis coefficient of low-temperature N₂ desorption was proposed, the types of pore structure were identified, and the effects of coal facies and rank on the pore structure were revealed. The results show that the \( R_{\text{max}} \) values of the 20 coal samples are between 0.74 and 3.38%, which belong to medium- and high-rank coal. In the coal macerals, the vitrinite is mainly collodetrinite. The inertinite is dominated by semifusinite, and some coal samples contain exinite. The coal samples investigated can be divided into two types. Type A samples mainly contain open pores, while type B samples are rich in bottle-shaped pores. Compared with type A coal samples, type B samples have the characteristics of smaller total pore volume (TPV), smaller average pore diameter (APD), larger specific surface area (SSA), and larger hysteresis coefficient. The coal samples are located in three regions of different coal facies, including low-level swamp (reed) facies, wetland herbaceous swamp facies, and wet forest swamp facies. The tissue preservation index (TPI) values of most coal samples are less than unity, which indicates that herbaceous plants have absolute dominance in the coal-forming plants in eastern Yunnan and western Guizhou. The maximum vitrinite reflectance (\( R_{\text{max}} \)), gelification index (GI), TPI, vitrinite content (V), inertinite content (I), Barrett-Joyner-Halenda pore volume (\( V_{\text{BJH}} \)), Brunauer-Emmett-Teller SSA (\( S_{\text{BET}} \)), and low-temperature N₂ desorption total hysteresis coefficient (\( H_{\text{t}} \)) were clustered using the R-type cluster analysis method. It is found that TPI is the main controlling factor of the pore structure of type A coal samples, while the pore structure of type B coal samples are jointly controlled by TPI and coal rank. Type B coal samples are mainly located in Zhuzang and Laochang high-rank coal research areas, while the distribution of type A coal samples is mainly in other medium—high-rank coal research areas. These results will contribute to the exploration and development of CBM and also guide the study of pore structures of other unconventional gas reservoirs.

1. INTRODUCTION
Coal is a complex porous organic medium, which provides abundant pore space for the storage and migration of coalbed methane (CBM). Therefore, the study of the pore structure of coal has practical significance for discovering the rules of CBM accumulation and migration. The pore structure characteristics of coal include pore type, total pore volume (TPV), specific surface area (SSA), pore size distribution (PSD), connectivity, and complexity.\(^1,2\) There are many factors that affect the pore structure of coal, including coal rank, coal maceral, coal structure, mineral content, and coal facies.\(^1,3,5\) Coal rank and coal facies are the two main factors controlling the evolution of the coal pore structure.\(^6,7\)

Eastern Yunnan and western Guizhou have the major coal and CBM resources in southern China and are also one of the key blocks for CBM exploration and development in China.\(^8−15\) Accumulated evidence has verified that the pore structure is controlled by the coal rank in this area.\(^3,13,14\) However, there are few studies on the combined influence of coal facies and coal rank on the pore structure, which means the control mechanism of the pore structure in a coal reservoir is still elusive. Coal facies refers to the original genetic type of coal, which is an important index to study coal-forming conditions, coal-forming process, and coal-forming original materials. Presently, gelification index (GI), tissue preservation index (TPI),\(^15\) groundwater influence index (GWI), vegetation index (VI),\(^16\) and cell structure preservation index (CPI)\(^17\) are commonly used to evaluate coal-forming plants, swamp medium conditions, and sedimen-
tary environment during peat accumulation. Transport index (TI)\(^{18}\) and the ratio of vitrinite to inertinite (V/I)\(^{19}\) are also used to reflect the strength of swamp hydrodynamic conditions and the sedimentary environment in the process of coal formation. Li et al.\(^{20}\) found that the coal reservoirs formed in the wet forest swamp have the best pore-fracture structures, accompanied with relatively high Langmuir volume and Langmuir pressure. This is basically consistent with the research results of Hou et al.\(^{2,3,4}\) The coal rank, one of the main factors controlling the pore structure, of different synclines in eastern Yunnan and western Guizhou varies greatly. Li et al.\(^{20}\) only considered the influence of coal facies on the pore structure, resulting in a lack of systematic understanding of the influencing factors of the pore structure.

According to the pore diameter classification method of Hodot\(^{2,22}\) and Yao et al.\(^{23,24}\) the pores or fractures are divided into five types in this paper, that is, microfractures (>10,000 nm), macro pores (1000–10,000 nm), mesopores (100–1000 nm), transition pores (10–100 nm), and micropores (<10 nm). Macropores and mesopores belong to seepage pores, while transition pores and micropores belong to adsorption pores. Gas transport is via laminar flow or turbulent flow in the seepage pores and via capillary condensation, physical adsorption, and diffusion in the adsorption pores.\(^\text{22-24}\) Coal exhibits a complex pore structure, which is difficult to describe with traditional Euclidean geometry, while fractal theory can effectively characterize the complex characteristics of the coal pore structure.\(^\text{25}\) As the concept of fractals was first proposed by Mandelbrot,\(^\text{25}\) it has been gradually used to characterize shapes and phenomena with self-similarity but no characteristic length in nature and has become a powerful tool to quantitatively describe irregular shapes.\(^\text{26}\) Based on the data of mercury intrusion porosimetry (MIP), low-temperature N\(_2\) adsorption/desorption (LT-N\(_2\)-GA), low-temperature CO\(_2\) adsorption (LT-CO\(_2\)-GA), and low-field nuclear magnetic resonance (NMR), the fractal formulas of different test methods were proposed.\(^\text{27-31}\)

In general, the fractal dimension of the pore structure of coal is between 2 and 3. The larger the fractal dimension is, the more complex the pore structure is and the rougher the surface is.\(^\text{3,5,31,32}\)

There are two basic types of effective pores in coal: semi-closed pores and open pores. Semi-closed pore is the pore type with one end closed and one end open (Figure 1a), while open pore (or thin neck bottle pore) (Figure 1c), which can also form distinct hysteresis loop characteristics due to the difference between the mercury injection/mercury ejection pressure and the adsorption/desorption pressure of the bottle neck and the bottle cavity.\(^\text{33-35}\) Chen et al.\(^{36}\) proposed a hysteresis coefficient to characterize the number of open pores according to the hysteresis characteristics of LT-N\(_2\)-GA. Based on previous studies, Zhang et al.\(^{2}\) introduced the modified hysteresis coefficient and calculated the hysteresis coefficient of MIP and LT-N\(_2\)-GA, respectively. However, their research is limited to the calculation of the hysteresis coefficient under a single pressure value, which cannot quantitatively characterize the entire area of the hysteresis loop, and the compression effect of the mercury injection pressure on the coal matrix has not been considered in the calculation of the MIP hysteresis coefficient.\(^\text{27,37,38}\) The data obtained do not effectively reflect the volume of open pores in coal.

In this paper, 20 coal samples were collected from eastern Yunnan and western Guizhou. Using the vitrinite reflectance, proximate analysis, maceral analysis, and LT-N\(_2\)-GA test data, we summarize the control effects of coal rank and coal facies on the pore structure of the coalbed, expound the hysteresis effect of low-temperature liquid nitrogen desorption, and develop the quantitative characterization method of open pore content in coal. These results provide the basis for efficient development of CBM.

2. GEOLOGICAL BACKGROUND

Eastern Yunnan and western Guizhou are located in the southwest of China, mainly including Enhong syncline (EH), Laochang syncline (LC), Tucheng syncline (TC), Panguan syncline (PG), Faer syncline (FE), Bide syncline (BD), Dahebian syncline (DHB), Agong syncline (Ag), and Zhuzhang syncline (ZZ) (Figure 2), with an area of about 2.58 × 10\(^{4}\) km\(^2\), and the geological resources of CBM are 2.2 to 2.75 × 10\(^{12}\) m\(^3\).\(^\text{13}\) The main coal-bearing strata in eastern Yunnan and western Guizhou are formed in the Late Permian. The coal-bearing strata of Xuanwei formation in the eastern Yunnan are mainly continental facies clastic rock sedimentation, and the part is the coastal transitional facies sedimentation. The delta plain sedimentary environment, the meandering river alluvial plain sedimentary environment, as well as braided river delta sedimentary environment are located in the upper, middle, and lower part of Xuanwei formation, respectively.\(^\text{39,40}\) The sedimentary facies of Changxing formation and the upper as well as lower part of Longtan formation in western Guizhou are lagoon tidal flat facies, delta front facies, and lagoon tidal flat facies, respectively.\(^\text{7}\) The thickness of the stratum is 27.19–279.69 m, mostly 100–270 m. Twenty five—sixty coal seams are generally contained in the coal-bearing strata, with a cumulative thickness of 13–27 m. Eight–fifteen coal seams are minable, with a cumulative thickness of 8–15 m.\(^\text{41}\) The main coal-bearing strata in western Guizhou are Longtan formation and Changxing formation. The provenance is mainly terrigenous clastic, but the clastic is relatively fine and quartz content is high. From west to east, continental facies and marine-continental transitional facies sedimentation are developed successively. The thickness of the stratum is 220–460 m, including 14–58 coal seams, with a cumulative thickness of 14.8–46.2 m. The minable coal seams are 2–24 coal seams, with a cumulative thickness of 3.0–29.8 m.\(^\text{42}\)

The coal rank in eastern Yunnan and western Guizhou is relatively abundant, with development from gas coal to...
Figure 2. Coal-bearing stratum histogram and sampling location in the study area.

Table 1. Basic Information of Coal Samples

| sampling location | sampling location | macroscopic coal rock structure | proximate analysis/% |
|-------------------|-------------------|---------------------------------|----------------------|
|                   |                   |                                 | $M_{ad}$ | $A_{ad}$ | $V_{ad}$ | $R_{max}$ | rank |
| 1                 | LC                | 7 + 8#                          | 1.26     | 4.76     | 7.04     | 2.32     | high  |
| 2                 | HF                | 13#                             | 1.32     | 20.97    | 6.57     | 2.09     | high  |
| 3                 | XB                | 5#                              | 0.97     | 17.99    | 8.19     | 2.15     | high  |
| 4                 | EH                | TJ 8#                           | 0.38     | 38.98    | 15.56    | 1.20     | medium |
| 5                 | HW                | 5#                              | 0.70     | 0.00     | 6.57     | 1.22     | medium |
| 6                 | TC                | 12 + 15#                        | 0.59     | 10.26    | 33.31    | 1.00     | medium |
| 7                 | SH                | 12#                             | 0.54     | 13.05    | 20.94    | 1.35     | medium |
| 8                 | SH                | 15#                             | 0.51     | 9.77     | 20.47    | 1.36     | medium |
| 9                 | PG                | 9#                              | 0.62     | 7.95     | 10.13    | 2.08     | high  |
| 10                | YLT               | 18−1#                           | 0.74     | 15.59    | 24.70    | 1.08     | medium |
| 11                | FE                | 7 + 10#                         | 0.36     | 25.12    | 19.96    | 1.40     | medium |
| 12                | DG                | 1#                              | 0.42     | 26.70    | 17.32    | 1.62     | medium |
| 13                | BD                | 5#                              | 0.48     | 28.28    | 20.07    | 1.52     | medium |
| 14                | HY                | 5#                              | 0.62     | 9.00     | 13.55    | 1.83     | medium |
| 15                | DHB               | NLZ 1#                          | 0.58     | 22.99    | 15.78    | 1.43     | medium |
| 16                | DH                | 601#                            | 2.48     | 12.45    | 32.20    | 0.74     | medium |
| 17                | AG                | WJB 6 + 7#                      | 1.01     | 23.14    | 7.29     | 2.35     | high  |
| 18                | ZZ                | FHS 15 + 17#                    | 1.48     | 19.98    | 6.24     | 2.90     | high  |
| 19                | HSHF              | 23#                             | 1.23     | 13.30    | 6.80     | 3.38     | high  |
| 20                | HYJ               | 16#                             | 1.45     | 16.80    | 6.81     | 2.84     | high  |

*$M_{ad}$ moisture, air-dried basis; $A_{ad}$ ash yield, air-dried basis; $V_{ad}$ volatile, air-dried basis; LC, Laochang syncline; EH, Enhong syncline; TC, Tucheng syncline; PG, Panguan syncline; FE, Faer syncline; BD, Bide syncline; DHB, Dahebian syncline; AG, Agong syncline; ZZ, Zhuzang syncline.*
anthracite, but the coal rank is unevenly distributed and varies widely. According to the data of coalfield drilling, it is found that the content of vitrinite is 50.3–97.8%, inertinite 1.0–41.1%, and trivial exinite. The main mineral content is clay mineral, and the second is oxide mineral.41 In the late Permian coal of western Guizhou, the content of vitrinite is 49.5–94%, inertinite 5.99–49.8%, and trivial exinite. The mineral content is mainly clay minerals and quartz, followed by pyrite and carbonate minerals.42 The study area has experienced three fold movements in Indochina, Yanshan, and Himalaya, respectively. The Yanshan movement has the strongest influence, which has controlled the preservation degree and storage state of coal bearing strata.43 Overall, the geological characteristics of eastern Yunnan and western Guizhou include abundant CBM resources, multiple and thin coal seams, high stress, and large variation of coal rank.8,9,44,45

### 3. SAMPLE COLLECTION AND TEST ANALYSIS METHOD

#### 3.1. Sample Collection and Pretreatment

Twenty samples (Figure 2, Table 1) were collected from 19 coal mines in eastern Yunnan and western Guizhou. After careful packaging on site, they were sent to the laboratory for relevant tests. Prior to industrial analysis test, coal samples were crushed, mixed, and split in proportion by machinery, and then screened to obtain the samples with particle size less than 0.2 mm. After drying for 1 h at 40 °C in air, these samples were put into a tight container for standby when they reached the state of air-dried quality.46 Before the analysis of vitrinite reflectance and maceral of coal, it is necessary to prepare polished grain mount. First, the samples were repeatedly sieved and crushed until they completely passed the test sieve with mesh diameter of 1 mm. Then, 100–200 g of air-dried samples with particle size less than 1 mm were split to 10–20 g samples for standby by coning and quartering method. The volume ratio of the coal sample and binder was 2:1. A briquette was formed by heating and pressing. Finally, one end face of the coal brick was ground and polished into a polished grain mount.47

#### 3.2. Analytical Test Method

Proximate analysis test was performed according to the international standards ISO 11722:1999,48 ISO 1171:1997,49 and ISO 562:1998.50 Vitrinite reflectance (R<sub>0.5</sub>) and coal maceral (500 points) were analyzed by a Leitz MPV-3 microphotometer on the polished surface of the polished grain mount.51–53

LT-N<sub>2</sub>GA was tested using an Autosorb IQ full-automatic specific surface and PSD analyzer according to the international standard ISO 15901-2:2006.54 Briefly, the samples were uniformly crushed and sieved. The samples (5–10 g) with particle size of 40–60 mesh (0.28–0.45 mm) were dried at 105 °C for 8 h, then vacuumized for 4 h. After that, the low-temperature N<sub>2</sub> adsorption test was performed under low-temperature conditions (77.3 K). The relative pressure during the adsorption was 0.05–0.995, and the corresponding pore diameter was 0.64–380.73 nm.

#### 3.3. Data Processing Method

##### 3.3.1. Pore Diameter Calculation

In the LT-N<sub>2</sub>GA tests, the pore radius can be calculated according to the Kelvin formula

\[
\eta = -\frac{2\gamma_m \cos \phi}{RT \ln(P/P_0)}
\]

where \( \eta \) is the pore radius, \( \gamma \) is the surface tension of liquid nitrogen, \( \gamma = 8.85 \times 10^{-3} \text{ N/m} \); \( \gamma_m \) is the molar volume of liquid nitrogen, \( \gamma_m = 34.65 \times 10^{-6} \text{ m}^3/\text{mol} \); \( \phi \) is the contact angle, \( \phi = 0^\circ \); \( T \) is the Kelvin temperature, \( T = 77.3 \text{ K} \); \( R \) is the gas constant, \( R = 8.315 \text{ J/(K-mol)} \). By substituting the values of \( \gamma, \gamma_m, \phi, T, \) and \( R \) into eq 1, the relationship between the pore diameter \( D_k \) in coal and the relative pressure can be obtained as follows

\[
D_k = -\frac{1.9084}{\ln(P/P_0)}
\]

where \( D_k \) is the pore diameter in coal tested by LT-N<sub>2</sub>GA, nm.

##### 3.3.2. Characterization Method of Homogeneity Degree of Pore Distribution

The porous media system of the coal reservoir has different heterogeneity characteristics on different scales. The fractal dimension can be effectively conducted to describe the heterogeneous characteristics of coal. Compared with the Brunauer–Emmett–Teller (BET) model and the thermodynamic model, the Frenkel-Halsey-Hill (FHH) model is proven to be the most effective method, which can accurately calculate the fractal dimension of adsorption pores through the data of gas isothermal adsorption.28,29,31 The FHH model is calculated as follows

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

where \( P \) is the equilibrium pressure, MPa; \( P_0 \) is the saturation pressure, MPa; \( V \) is the volume of the adsorbed gas at the equilibrium pressure \( P \), mL/g; \( C \) is constant; \( k \) is the slope of the double logarithmic curve of \( \ln V \) and \( \ln(\ln(P_0/P)) \), and the fractal dimension of the pore structure is \( D = k + 3 \).

##### 3.3.3. Characterization Parameters of Desorption Hysteresis

In the adsorption process of low-temperature liquid nitrogen, the adsorption isotherms have different adsorption characteristics at relative pressures of 0–0.5 and 0.5–1. The reason for the difference in adsorption characteristics is that the main controlling factors are different at different adsorption stages. At the relative pressure of 0–0.5, the adsorption characteristic of coal is mainly controlled by van der Waals force, while the adsorption characteristic of coal is mainly manifested as capillary condensation at the relative pressure of 0.5–1.\(^{24,46}\) Tang et al.\(^{55}\) further divided the low-temperature N<sub>2</sub> adsorption curve of coal into three regions, namely monolayer adsorption, multilayer adsorption, and capillary condensation (Figure 3). The results showed that the adsorption volume of nitrogen molecules on the pore surface increased slowly due to the effect of surface tension in the relatively low-pressure region.
1. In the relatively high-pressure region 2, nitrogen molecules were adsorbed by van der Waals force in the pore space, and the adsorption volume increased rapidly from single-layer adsorption to multilayer adsorption. In region 3, capillary condensation resulted in a sharp increase in the adsorption volume. In this paper, the adsorption curve shapes of coal samples are basically the same as that obtained by Tang et al.\textsuperscript{55} so we also use the same classification standard.

The low-temperature N\textsubscript{2} desorption process has a significant hysteresis phenomenon compared with the adsorption process caused by open pores and ink bottle pores, thus resulting in a hysteresis loop (Figure 4). In this study, we describe quantitatively the hysteresis characteristics of low-temperature N\textsubscript{2} desorption. The hysteresis coefficient of low-temperature N\textsubscript{2} desorption is proposed. The area of the hysteresis loop is the same as that obtained by Tang et al.,\textsuperscript{55} so we also use the same classification standard.

![Figure 4](image-url)\textsuperscript{55}

The ranges of moisture, ash, volatile matter, and macerals of the coal samples from eastern Yunnan and western Guizhou are shown in Tables 1 and 2. The results show that the ranges of moisture content, ash yield, and volatile matter yield are 0.36–2.48, 3.38–38.98, and 6.24–33.31\%, respectively. The range of maximum vitrinite reflectance is 0.74–3.38\%. According to the ISO 11760:2005\textsuperscript{56} classification standard, 8 coal samples are high-rank coal, and 12 coal samples belong to medium-rank coal (Table 1).

The ranges of vitrinite content (V), inertinite content (I), exinite content (E), and mineral content (M) are 43.2–88.2, 7.7–41.7, 0.0–16.9, and 0.5–36.7\%, respectively. Vitrinite is dominated by colloidetrinitrinite (30.1–67.7\%) (Figure 5a), followed by collotelinitrinite (4.9–34.8\%) (Figure 5b) and telinite (0.0–19.4\%) (Figure 5c). The inertinite is mainly seminisinitrinite.

\[ S_2 = \int_{0.5}^{0.8263} (f_{22}(x) - f_{21}(x))dx \]  
\[ S_3 = \int_{0.95}^{0.8263} (f_{32}(x) - f_{31}(x))dx \]  
\[ S_4 = \int_{0.95}^{0.9811} (f_{42}(x) - f_{41}(x))dx \]  
\[ S_5 = \int_{0.9811}^{0.995} (f_{44}(x) - f_{41}(x))dx \]  

where \( S_1, S_2, S_3, S_4, \) and \( S_5 \) are hysteresis coefficients of relative pressures of 0.15–0.5, 0.5–0.8263, 0.8263–0.95, 0.95–0.9811, and 0.9811–0.995, respectively. mL/g; \( f_{ij}(x) \) are the fitting functions of adsorption curve and desorption curve of \( S_1 \) to \( S_5 \). mL/g; \( f_{ij}(x) \) are the fitting functions of adsorption curve and desorption curve of \( S_1 \) to \( S_5 \). mL/g; \( f_{ij}(x) \) are the fitting functions of adsorption curve and desorption curve of \( S_1 \) to \( S_5 \).

3.3.4. Characterization Parameters of Coal Facies. In this paper, GI and TPI are used to study the coal-forming plants, swamp medium conditions, and sedimentary environments of peat. GI refers to the ratio of gelified microcomponents to non-gelified microcomponents in coal (eq 9), which is used to reflect the water level variation characteristics of ancient peat swamp and the gelation degree of plant remains. Greater the GI value, higher the gelation degree and deeper the water in the swamp.\textsuperscript{15} TPI is the ratio of the macerals in coal showing the cell structure to the macerals in which the cell structure is destroyed (eq 10). The value of TPI not only reflects the natural fragmentation degree of plant remains, but also reflects the intensity of oxidative degradation. Higher the TPI value, better the preservation of the plant structure, that is, weaker the mechanical fragmentation and chemical degradation of the plant remains in the swamp. In addition, TPI is also used as an important indicator to measure the proportion of woody plants in the original swamp.\textsuperscript{15}
Table 2. Macerals of Coal Sample

| sample no. | V   | T   | C1  | C2  | C3  | VD  | I   | F   | SF  | Ma  | ID  | E   | Sp  | Cu  | Re  | ED  | M/% | GI   | TPI | coal facies type |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----------------|
| 1          | 72.8| 1.9 | 34.8| 36.1| 0.0 | 0.0 | 24.3| 9.5 | 11.0| 0.0 | 3.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.9 | 3.00 | 1.43 | D-1             |
| 2          | 79.7| 7.1 | 25.5| 47.2| 0.0 | 0.0 | 11.3| 2.4 | 5.6 | 0.0 | 3.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 9.0 | 7.09 | 0.80 | A               |
| 3          | 75.4| 3.5 | 16.3| 55.6| 0.0 | 0.0 | 10.1| 0.0 | 5.3 | 0.0 | 4.8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 14.5| 7.44 | 0.42 | A               |
| 4          | 55.7| 0.0 | 7.4 | 48.3| 0.0 | 0.0 | 26.6| 12.8| 12.3| 0.0 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 17.7| 2.09 | 0.65 | C               |
| 5          | 54.2| 2.3 | 7.0 | 44.9| 0.0 | 0.0 | 35.5| 0.9 | 23.8| 0.9 | 9.3 | 4.7 | 2.3 | 1.4 | 1.0 | 0.0 | 5.6 | 1.62 | 0.62 | C               |
| 6          | 55.1| 1.4 | 16.9| 36.7| 0.0 | 0.0 | 27.5| 6.8 | 15.0| 0.0 | 3.9 | 16.9| 3.9 | 1.9 | 2.4 | 0.0 | 0.5 | 2.15 | 0.99 | C               |
| 7          | 73.1| 4.3 | 18.4| 50.4| 0.0 | 0.0 | 21.8| 6.8 | 9.8 | 0.4 | 3.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 5.1 | 3.66 | 0.72 | C               |
| 8          | 56.9| 1.4 | 6.6 | 48.8| 0.0 | 0.0 | 41.7| 18.5| 15.2| 0.0 | 7.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.4 | 1.39 | 0.75 | C               |
| 9          | 74.6| 0.5 | 12.2| 62.0| 0.0 | 0.0 | 22.9| 5.9 | 3.4 | 1.0 | 8.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.4 | 4.31 | 0.31 | C               |
| 10         | 47.5| 1.5 | 11.4| 34.7| 0.0 | 0.0 | 40.6| 9.4 | 18.3| 4.5 | 7.9 | 10.9| 5.4 | 1.5 | 1.5 | 0.0 | 1.0 | 1.46 | 0.86 | C               |
| 11         | 58.9| 1.5 | 12.7| 44.7| 0.0 | 0.0 | 21.8| 9.6 | 11.7| 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 19.3| 2.70 | 0.79 | C               |
| 12         | 43.2| 4.0 | 5.0 | 33.2| 0.0 | 1.0 | 20.1| 4.5 | 14.1| 0.0 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 36.7| 2.15 | 0.80 | C               |
| 13         | 61.3| 1.0 | 4.9 | 55.4| 0.0 | 0.0 | 12.7| 0.0 | 8.3 | 0.0 | 4.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 26.0| 4.81 | 0.24 | C               |
| 14         | 67.4| 1.4 | 20.6| 45.4| 0.0 | 0.0 | 28.9| 10.6| 10.6| 0.0 | 6.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 3.7 | 2.45 | 0.83 | C               |
| 15         | 61.0| 0.5 | 9.6 | 50.9| 0.0 | 0.0 | 23.4| 1.9 | 14.2| 0.0 | 7.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 15.6| 2.61 | 0.45 | C               |
| 16         | 58.3| 0.4 | 11.6| 46.3| 0.0 | 0.0 | 19.9| 4.2 | 12.5| 0.0 | 3.2 | 7.4 | 6.0 | 0.0 | 0.0 | 0.0 | 14.4| 2.93 | 0.58 | C               |
| 17         | 71.9| 7.6 | 15.6| 48.8| 0.0 | 0.0 | 12.1| 2.0 | 8.6 | 0.0 | 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 16.0| 5.98 | 0.67 | A               |
| 18         | 88.2| 7.7 | 12.8| 67.7| 0.0 | 0.0 | 7.7 | 3.1 | 2.6 | 0.0 | 2.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 4.1 | 11.47 | 0.38 | A               |
| 19         | 82.0| 6.5 | 26.3| 49.3| 0.0 | 0.0 | 12.0| 3.2 | 8.3 | 0.0 | 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 6.0 | 6.85 | 0.89 | A               |
| 20         | 66.0| 19.4| 16.5| 30.1| 0.0 | 0.0 | 31.1| 10.2| 18.0| 1.5 | 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.9 | 2.32 | 1.97 | D-1             |

*V, vitrinite group; T, telinite; C1, collotelinite; C2, collodetrinite, C3, corpogelinite; VD, vitrodetrinite; I, inertinite group; F, fusinite; SF, semifusinite; Ma, macrinite; ID, inertodetrinite; E, exinite group; Sp, sporinite; Cu, cutinite; Re, resinite; ED, exodetrinite; M, mineral matter; GI, gelification index; TPI, tissue preservation index.*
(2.6–23.8%) (Figure 5d), followed by fusinite (0.0–18.5%) (Figure 5e) and inertodetrinite (0.5–9.3%) (Figure 5f). Except for HW, TC, YLT, and DH coal samples, which contain a small amount of exinite, other coal samples basically have no exinite (Table 2).

4.2. LT-N$_2$GA Pore Structure Characteristics. Based on the classification method of Sing, the pore structure of 20 coal samples in eastern Yunnan and western Guizhou is divided into two types. Among them, 16 coal samples belong to the type A pore structure, which are mainly composed of open pores, with relatively small hysteresis loops, and the PSD curve shows a “double-peak” structure (Figure 6a,b). The four coal samples are the type B pore structure, which are mainly composed of ink bottle pores (or narrow neck bottle pores), with large hysteresis loops, and the PSD curve shows a “single peak” structure (Figure 6c,d). Open pores are favorable for CBM adsorption, desorption, and seepage, whereas ink pores are beneficial for CBM enrichment, but not for CBM seepage.$^{2,31}$

As shown in Table 3, the Barrett-Joyner-Halenda (BJH) pore volume ($V_{\text{BJH}}$), BET SSA ($S_{\text{BET}}$), and average pore diameter (APD) of type A coal samples are 0.0008–0.0051 mL/g (avg. 0.0021), 0.131–0.739 m$^2$/g (avg. 0.305), and 20.735–37.362 nm (avg. 28.748), respectively. What’s more, the TPVs of type A coal samples are mainly composed of mesopores and transition pores, while the SSAs are mainly composed of micropores. In addition, the $V_{\text{BJH}}$, $S_{\text{BET}}$, and APD of type B coal samples are 0.0011–0.0023 mL/g (avg. 0.0018), 0.718–9.243 m$^2$/g (avg. 4.809), and 4.240–13.495 nm (avg. 7.654 nm). Moreover, the TPV of type B coal samples are mainly composed of micropores and transition pores, while the SSA is mainly composed of micropores. Compared with type A coal samples, type B coal

Figure 5. Photographs of different coal maceral, collodetrinite (a), colotelinite (b), telinite (c), semifusinite (d), fusinite (e), and inertodetrinite (f).

Figure 6. Low-temperature N$_2$ adsorption/desorption curves (a,c) and PSD curves (b,d) of 20 coal samples.
Table 3. Coal Pore Structure Analysis Results by LT-N$_2$GA$^a$

| sample no. | $V_1$ | $V_2$ | $V_3$ | $V_{BJH}$/mL/g | SSA$_1$ | SSA$_2$ | SSA$_3$ | $S_{BET}$ (m$^2$/g) | APD (nm) | $P/P_0$ 0.05−0.5 (0.64−2.75 nm) | $P/P_0$ 0.5−0.995 (2.75−380.73 nm) | loop type |
|------------|-------|-------|-------|----------------|--------|--------|--------|----------------|--------|-------------------------------|-------------------------------|----------|
| 1          | 27.26 | 54.70 | 18.04 | 0.0028         | 2.89   | 31.69  | 65.42  | 0.495          | 23.619 | -0.3642 2.6358 0.9838       | -0.4970 2.5030 0.9941        | A        |
| 2          | 20.27 | 36.09 | 43.64 | 0.0021         | 1.09   | 10.93  | 87.98  | 0.718          | 13.495 | -0.3651 2.6349 0.9839       | -0.3862 2.6138 0.9957        | B        |
| 3          | 41.89 | 46.74 | 11.37 | 0.0015         | 5.93   | 34.80  | 59.27  | 0.191          | 31.744 | -0.1926 2.8074 0.9197       | -0.5755 2.4245 0.9901        | A        |
| 4          | 31.36 | 45.28 | 23.36 | 0.0051         | 2.79   | 21.28  | 75.93  | 0.739          | 26.765 | -0.5717 2.4283 0.9973       | -0.4925 2.5075 0.9987        | A        |
| 5          | 45.46 | 42.50 | 12.04 | 0.0019         | 6.74   | 29.77  | 63.49  | 0.256          | 30.108 | -0.5039 2.4961 0.9824       | -0.5296 2.4704 0.9954        | A        |
| 6          | 33.16 | 43.04 | 23.80 | 0.0019         | 3.01   | 20.48  | 76.51  | 0.37           | 20.735 | -0.5690 2.4310 0.9949       | -0.4424 2.5576 0.9989        | A        |
| 7          | 44.59 | 44.66 | 10.75 | 0.0016         | 7.06   | 35.66  | 57.28  | 0.185          | 33.315 | -0.2492 2.7508 0.9642       | -0.5686 2.4314 0.9888        | A        |
| 8          | 48.98 | 41.62 | 9.40  | 0.0014         | 8.57   | 38.03  | 53.40  | 0.159          | 37.362 | -0.6079 2.3921 0.9762       | -0.5616 2.4384 0.9842        | A        |
| 9          | 41.03 | 49.19 | 9.78  | 0.0008         | 6.92   | 39.41  | 53.67  | 0.131          | 26.458 | -0.3148 2.6852 0.9879       | -0.5381 2.4619 0.9843        | A        |
| 10         | 35.36 | 42.44 | 22.20 | 0.0026         | 3.35   | 22.57  | 74.08  | 0.036          | 31.398 | -0.5573 2.4427 0.9925       | -0.5154 2.4846 0.9984        | A        |
| 11         | 44.81 | 50.56 | 4.63  | 0.0014         | 10.78  | 55.60  | 33.62  | 0.181          | 32.293 | -0.3381 2.6619 0.9399       | -0.5834 2.4166 0.9913        | A        |
| 12         | 35.89 | 49.03 | 15.08 | 0.0026         | 4.24   | 28.37  | 67.39  | 0.452          | 24.315 | -0.5243 2.4757 0.9861       | -0.4809 2.5191 0.9933        | A        |
| 13         | 31.69 | 49.64 | 18.87 | 0.0026         | 3.39   | 27.18  | 69.43  | 0.463          | 22.886 | -0.4309 2.5691 0.9975       | -0.4458 2.5542 0.9974        | A        |
| 14         | 39.01 | 47.37 | 13.62 | 0.0015         | 5.32   | 32.63  | 62.05  | 0.239          | 26.301 | -0.3258 2.6742 0.9829       | -0.5272 2.4728 0.9922        | A        |
| 15         | 45.73 | 44.24 | 10.03 | 0.0015         | 7.64   | 33.44  | 58.92  | 0.196          | 30.794 | -0.3362 2.6638 0.9455       | -0.5837 2.4163 0.9879        | A        |
| 16         | 49.90 | 42.28 | 7.82  | 0.0014         | 9.83   | 38.65  | 51.52  | 0.178          | 33.077 | -0.3500 2.6600 0.9422       | -0.5713 2.4287 0.9935        | A        |
| 17         | 24.91 | 52.60 | 22.49 | 0.0025         | 2.19   | 22.60  | 73.21  | 0.342          | 28.800 | -0.2485 2.7515 0.9518       | -0.5905 2.4095 0.9907        | A        |
| 18         | 17.45 | 46.88 | 35.67 | 0.0011         | 1.00   | 14.21  | 84.79  | 1.108          | 8.553  | -0.4289 2.5711 0.9542       | -0.2897 2.7103 0.9970        | B        |
| 19         | 24.35 | 33.92 | 41.73 | 0.0017         | 1.25   | 7.73   | 91.02  | 0.243          | 4.327  | -0.8552 2.1448 0.9998       | -0.1200 2.8800 0.9631        | B        |
| 20         | 21.39 | 30.16 | 48.45 | 0.0023         | 0.94   | 6.09   | 92.97  | 0.167          | 4.240  | -0.6280 2.3720 0.9577       | -0.1247 2.8753 0.9911        | B        |

$^a$V$_1$, mesopores volume content (100−1000 nm); V$_2$, transitional pores volume content (10−100 nm); V$_3$, micropores volume content (<10 nm); SSA$_1$, mesopores SSA content (100−1000 nm); SSA$_2$, transitional pores SSA content (10−100 nm); SSA$_3$, micropores SSA content (<10 nm); V$_{BJH}$, BJH pore volume; $S_{BET}$, BET SSA; APD, average pore diameter; D$_1$, fractal dimensions with $P/P_0$ ranging from 0.05 to 0.5; D$_2$, fractal dimensions with $P/P_0$ ranging from 0.5−0.995.
samples possess the characteristics of smaller TPV, smaller APD, and larger SSA.

In order to further analyze the pore structures of two types of coal samples, the fractal dimensions of 20 coal samples were measured. Figure 7 shows the scatter diagram of low-temperature N₂ fractal of type A coal samples (a) and type B coal samples (b). Figure 8 illustrates the relationship between $R_{\text{max}}$ and $D_1$ (a) and $D_2$ (b).

Table 4. Calculation Results of Hysteresis Coefficient Based on LT-N₂GA

| sample no. | $S_1$ | $S_2$ | $S_3$ | $H_1$ | $H_2$ | $H_3$ | $H_4$ | $H_5$ | $H_6$ | $H_7$ | $H_8$ | $H_9$ | $H_{10}$ |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 1         | 0.0398 | 0.0718 | 0.0389 | 0.0105 | 0.0030 | 0.1116 | 0.0494 | 0.0030 | 0.1640 | 68.06 | 30.12 | 1.82 |
| 2         | 0.0905 | 0.1587 | 0.0574 | 0.0104 | 0.0021 | 0.2473 | 0.0678 | 0.0021 | 0.3172 | 77.95 | 21.38 | 0.67 |
| 3         | 0.0064 | 0.0229 | 0.0099 | 0.0034 | 0.0016 | 0.0294 | 0.0133 | 0.0016 | 0.0443 | 66.23 | 30.09 | 3.68 |
| 4         | 0.0452 | 0.1188 | 0.0571 | 0.0118 | 0.0030 | 0.1640 | 0.0689 | 0.0030 | 0.2359 | 69.53 | 29.22 | 1.25 |
| 5         | 0.0096 | 0.0245 | 0.0097 | 0.0030 | 0.0017 | 0.0341 | 0.0128 | 0.0017 | 0.0485 | 70.20 | 26.32 | 3.48 |
| 6         | 0.0114 | 0.0395 | 0.0179 | 0.0043 | 0.0017 | 0.0509 | 0.0222 | 0.0017 | 0.0748 | 67.99 | 29.70 | 2.31 |
| 7         | 0.0031 | 0.0161 | 0.0112 | 0.0036 | 0.0017 | 0.0192 | 0.0148 | 0.0017 | 0.0357 | 53.81 | 41.56 | 4.63 |
| 8         | 0.0064 | 0.0152 | 0.0116 | 0.0049 | 0.0029 | 0.0216 | 0.0165 | 0.0029 | 0.0411 | 52.65 | 40.23 | 7.12 |
| 9         | 0.0084 | 0.0146 | 0.0095 | 0.0022 | 0.0009 | 0.0230 | 0.0116 | 0.0009 | 0.0355 | 64.73 | 32.75 | 2.52 |
| 10        | 0.0102 | 0.0463 | 0.0273 | 0.0110 | 0.0064 | 0.0565 | 0.0383 | 0.0064 | 0.1012 | 55.85 | 37.84 | 6.31 |
| 11        | 0.0059 | 0.0096 | 0.0098 | 0.0048 | 0.0035 | 0.0155 | 0.0147 | 0.0035 | 0.0336 | 46.00 | 43.60 | 10.40 |
| 12        | 0.0314 | 0.0526 | 0.0234 | 0.0063 | 0.0027 | 0.0840 | 0.0297 | 0.0027 | 0.1164 | 72.18 | 25.54 | 2.28 |
| 13        | 0.0058 | 0.0260 | 0.0156 | 0.0059 | 0.0023 | 0.0318 | 0.0215 | 0.0023 | 0.0556 | 57.16 | 38.67 | 4.17 |
| 14        | 0.0144 | 0.0293 | 0.0158 | 0.0041 | 0.0015 | 0.0437 | 0.0199 | 0.0015 | 0.0651 | 67.17 | 30.50 | 2.33 |
| 15        | 0.0088 | 0.0215 | 0.0126 | 0.0058 | 0.0039 | 0.0302 | 0.0184 | 0.0039 | 0.0525 | 57.51 | 35.01 | 7.48 |
| 16        | 0.0042 | 0.0120 | 0.0090 | 0.0018 | 0.0015 | 0.0162 | 0.0108 | 0.0015 | 0.0284 | 56.79 | 38.01 | 5.20 |
| 17        | 0.0328 | 0.0796 | 0.0431 | 0.0103 | 0.0025 | 0.1124 | 0.0534 | 0.0025 | 0.1683 | 66.77 | 31.73 | 1.50 |
| 18        | 0.2092 | 0.1935 | 0.0601 | 0.0096 | 0.0014 | 0.4026 | 0.0697 | 0.0014 | 0.4737 | 84.98 | 14.72 | 0.30 |
| 19        | 1.0422 | 0.6004 | 0.1378 | 0.0215 | 0.0036 | 1.6426 | 0.1593 | 0.0036 | 1.8055 | 90.98 | 8.42 | 0.20 |
| 20        | 0.7057 | 0.4929 | 0.1174 | 0.0163 | 0.0030 | 1.1986 | 0.1337 | 0.0030 | 1.3353 | 89.76 | 10.01 | 0.23 |

$H_1$, micropores hysteresis coefficient (1.01–10 nm), $H_2$, transitional pores hysteresis coefficient (10–100 nm), $H_3$, mesopores hysteresis coefficient (100–380.73 nm), $H_4$, total hysteresis coefficient (1.01–380.73 nm), $H_5 = S_1 + S_2$, $H_6 = S_3 + S_4$, $H_7 = S_5$, $H_8 = S_6$, $H_9 = S_7$, $H_{10} = S_8$.
calculated according to the FHH fractal model (eq 3). Numerous studies have provided evidence that when calculating the fractal dimension of low-temperature N2 of coal, there is an obvious turning point at the relative pressure of 0.5, and then the fractal dimension is divided into two parts.2,24,31 In our study, the fractal dimension of coal samples is also calculated by this method (Figure 7). The results show that the fractal dimensions $D_1$ and $D_2$ of type A coal samples are $2.3921 - 2.8074$ (avg. 2.5947) and $2.4095 - 2.5576$ (avg. 2.4685), and the fractal dimensions $D_1$ and $D_2$ of type B coal samples are $2.1448 - 2.6349$ (avg. 2.4307) and $2.6138 - 2.8800$ (avg. 2.7699), respectively (Table 3). Type A coal samples have a more complex pore structure in the relatively low-pressure stage ($P/P_0 < 0.5$), while type B coal samples have a more complex pore structure in the relatively high-pressure stage ($P/P_0 > 0.5$). With the increase of coal rank, the compaction degree of coal continues to increase, and part of the seepage pores are transformed into adsorption pores. At the same time, hydrocarbon generation generates a large number of gas pores, which gradually increase the content of adsorption pores.58 This is the reason why the type A coal sample has a larger fractal dimension in the low-relative-pressure stage and a smaller fractal dimension in the high-relative-pressure stage (Figure 8).

4.3. Hysteresis Characteristics of Low-Temperature N2 Desorption. Based on eqs 4–8, the low-temperature N2 desorption total hysteresis coefficients ($H_t$) of 20 coal samples are calculated using Matlab software. The results show that the $H_t$ values of type A coal samples are $0.0284 - 0.2359$ mL/g (avg. 0.0813), among which the contents of micropores, transition pores, and mesopores are $46 - 72.18\%$ (avg. 62.04), $25.54 - 43.6\%$ (avg. 33.81), and $1.25 - 10.4\%$ (avg. 4.15), respectively. However, the $H_t$ values of type B coal samples are $0.3172 - 1.8055$ mL/g (avg. 0.9829), and the contents of micropores, transition pores, and mesopores are $77.96 - 90.98\%$ (avg. 85.92), $8.82 - 21.38\%$ (avg. 13.73), and $0.20 - 0.67\%$ (avg. 0.35), respectively (Table 4). The hysteresis coefficients of the two types of coal samples gradually increase with the decrease of the pore diameter and the micropores dominate (Figure 9).

The hysteretic phenomenon of low-temperature N2 desorption in type A coal samples is mainly caused by the open pores. Herein, the hysteresis coefficient of the TJ (Tuanjie) sample is the largest, followed by the SB (Sebu) and WJB (Wenjiaba) samples, indicating that the volume of open pores in the TJ sample is the largest, which is most conducive to the development of CBM. The hysteretic phenomenon of low-temperature N2 desorption in type B coal samples mainly results from the ink bottle pores. Here, the hysteresis coefficient of the HSHF (HuashanHongfa) sample is the largest, followed by the HYJ (Hongyanjiao) and FHS (Fenghuangshan) samples, indicating that the volume of ink bottle pores in the HSHF sample is the largest (Figure 9). Compared with open pores, the hysteretic phenomenon of low-temperature N2 desorption of the ink bottle pores is more significant. Ink bottle pores have
stron stronger adsorption capacity but are not conducive to the desorption and seepage of CBM, which brings challenges to the efficient development of CBM. Let us further discuss the relationship between the hysteresis coefficient and the fractal dimension. In the low-relative-pressure stage, the area of hysteresis loop decreases with the increase of fractal dimension (Figure 10a). In the high-relative-pressure stage, the area of hysteresis loop increases with the increase of fractal dimension (Figure 10b). The results show that in the low-relative-pressure stage, the more complex the pore structure is, the less obvious the phenomenon of desorption hysteresis is. In the stage of high-relative-pressure, the more complex the pore structure is, the more evident the phenomenon of desorption hysteresis is.

4.4. Coal Facies Characteristics. Based on eqs 9 and 10, GI and TPI values of 20 coal samples were calculated. The TPI-GI facies diagram is obtained by projection points of the 20 coal samples. As evidenced in Figure 11, TPI value of most coal samples is less than unity, which reflects that herbaceous plants have absolute advantage in coal-forming plants in the eastern Yunnan and western Guizhou. The 20 coal samples are located in three different coal facies areas (Figure 11), and the characteristics of the three coal facies types are as follows:

(1) Low-level swamp (reed) facies A. TPI value is less than unity, and GI value is greater than 5. Five coal samples are located in this coal facies. The peat swamp environment represented by the coal facies is a low-level swamp dominated by herbaceous plants, with deep water overlying and relatively strong reducibility of the environment, which is conducive to gelation. Strong reduction results in high content of vitrinite in the coal macerals. As presented in Tables 2 and 3, V_{BET}, S_{BET}, APD, D_1, and D_2 of facies A samples are 0.0023–0.0028 mL/g (avg. 0.0026), 0.495–8.167 m²/g (avg. 4.331), 4.24–23.619 nm (avg. 13.929), 2.372–2.6358 (avg. 2.5039), and 2.503–2.8753 (avg. 2.6892), respectively.

(2) Wetland herbaceous swamp facies C. TPI value is less than unity, and GI value is less than 5. Thirteen coal samples are located in this coal facies. The peat swamp environment represented by the coal facies is a wetland herbaceous swamp dominated by herbaceous plants. The overlying water is relatively shallow, and the conditions of weak reduction and even oxidation are favorable for oxidation. Compared with low-level swamp facies, the content of vitrinite in the coal macerals is relatively low. The V_{BET}, S_{BET}, APD, D_1, and D_2 of facies C samples are 0.0011–0.0025 mL/g (avg. 0.0018), 0.191–9.243 m²/g (avg. 2.32), 4.327–31.744 nm (avg. 17.384), 2.1448–2.8074 (avg. 2.5819), and 2.4095–2.88 (avg. 2.6076) (Tables 2 and 3), respectively.

(3) Wet forest swamp facies D-1. TPI value is greater than unity, and GI value is between 1 and 5. Two samples are located in this coal facies. The peat swamp environment represented by the coal facies is a wet forest swamp dominated by woody plants. The overlying water is relatively shallow, and the environment has strong oxidation. Strong oxidation and dehydrogenation and deoxidation lead to high content of inertinite in the coal macerals. The V_{BET}, S_{BET}, APD, D_1, and D_2 of facies D-1 samples are 0.0008–0.0051 mL/g (avg. 0.0020), 0.131–0.739 m²/g (avg. 0.297), 20.735–37.362 nm (avg. 28.908), 2.3921–2.7508 (avg. 2.5631), and 2.4163–2.5576 (avg. 2.4738) (Tables 2 and 3), respectively.

Further analysis demonstrates that the TPI and GI data of the type B coal samples show a negative logarithmic relationship with a high correlation (R^2 = 0.9987) (Figure 11), indicating that this trend line may be used as a basis for identifying ink bottle pores. The trend line spans three coal facies such as low-level swamp facies, shallow water-covered forest swamp facies, and wet forest swamp facies, indicating the complexity of coal-forming environment and the diversity of coal-forming plants in type B coal samples.

4.5. Geological Control Factors. In order to study the comprehensive influence of coal facies and coal rank on the pore structure, the R-type cluster analysis module of SPSS software is used to assay R_{o,max}, GI, TPI, V, I, V_{BET}, S_{BET}, and H, The cluster results of type A coal samples can be divided into three categories (Figure 12). The first cluster shows that H and S_{BET} are closely related to V_{BET}, TPV and SSA of open pores were incremental with the increase of the TPV of coal. In the second cluster, inertinite and TPI have a good correlation because the inertinite is mainly composed of fusinite and semifusinite (Table 2), which are the main parameters to calculate TPI. In the third cluster, vitrinite and R_{o,max} are closely correlated with GI. The larger GI value testifies for the deeper water depth of the swamp and the relatively stronger reducibility of the sedimentary
environment, which is conducive to gelation. Strong reduction is responsible for high content of vitrinite in coal macerals.\textsuperscript{15} In addition, with the increase of coal rank, the vitrinite increases, while the inertinite decreases.\textsuperscript{14} Here, $R_{\text{o, max}}$ and GI also show a positive correlation. Further analysis shows that $V_{\text{BJH}}$ is strongly correlated with TPI (Figure 13a), while the correlation with $R_{\text{o, max}}$ and GI is small (Figure 13b,c), thus indicating that TPI is the main controlling factor for the pore structure of type A coal samples (Figure 13).

The cluster results of type B coal samples can also be divided into three categories with small cluster coefficient, indicating that the correlation between the cluster indexes of type B coal samples is stronger (Figure 14). The first cluster shows that $V_{\text{BJH}}$ and inertinite have a good correlation with TPI. According to the analysis, TPV of type B coal samples is mainly made up of micropores and transition pores (Table 3). It is reported that telinite and collotelinite in TPI calculation parameters have great potential to produce micropores and transition pores.\textsuperscript{1} Moreover the inertinite of type B coal samples is mainly composed of fusinite and semifusinite (Table 2). In the second cluster, the $H_t$ and $R_{\text{o, max}}$ are closely related to the $S_{\text{BET}}$, indicating that the low-temperature $N_2$ desorption hysteresis phenomenon of type B coal samples has an important relationship with the SSA. In addition, with the increase of coal rank, the SSA of coal gradually increases,\textsuperscript{14} and the adsorption capacity increases. In the third cluster, GI is closely correlated with vitrinite. The larger the GI value, deeper the water depth of the swamp and relatively stronger the reducibility of the sedimentary environment, which is conducive to gelation. The strong reduction results in high content of vitrinite in the coal macerals.\textsuperscript{15}

5. CONCLUSIONS

(1) According to the hysteresis loop characteristics of the LT-$N_2$GA curves of coal, the pore types of 20 coal samples in the eastern Yunnan and western Guizhou can be divided into two types. Type A coal samples mainly contain open pores, and type B coal samples are rich in ink bottle pores. We found that type B coal samples have the characteristics of smaller TPV, smaller APD, and larger SSA.

(2) The hysteresis coefficient was, for the first time, proposed to characterize the hysteresis loop area of coal generated by LT-$N_2$GA. In type A coal samples, the TJ coal sample has the largest hysteresis coefficient and open pore...
volume, which is most conducive to the development of CBM. However, the hysteresis coefficient and ink bottle pore volume of the HSHF sample is the largest, which is beneficial to the adsorption of CBM.

(3) Through the TPI-GI facies diagram casting of 20 coal samples, it is found that these samples are located in three different coal facies regions. The TPI and GI data of type B coal samples show a good negative logarthmic relationship, and the fitting curve can also be used as a basis for identifying ink bottle pores.

(4) The \( R_{\text{max}} \), GI, TPI, \( V_{\text{I}}, \) \( V_{\text{BH}}, \) \( S_{\text{BET}}, \) and \( H_{\text{c}} \) can be clustered using the R-type cluster analysis method. TPI is the main controlling factors of the pore structure of type A coal samples, while the pore structure of type B coal samples are jointly controlled by TPI and coal rank. The open pore volume is closely related to TVP, while the ink bottle pores volume is mainly correlated with SSA.

**REFERENCES**

(1) Zhang, S.; Tang, S.; Tang, D.; Pan, Z.; Yang, F. The characteristics of coal reservoir pores and coal facies in LiuLin district, Hedong coal field of China. Int. J. Coal Geol. 2010, 81, 117–127.

(2) Zhang, Z.; Qin, Y.; Yang, Z.; Zhao, J.; Yi, T. Segmentation of multi-coal seam pore structure in single well profile and its sedimentary control: a case study of Well Y1 in Panguang syncline, western Guizhou, China. Arabian J. Geosci. 2019, 12, 469.

(3) Ren, P.; Xu, H.; Tang, D.; Li, Y.; Chen, Z.; Sun, C.; Zhang, F.; Chen, S.; Xin, F.; Cao, L. Pore structure and fractal characterization of main coal-bearing synclines in western Guizhou, China. J. Nat. Gas Sci. Eng. 2019, 63, 58–69.

(4) Zhao, J.; Xu, H.; Tang, D.; Mathews, J. P.; Li, S.; Tao, S. Coal seam porosity and fracture heterogeneity of macrolithotypes in the Hancheng Block, eastern margin, Ordos Basin, China. Int. J. Coal Geol. 2016, 159, 18–29.

(5) Yu, S.; Bo, J.; Fengl, L.; Jiegang. L. Structure and fractal characteristic of micro- and meso-pores in low, middle-rank tectonic deformed coals by \( \text{CO}_2 \) and \( \text{N}_2 \) adsorption. Micropor. Mesopor. Mat. 2017, 253, 191–202.

(6) Marchioni, D.; Kalkreuth, W. Coal facies interpretations based on lithotype and maceral variations in Lower Cretaceous (Gates Formation) coals of Western Canada. Int. J. Coal Geol. 1991, 18, 125–162.

(7) Silva, M. B.; Kalkreuth, W. Petrological and geochemical characterization of Candiota coal seams, Brazil—implication for coal facies interpretations and coal rank. Int. J. Coal Geol. 2005, 64, 217–238.

(8) Qin, Y.; Moore, T. A.; Shen, J.; Yang, Z.; Shen, Y.; Wang, G. Resources and geology of coalbed methane in China: a review. Int. Geol. Rev. 2018, 60, 777–812.

(9) Yang, Z.; Zhang, Z.; Qin, Y.; Wu, C.; Yi, T.; Li, Y.; Tang, J.; Chen, J. Optimization methods of production layer combination for coalbed methane development in multi-coal seams. Pet. Explor. Dev. 2018, 45, 312–320.

(10) Yang, Z.; Li, Y.; Qin, Y.; Sun, H.; Zhang, P.; Zhang, Z.; Wu, C.; Li, C.; Chen, C. Development unit division and favorable area evaluation for joint mining coalbed methane. Pet. Explor. Dev. 2019, 46, 583–593.

(11) Tao, S.; Chen, S.; Pan, Z. Current status, challenges, and policy suggestions for coalbed methane industry development in China: A review. Energy Sci. Eng. 2019, 7, 1059–1074.

(12) Tao, S.; Pan, Z.; Tang, S.; Chen, S. Current status and geological conditions for the applicability of CBM drilling technologies in China: A review. Int. J. Coal Geol. 2019, 202, 95–108.

(13) Li, S.; Tang, D.; Pan, Z.; Xu, H.; Guo, L. Evaluation of coalbed methane potential of different reservoirs in western Guizhou and eastern Yunnan, China. Fuel 2015, 139, 257–267.

(14) Chen, S.; Tao, S.; Tang, D.; Xu, H.; Li, S.; Zhao, J.; Jiang, Q.; Yang, H. Pore Structure Characterization of Different Rank Coals Using \( \text{N}_2 \) and \( \text{CO}_2 \) Adsorption and Its Effect on \( \text{CH}_4 \) Adsorption Capacity: A Case in Panguang Syncline, Western Guizhou, China. Energy Fuels 2017, 31, 6034–6044.

(15) Diessel, C. F. K. On the correlation between coal facies and depositional environments. In Proceeding 20th Symposium of Department Geology; University of New Castle: New South Wales, 1986; pp 19–22.

(16) Calder, J. H; Gilbing, M. R.; Mukhopadhyay, P. K. Peat formation in a westphalian B piedmont setting, cumberland basin, Nova Scotia: Implications for the maceral-based interpretation of rhatophytic and raised paleomes. Contribution series No. 91-002. Bull. Soc. Geol. Fr. 1991, 162, 283–298.
(17) Staub, J. R. Marine flooding events and coal bed seam architecture in southern West Virginia. *Int. J. Coal Geol.* 2002, 49, 123–145.

(18) Ma, X. X. Petrology and Coal Facies of the Main Coal Seams of the Late Permian in Shuicheng. Doctoral Dissertation, China University of Mining and Technology, Guizhou, Beijing, 1988 (In Chinese).

(19) Marques, M. Coal facies and depositional environments of the Aurora and Cabeza de Vaca Units, Peñarroya–Belmez–Espiel Coalfield (Cordoba, Spain). *Int. J. Coal Geol.* 2002, 48, 197–216.

(20) Li, S.; Tang, D.; Pan, Z.; Xu, H. Influence and control of coal facies on physical properties of the coal reservoirs in Western Guizhou and Eastern Yunnan, China. *Int. J. Oil, Gas and Coal Technol.* 2014, 8, 221–234.

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

(22) Hodot, B. B. Outburst of Coal and Coalbed Gas; China Industry Press: Beijing, 1966 (In Chinese).

(23) Yao, Y. B.; Liu, D. M.; Huang, W. H.; Tang, D. Z.; Tang, S. H. Study on Pore-Fracture System of Coal Reservoirs and Coalbed Methane Production Performance in Lianghui Coalfield. *J. China Coal Soc.* 2006, 2, 163–168. (in Chinese with an English abstract)

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

(25) Mandelbrot, B. B. *Les Objets Fractals: Formes, Hazard et Dimension*; Flammarion: Paris, France, 1975.

(26) Fu, X.; Qin, Y.; Zhang, W.; Wei, C.; Zhou, R. Fractal classification and natural classification of coal pores based on coalbed methane. *Chin. Sci. Bull.* 2005, 50, 66–71. (in Chinese with an English abstract)

(27) Friesen, W. I.; Mikula, R. J. Fractal dimensions of coal particles. *J. Colloid Interf. Sci.* 1987, 120, 263–271.

(28) Pleifer, P.; Cole, M. W. Fractals in surface science: scattering and thermodynamics of adsorbed films (II). *New J. Chem.* 1990, 14, 221–232.

(29) Jaroniec, M.; Kruk, M.; Olivier, J. Fractal analysis of composite adsorption isotherms obtained by using density functional theory data for argon in slurry pores. *Langmuir* 1997, 13, 1031–1035.

(30) Ouyang, Z.; Liu, D.; Cai, Y.; Yao, Y. Fractal Analysis on Heterogeneity of Pore–Fractures in Middle–High Rank Coals with NMR. *Energy Fuels* 2016, 30, 5449–5458.

(31) Fu, H.; Tang, D.; Xu, T.; Xu, H.; Tao, S.; Li, S.; Yin, Z.; Chen, B.; Zhang, C.; Wang, L. 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* 2017, 193, 254–264.

(32) Wang, B.; Qin, Y.; Shen, J.; Zhang, Q.; Wang, G. Pore structure characteristics of low-and medium-rank coals and their differential adsorption and desorption effects. *J. Petrol. Sci. Eng.* 2018, 165, 1–12.

(33) Qin, Y. *Micropetrological Characteristics and Structural Evolution of High Rank Coal in China*; China University of Mining and Technology Press: Xuzhou, 1994 (In Chinese).

(34) Fu, X. H.; Qin, Y.; Wei, C. T. *Coalbed Methane Geology*; China University of Mining and Technology Press: Xuzhou, 2007 (In Chinese).

(35) Kondo, S., Ishikawa, T., Abe, I. *Adsorption science*; Chemical Industry Press: Beijing, 2005 (In Chinese).

(36) Chen, Y.; Qin, Y.; Wei, C.; Huang, L.; Shi, Q.; Wu, C.; Zhang, X. Porosity changes in progressively pulverized anthracite subsamples: Implications for the study of closed pore distribution in coals. *Fuel* 2018, 225, 612–622.

(37) Zhang, X.; Wu, C.; Liu, S. Characteristic analysis and fractal model of the gas-water relative permeability of coal under different confining pressures. *J. Petrol. Sci. Eng.* 2017, 159, 488–496.

(38) Zhang, S.; Wu, C.; Liu, H. Comprehensive characteristics of pore structure and factors influencing micropore development in the Loachang mining area, eastern Yunnan, China. *J. Petrol. Sci. Eng.* 2020, 190, 107090.

(39) Shao, L. Y.; Gao, C. X.; Zhang, C.; Wang, H.; Guo, L. J.; Gao, C. H. Sequence – palaeogeography and coal accumulation of Late Permian in southwestern China. *Acta Sedimentol. Sin.* 2013, 31, 856–866. (in Chinese with English abstract)

(40) Wang, X.; Shao, L.; Eriksson, K. A.; Yan, Z.; Wang, J.; Li, H.; Zhou, R.; Lu, J. Evolution of a plume-influenced source-to-sink system: An example from the coupled central Emeishan large igneous province and adjacent western Yangtze cratonic basin in the Late Permian, SW China. *Earth Sci. Rev.* 2020, 207, 103224.

(41) Qin, Y., Luo, J., Shen, J. *Coalbed Methane Resources and Mining Geological Conditions in Yunnan Province*; China University of Mining and Technology Press: Xuzhou, 2018b (In Chinese).

(42) Qin, Y., Gao, D. Prediction and Evaluation of Coalbed Methane Resource Potential in Guizhou Province; China University of Mining and Technology Press: Xuzhou, 2012 (In Chinese).

(43) Xu, H.; Sang, S.; Yang, J.; Jin, J.; Hu, Y.; Liu, H.; Li, J.; Zhou, X.; Ren, B. Selection of suitable engineering modes for CBM development in zones with multiple coalbeds: A case study in western Guizhou Province, Southwest China. *J. Nat. Gas Sci. Eng.* 2016, 36, 1264–1275.

(44) Gao, D.; Qin, Y.; Yi, T. S. CBM geology and exploring-developing stratagem in Guizhou Province, China. *Procedia Earth Planet. Sci.* 2009, 1, 882–887.

(45) Zhang, Z.; Qin, Y.; Yang, Z.; Jin, J.; Wu, C. Fluid energy characteristics and development potential of coalbed methane reservoirs with different synclines in Guizhou, China. *J. Nat. Gas Sci. Eng.* 2019b, 71, 102981.

(46) ISO 18283:2006—Hard Coal and Coke, Manual Sampling, 2006.

(47) ISO 7404-2:1995—Methods for the Petrographic Analysis of Bituminous Coal and Anthracite, Part 3: Method of Determining of Moisture in the General Analysis Test Sample by Drying in Nitrogen, 1999.

(48) ISO 11722:1999—Solid Mineral Fuels—Hard Coal—Determination of Moisture in the General Analysis Test Sample by Drying, 1999.

(49) ISO 1171:1997—Solid Mineral Fuels—Determination of Ash, 1997.

(50) ISO 562:1998—Hard Coal and Coke—Determination of Volatile Matter, 1998.

(51) ISO 7404-5:1994—Methods for the Petrographic Analysis of Bituminous Coal and Anthracite—Part 5: Method of Determining Microscopically the Reflectance of Vitrinite, 1994.

(52) ISO 7404-3:2009—Methods for the Petrographic Analysis of Coals—Part 3: Method of Determining Maceral Group Composition, 2009.

(53) Tao, S.; Pan, Z.; Chen, S.; Tang, S. Coal seam porosity and fracture heterogeneity of marcolithotypes in the Fanzhuang block, Guizhou Province, Southwest China. *Acta Sedimentol. Sin.* 2020, 866. (in Chinese with English abstract)

(54) ISO 15901-2:2006—Pore size Distribution and Pore Size of Solid Materials by Mercury Porosimetry and Gas Adsorption—Part 2: Analysis of Mesopores and Macropores by Gas Adsorption, 2006.

(55) Tang, J.; Feng, L.; Li, Y.; Liu, J.; Liu, X. Fractal and pore structure analysis of Shengli lignite during drying process. *Powder Technol.* 2016, 303, 251–259.

(56) ISO 11760-2005—Classification of Coals, 2005.

(57) Singh, K. S. W. Reporting physiosorption data for gas/solid systems with special reference to the determination of surface area and porosity (Recommendations 1984). *Pure Appl. Chem.* 1985, 57, 603–619.

(58) Guo, L. L.; Tang, D. Z.; Xu, H.; Li, S.; Gao, L. J. Analysis on physical property features of different coal rank coal reservoirs in western Guizhou and eastern Yunnan area. *Coal Sci. Technol.* 2014, 42, 99–103. (in Chinese with an English abstract)