Coal Macrolithotype Distribution and Its Genetic Analyses in the Deep Jiaozuo Coalfield Using Geophysical Logging Data
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ABSTRACT: Coal macrolithotypes are closely correlated with coal macerals and pore–fracture structures, which greatly influence the changes in gas content and the coal structure. Traditional macrolithotype identification in coalbed methane (CBM) wells mostly depends on core drilling observation, which is expensive, time-consuming, and difficult for broken core extraction. Geophysical logging is a quick and effective method to address this issue. We obtained coal cores from 75 wells in the deep regions of the Jiaozuo Coalfield, northern China, quantitatively analyzed the logging cutoff number corresponding to various macrolithotypes, and established natural γ (GR), deep lateral resistivity (LLD), and γ−γ log (GGL) response rules for each coal macrolithotype. The formation mechanisms of different coal macrolithotypes are discussed from the perspective of coal facies and pore structures. The results show that GGL decreased but GR and LLD increased from bright coal to dull coal. Most coal macrolithotypes can be distinguished based on the established thresholds of various logging curves. However, excessively high or low ash yields significantly affect the validity of identification. The vertical coal macrolithotypes attributed to the peat marsh environment in Shanxi Formation mostly comprise three to six sublayers; dull or semi-dull coals are predominant close to the 21 coal seam, and the bright or semi-bright types usually appear in the middle part. The semi-bright and bright coals are usually vitrinite rich, whereas the semi-dull and dull coals are primarily inertinite rich. For pore structure arguments, the highest average specific surface area ($S_{BET}$) and the total pore volume ($V_{BJH}$) are found in bright coals, followed by dull and semi-bright coals; those of semi-dull coals are the lowest. However, $S_{BET}$ and $V_{BJH}$ change significantly for different samples, even though the coal macrolithotype is the same. Therefore, the macrolithotype is not the key factor determining the coal parameters of pore structures. Rapid and effective identification of coal macrolithotypes can help determine the CBM enrichment area, the CBM well location, and the exploration horizon.

1. INTRODUCTION
Coalbed methane (CBM) is an important unconventional natural gas in the world.¹ However, no significant breakthrough in CBM well production has been performed in China, and total gas production primarily depends on a few areas.² Unlike conventional natural gas, CBM successful exploitation involves complex system engineering that is primarily constrained by both geological and engineering factors.³ The coal macrolithotype, as a fundamental geological factor, is primarily controlled by the peat marsh sedimentary environment,⁴ which macroscopically controls the spatial distribution of coal reservoir heterogeneity and affects the CBM enrichment and development effect to some extent.⁵

The proportions of vitrain and clarain are used to divide coal macrolithotypes into four types: bright coal (vitrain + clarain > 80%, in volume), semi-bright coal (50% < vitrain + clarain < 80%, in volume), semi-dull coal (20% < vitrain + clarain < 50%, in volume), and dull coal (vitrain + clarain < 20%, in volume).⁶ The coal macrolithotype greatly affects the porosity and percolation rate of the coal seam⁷,⁸ and is an evaluation index for the effect of underground gas extraction.⁹ Additionally, the macrolithotype is closely related to the adsorption capacity,¹⁰ gas content,¹¹ desorption velocity,¹² and mechanical properties.¹³ Coal macrolithotypes of underground coal mines and coal cores in CBM wells are currently identified based on on-site observations and descriptions. Scholars have preliminarily identified coal macrolithotypes for boreholes without coal cores using logging curves.⁹ Coal seams have similar materials in the same coalfield or mining area, which is the basis for identifying coal macrolithotype using logging curves. Because of
its high speed, high efficiency, and low cost, well logging technology is commonly used for CBM exploration and exploitation.\textsuperscript{14−16} The response criteria of logging curves to coal macrolithotypes can be established to predict coal macrolithotypes without cores. This method is significant for optimizing the CBM well locations and laying out/designing the underground gas drainage boreholes. The logging curve responses of coal reservoirs are characterized by higher resistivity (RT), higher acoustic time difference (AC), lower density (DEN), and lower natural $\gamma$ (GR) than those of sandstone reservoirs.\textsuperscript{17,18} The differences in logging responses among various coal macrolithotypes are the basis for predicting coal macrolithotypes using logging curves.\textsuperscript{9} From bright to dull coal, the coal ash content and the density value increase with decreasing pore and fracture spaces and vitrinite contents. Correspondingly, DEN and GR logging values gradually increase, whereas deep lateral resistivity (LLD) and AC values progressively decrease.\textsuperscript{9} A previous investigation showed that ash yield in coals affects the response rules of the logging data when distinguishing different coal structures,\textsuperscript{19} as the ash content directly determines coal density. Therefore, coal seams with similar ash yields should be the basis for logging

Figure 1. Location and geological structure outline of the Machang region in the deep Jiaozuo Coalfield.

This page contains a description of the logging technology used for coal-bed methane (CBM) exploration and the criteria for establishing logging curve responses to predict coal macrolithotypes. The differences in logging responses among various coal macrolithotypes are used to distinguish between different coal structures.
identification. However, the influence of the ash yield on coal macrolithotype identification requires further study.

Differences in coal macerals are a prerequisite for determining coal macrolithotypes due to the relationship between coal macrolithotypes and vitrinite contents, which are controlled by peat marsh environments and coal facies.\textsuperscript{20,21} Previous studies have found that bright coals and parts of semi-bright coals were mainly deposited in forest swamp facies, dull coals usually were developed from dry swamp facies, and semi-dull coals and a part of semi-bright types were from active water swamp facies.\textsuperscript{9,22} Therefore, gelatinization plays a dominant role in the formation of semi-bright coals and bright coals, whereas dull coals and semi-dull coals have relatively complex compositions, which may be attributed to high fusinite, high liptinite, or high

Figure 2. Lithology column and depositional environment of the Permian strata in the Jiaozuo Coalfield.

Table 1. Macrolithotype, Maximum Vitrinite Reflectance, Proximate Analysis, Maceral Composition, and Low-Pressure Nitrogen Adsorption Results\textsuperscript{a}

| no. | sample no. | macrolithotype | \( R_{\text{oo, max}} \) (%) | \( M_{\text{ad}} \) (%) | \( A_{\text{ad}} \) (%) | \( V_{\text{ad}} \) (%) | \( FC_{\text{ad}} \) (%) | \( V \) (%) | \( I \) (%) | \( L \) (%) | \( M \) (%) | \( S_{\text{BET}} \) (\( \text{m}^2/\text{g} \)) | \( V_{\text{BJH}} \) (\( 10^{-3} \text{ cm}^3/\text{g} \)) |
|-----|------------|----------------|-----------------|----------------|----------------|----------------|----------------|----------------|--------|--------|--------|--------|----------------|----------------|
| 1   | JLS-1      | dull           | 2.97            | 2.97           | 19.8           | 10.31          | 66.92          | 71.28          | 24.56  | 2.77   | 1.39   | 0.86   | 1.19            | 0.86            |
| 2   | JLS-2      | bright         | 2.73            | 1.74           | 6.16           | 9.98           | 82.12          | 85.56          | 13.15  | 0.86   | 0.43   | 0.09   | 0.41            | 0.41            |
| 3   | JLS-3      | semi-bright    | 3.07            | 2.00           | 10.82          | 6.03           | 81.15          | 82.38          | 15.20  | 1.76   | 0.66   | 0.30   | 0.47            | 0.47            |
| 4   | JLS-4      | semi-bright    | 3.00            | 1.58           | 13.4           | 5.81           | 79.21          | 79.87          | 16.93  | 2.56   | 0.64   | 0.60   | 0.82            | 0.82            |
| 5   | GHS-1      | bright         | 3.01            | 2.46           | 13.16          | 5.69           | 78.69          | 85.30          | 12.97  | 1.15   | 0.58   | 0.96   | 1.27            | 1.27            |
| 6   | GHS-3      | bright         | 2.94            | 2.14           | 6.35           | 5.45           | 86.06          | 81.48          | 16.16  | 1.67   | 1.68   | 0.07   | 0.32            | 0.32            |
| 7   | YMZ-2      | semi-bright    | 2.93            | 2.75           | 7.61           | 5.52           | 84.12          | 77.93          | 19.31  | 2.07   | 0.69   | 0.30   | 0.66            | 0.66            |
| 8   | YMZ-3      | semi-dull      | 2.91            | 1.58           | 10.32          | 5.86           | 82.24          | 70.42          | 24.17  | 4.16   | 0.26   | 1.25   | 0.57            | 0.57            |
| 9   | YMZ-4      | semi-dull      | 2.88            | 2.36           | 10.06          | 7.39           | 80.19          | 79.47          | 16.72  | 2.93   | 0.88   | 0.29   | 0.58            | 0.58            |
| 10  | FZE-2      | dull           | 2.95            | 1.29           | 12.96          | 5.9            | 79.85          | 73.18          | 23.75  | 1.53   | 1.53   | 0.15   | 0.25            | 0.25            |
| 11  | FY-1       | semi-dull      | 2.89            | 1.67           | 12.38          | 5.44           | 80.51          | 82.61          | 16.15  | 0.62   | 0.62   | 0.33   | 0.66            | 0.66            |
| 12  | ZMC-1      | bright         | 3.06            | 1.58           | 9.05           | 8.13           | 81.24          | 86.55          | 10.69  | 1.38   | 1.38   | 0.86   | 1.12            | 1.12            |
| 13  | F0401      | bright         | 3.12            | 2.87           | 6.1            | 6.34           | 84.69          | 91.35          | 8.65   | 0      | 1.72   | 4.72   |                 |                 |

\( R_{\text{oo, max}} \), maximum vitrinite reflectance; \( M_{\text{ad}} \), moisture content; \( A_{\text{ad}} \), ash yield; \( V_{\text{ad}} \), volatile; \( FC_{\text{ad}} \), fixed carbon; \( V \), vitrinite; \( I \), inertinite; \( L \), liptinite; \( M \), mineral; \( S_{\text{BET}} \), specific surface area; \( V_{\text{BJH}} \), total pore volume; and \( \text{ad} \), air-dried basis.
minerals. Coal macrolithotypes are still recognized through field observations and rarely evaluated using geophysical logging data. The use of logging evaluation methods (e.g., the threshold method) to determine coal macrolithotype distribution in mining areas or coal fields improves the exploration and development of CBM wells and gas prevention in coal mines.

2. GEOLOGICAL SETTINGS

The Jiaozuo Coalfield, located in northwestern Henan Province, has a length of approximately 60 km and a width of about 15 km and covers an area of approximately 970 km². The coalfield is located in the southern Taihang tectonic region attached to the North China Plate (Figure 1). In the Taihang fault uplift area, the geological structure is characterized by fault-block forms; the dip angle of the strata is small, generally less than 20°. The two groups of faults (NE- and NWW-trending) are generally high-angle normal faults. Grabens, horsts, tilting fault blocks, and rifting basins were formed under the influence of geological activities. The Machang exploration area is located in the southeastern (deep) Jiaozuo Coalfield and features a relatively simple structural condition; the monoclinal structure has a NE strike and dip angles in the range of 2°–14°. The dominant structure type in the Jiaozuo Coalfield is commonly dominated by faults accompanied by small, wide, and slow folds (Figure 1). The Machang exploration area is divided into northern, central, and southern blocks by the Nanzhangmen, Fenghuangling, and Dongcun boundary faults (Figure 1).

Table 2. Logging Response of Different Macrolithotypes and Partings in the Machang Exploration Area

| macrolithotype or parting | GGL (CPS) | LLD (Ω·m) | GR (API) |
|--------------------------|-----------|------------|----------|
| dull coal                | 732.1−1289.9 (966.8) | 77.7−1198.6 (526.6) | 77.2−180.6 (117.9) |
| semi-dull coal           | 873.3−2350.8 (1472.2) | 150.2−1346.6 (805.6) | 38.2−155.5 (94.5) |
| semi-bright coal         | 957.5−3389.1 (1921) | 230.3−1746.7 (1125.2) | 28.3−145.2 (76.7) |
| bright coal              | 1647.2−3805.5 (2677.7) | 444.2−3250.3 (1787.9) | 18.8−63.4 (46.5) |
| dull coal                | 732.1−1289.9 (966.8) | 77.7−1198.6 (526.6) | 77.2−180.6 (117.9) |
| semi-dull coal           | 873.3−2350.8 (1472.2) | 150.2−1346.6 (805.6) | 38.2−155.5 (94.5) |
| semi-bright coal         | 957.5−3389.1 (1921) | 230.3−1746.7 (1125.2) | 28.3−145.2 (76.7) |
| bright coal              | 1647.2−3805.5 (2677.7) | 444.2−3250.3 (1787.9) | 18.8−63.4 (46.5) |

*aAverage value.

Figure 3. $\gamma-log (GGL)$ change characteristics with different coal macrolithotypes and partings in the Machang exploration area, Jiaozuo Coalfield.

Figure 4. Natural $\gamma$ (GR) characteristics with different coal macrolithotypes and partings in the Machang exploration area, Jiaozuo Coalfield.

Figure 5. Deep lateral resistivity (LLD) characteristics with various coal macrolithotypes and partings in the Machang exploration area, Jiaozuo Coalfield.

Figure 6. Variation relationship of the density logging response with resistivity and natural $\gamma$ logging curves of different coal macrolithotypes in the Machang exploration area.
flat lagoon for the Taiyuan Formation to a delta for the overlying Shanxi Formation strata (Figure 2). The 21 coal seam developed in the lower Shanxi Formation is located approximately 75 m below the Shaguoyao sandstone and 20 m above the L8 limestone (Figure 2). Borehole data show that the coal seam thickness in the Shanxi Formation ranges from 0.91 to 10.50 m with an average of 6.72 m; this coal seam is the principal target for CBM exploitation in the Jiaozuo Coalfield. The lithology of the direct roof primarily consists of gray-black sandy mudstone and mudstone, but the floor lithology of the 21 coal seam is mostly covered by thick mudstone and carbonaceous mudstone (Figure 2). The average maximum value of vitrinite reflectance ($R_{\text{omax}}$) is 2.81%, and the gas content of coal is generally between 25 and 40 m$^3$/t.21

### 3. METHODOLOGY

Field identification of multiple coal macrolithotypes and partings was conducted on fresh 21 coal cores in the 75 CBM wells. We performed coal maceral identification with 500 recording points, $R_{\text{omax}}$ testing, proximate analysis, and low-pressure $N_2$ adsorption experiments to further analyze the genesis of various coal macrolithotypes. The coal macerals including vitrinite, inertinite, and liptinite were quantitatively observed using an OLYMPUS BX51 microscope under oil immersion with reflected light; no fewer than 500 effective measurement points were necessary for each sample. The $R_{\text{omax}}$ measurement was conducted and no fewer than 50 effective measurement points were required. The proximate analysis of coal was performed and included moisture, ash, volatiles, and fixed carbon in coals. The moisture and ash contents were determined using the air drying and rapid ash methods, respectively. The low-pressure nitrogen adsorption was conducted and the pore structure parameters, including specific surface area ($S_\text{BET}$), pore size distribution (PSD), and total pore volume ($V_{\text{BJH}}$), were determined using a Quantachrome NOVA 2000e analyzer. Each sample of 5−10 g was dried at 105 °C for 8 h and crushed using sieves with 40−60 meshes corresponding to the size range of 0.28−0.42 mm for this experiment. Nitrogen adsorption−desorption isotherms with relative pressure ranging from 0.01 to 0.99 at 77 K were derived.25

During the drilling process, the drill pipes were deformed and stretched; thus, the drilling depth obtained using the accumulated drill pipes was greater than that of the actual drilling location. In this study, the coal seam depth measurement was calibrated using the method proposed in a previous investigation for comparison with geophysical logging data.26

### Table 3. Logging Identification Criteria for Coal Macrolithotypes in the Machang Exploration Area

| macrolithotype or parting | GGL (CPS) | LLD (Ω·m) | GR (API) |
|---------------------------|-----------|-----------|--------|
| parting                   | <1200     | <770      | >88    |
| dull coal                 | <1200     | 77−1200 (526)$^a$ | >77 |
| semi-dull coal            | <1200     | 428−1450 (880) | >38 |
|                           | >1200     | 150−1300 (694) |       |
| semi-bright coal          | <1400     | 315−2325 (1457) | >28 |
|                           | >1400     | 230−1600 (1019) |       |
| bright coal               | >1600     | 444−3250 (1787.9) | >16 |

$^a$Average value.
We used specific methods and steps to identify coal macro-lithotypes and partings through logging curve responses as follows. First, the coal macro-lithotypes of coal cores in each borehole were identified by field observation and the corresponding depths were recorded. The method above was used to correct the borehole depth. Second, the maximum, minimum, and average values of LLD, GR, and GGL logging data corresponding to each coal macro-lithotype were recorded. Third, we established and verified the mathematical relationship between the response values of different logging curves and relevant coal macro-lithotypes including typical bright, dull, semi-bright, and semi-dull coals and identified different threshold values for each coal macro-lithotype. We further modified the established thresholds according to the macro-lithotype logging responses from other wells. Fourth, an established criterion was used to predict the spatial distribution of the coal macro-lithotypes in the CBM well with only logging curves and no coal cores.

4. RESULTS

4.1. Relevant Experimental Analyses. Thirteen coal samples, including five bright coals, three semi-bright coals, three semi-dull coals, and two dull coals, were selected to perform the experiments of $R_{\text{o,max}}$, proximate analysis, coal maceral, and low-pressure N$_2$ adsorption (Table 1). The $R_{\text{o,max}}$ values range from 2.73 to 3.12% with an average of 2.96%. In terms of proximate analyses, the contents of moisture ($M_{\text{ad}}$), ash yield ($A_{\text{ad}}$), volatile matter ($V_{\text{ad}}$), and fixed carbon ($F_{\text{C_{ad}}}$) on an air-dried basis range from 1.29 to 2.97%, 6.1 to 19.8%, 5.44 to 10.31%, and 66.92 to 86.06%, respectively. The average ash yields in bright coals, semi-bright coals, semi-dull coals, and dull coals are 8.16, 10.61, 10.92, and 16.38%, respectively. Therefore,
from bright to dull coals, there is a decreasing trend for the ash yields. It is noted that the ash content between semi-bright coals and semi-dull coals is similar, indicating that more details are necessary for identifying these two macrolithotypes using geophysical logging data. The results of coal maceral analyses of 13 Shanxi coals show that the vitrinite content is the highest (ranging from 71.28 to 91.35% with an average of 80.56%), followed by inertinite (ranging from 8.65 to 24.56% with an average of 16.81%), liptinite (ranging from 0 to 4.16% with an average of 1.73%), and mineral (ranging from 0 to 4.16% with an average of 1.73%). The average $S_{BET}$ and $V_{BJH}$ of bright, semi-bright, semi-dull, and dull coals are 0.740, 0.395, 0.294, and 0.504 m$^2$/g and 1.567 $\times$ 10$^{-3}$, 0.648 $\times$ 10$^{-3}$, 0.603 $\times$ 10$^{-3}$, and 0.718 $\times$ 10$^{-3}$ cm$^3$/g, respectively.

4.2. Use of Well Logging Data to Identify Coal Macrolithotypes. 4.2.1. Well Logging Data. The GGL, LLD, GR, and CAL logging curves are the most closely related to coal macrolithotypes. However, the CAL response is easily affected by the drilling process; thus, GGL (inversely proportional to the density value), LLD, and GR logging curves are usually selected for coal macrolithotype identification and its evaluation.

The logging response characteristics of different coal macrolithotypes can be summarized as follows: (1) coals with low ash content usually have a lower density and a higher GGL value; (2) high-density coals generally have poor reservoirs with low LLD values; (3) coals with higher minerals and ash content usually have greater GR values; and (4) coals with higher LLD values are characterized by higher vitrinite content, better pore and fracture development, and higher CH$_4$ adsorption capacity. Furthermore, carbonaceous mudstone partings are found in coals, which are easily identified using well

Figure 9. Field description and logging interpretation of coal macrolithotypes in Well 0403.

Figure 10. Field description and logging interpretation of coal macrolithotypes in Well 0404 (keys are the same as Figure 8).
logging because of their relatively low GGL, low LLD, and high GR.\textsuperscript{21} Table 2 lists the coal macrolithotypes (partings) and their logging responses in the study area. (1) The GGL value decreases as coal density increases (Figure 3), and the GR value increases due to higher ash yield (Figure 4); (2) from bright coal to the parting, the decrease in vitrinite content decreases the gas content in coals and gradually decreases the corresponding LLD value (Table 2 and Figure 5) due to the decreased ability to conduct electricity and increased resistivity from low to high gas contents in coals;\textsuperscript{9} and (3) LLD is negatively associated with GGL, whereas GR values are positively associated with the GGL value (Figure 6).

4.2.2. Cutoff Value of the Determined Macrolithotype Using Well Logging Data. Various characteristics of different logging types and their key separating values corresponding to each macrolithotype are shown in Table 3. Dull coal is characterized by GR values greater than 77 API, LLD values greater than 1200 $\Omega \cdot m$, and GGL values less than 1200 CPS. Semi-dull coal has GR cutoff values greater than 38 API and diverse GGL and LLD threshold value ranges. For GGL values less than 1200 CPS, LLD values range from 428 to 1450 $\Omega \cdot m$; for GGL values greater than 1200 CPS, LLD values range from 150 to 1300 $\Omega \cdot m$. For GGL values greater than 1200 CPS, the GR cutoff values of semi-bright coal are greater than 28 API, and the threshold values of GGL and LLD need to be specifically analyzed. For GGL values less than 1400 CPS, LLD values range from 315 to 2325 $\Omega \cdot m$; for GGL values greater than 1400 CPS, LLD values range from 230 to 1600 $\Omega \cdot m$. The GR values corresponding to bright coal are relatively low (down to 16 API), and the LLD and GGL boundaries are limited as follows: GGL $> 1600$ CPS and $444 \Omega \cdot m < LLD < 3250 \Omega \cdot m$. The coal partings are characterized by high density, strong radioactivity, and low gas content.\textsuperscript{9} In this study, the logging identification standard of parting is set as follows: GGL $< 1200$ CPS, LLD $< 770\Omega \cdot m$, and GR $> 88$ API (Table 3). Density logging curves have the highest priority, which should be analyzed first to judge different coal macrolithotypes, followed by LLD and GR logging curves as auxiliary judgments.

4.3. Comparison of Field Identification and Logging Interpretation for Coal Macrolithotypes. We performed contrastive analyses between field identification and logging interpretation for coal macrolithotypes using cores from drilling...
wells 0403, 0404, 1401, and 4002 in the deep Jiaozuo Coalfield. The field observation investigated that coal macrolithotypes of Well 4002 were semi-bright, bright, parting, and semi-bright from top to bottom; however, the logging interpretation results corresponded to semi-bright, bright, semi-bright, parting, and semi-bright coals, which was more consistent with the actual coal core situation (Figure 7). Therefore, the logging curve has certain advantages for coal macrolithotype identification. Furthermore, the corresponding LLD values of bright coals are significantly high, indicating that a high LLD value is an effective symbol for bright coal identification. Field observations and logging identification showed semi-dull, semi-bright, bright, and semi-dull coal macrolithotypes in Well 1401 from top to bottom. The GGL values of all coal macrolithotypes were greater than 2000 CPS, indicating relatively light coal density (Figure 8). The coal macrolithotypes of Well 0403 from top to bottom were vertically distributed with dull, semi-bright, and semi-dull coals. The GGL values of the coals of Well 0403 were lower than 1000 CPS, indicating that the coal density was relatively high, with no bright coal (Figure 9). The coal macrolithotypes of Well 0404 were semi-dull, bright, semi-bright, bright, semi-bright, and semi-dull from top to bottom (Figure 10). The coal GGL values were greater than 1600 CPS, indicating relatively light coal density. Thus, the coal macrolithotypes were mostly bright and semi-bright coals (Figure 10). Furthermore, field identification and logging interpretation results for the transitional layers during different coal macrolithotypes contain uncertainties—especially close to the roof, floor, and carbonaceous mudstone that could be attributed to the logging curve reading intervals (0.05 m). Several genetic relationships were found from different coal macrolithotypes. Bright coal transitions to semi-bright or semi-dull coals, but a direct change to dull coal is difficult. The vertical genetic relationship (a gradual change) during various coal macrolithotypes is the most possible reason for the difficult transition from bright to dull coal or from dull to bright coal. Thus, coal macrolithotype changes could be determined by the peatland sedimentary environment.

### 4.4. Spatial Distribution of Coal Macrolithotypes in the Machang Exploration Area

#### 4.4.1. Vertical Distribution of Coal Macrolithotypes

Among the 75 drilling boreholes in the Machang exploration area, most macrolithotypes vertically consist of three to six sublayers; a few drilling boreholes (e.g., Well 0404) consist of seven sublayers. The typical vertical profile shows that the coal macrolithotypes close to the coal roof and coal floor in the study area are dominated by dull/semi-dull coals, whereas the middle part is usually accompanied by semi-bright and bright coals. The vertical combination type is characterized by bright (semi-bright) coal in the middle and dull or semi-dull coals at the top and bottom, which is a major feature of coal macrolithotypes in the study area and accounts for approximately 60% of all boreholes. The vertical distribution of coal macrolithotypes from NE to SW is shown in Figure 11. The distribution has several defining characteristics. First, dull coal is concentrated at the coal top and coal bottom, perhaps due to peat marsh exposure and increased amounts of pyrofusinite with enhanced fusainization. Second, we found a genetic relationship between each sublayer in the vertical direction. The vertical distribution is strongly influenced by the peatland sedimentary environment.
distribution in the four wells including 0403, 0404, 1401, and 4002 shows that the proportion of one coal macrolithotype cross is approximately 30%. Third, bright coal is mostly located in the middle of the vertical intervals and interbedded by semi-bright or semi-dull coals, perhaps because of enhanced peat marsh gelatinization and increased vitrinite content. Fourth, no significant changes in coal macrolithotypes were found on either side of the faults, indicating that the geological structure has little influence on the coal macrolithotypes.

Figure 12 shows the vertical distribution of the coal macrolithotypes along the NW−SE direction. The section is taken from the southern Machang exploration area, and the buried depth successively increases from NW to SE. We found no significant vertical changes for the thickness of various coal macrolithotypes with increased buried depths; thus, the coal macrolithotype distribution is unrelated to buried depth (Figure 12). The vertical distribution of the coal macrolithotypes is similar to that of the relevant summary (Figure 11).

4.4.2. Horizontal Distribution of Coal Macrolithotypes.
Dull coal is poorly developed (Figure 13) in the Machang exploration area and only found in the 21 boreholes. The average thickness of dull coal is 0.26 m, accounting for 4.55% of the total coal thickness ($T_c$). The average thicknesses ($A_c$) of dull coal in the southern, central, and northern blocks are 0.23, 0.3, and 0.17 m and account for 4.02, 4.77, and 2.89% of $T_c$, respectively. The maximum cumulative thickness ($M_c$) of dull coal (2.35 m) is found in Well 1204. Dull coal is generally more developed in the southern and central blocks than in the northern block. However, owing to limited data from exploration wells in the northern block, the control range of the dull coal distribution is limited.

Semi-dull coal in the Machang exploration area is generally more developed than dull coal (Figure 14). The study area contains three full semi-dull coal wells, including 1602 and 3201 in the southern block and 6004 in the central block. The average thickness of semi-dull coal is 1.38 m, accounting for 23.06% of the $A_c$ in the Machang block. Specifically, the $A_c$ values of semi-dull coal in the southern, central, and northern blocks are 1.52, 1.31, and 0.66 m, accounting for 26.61, 21.14, and 11.17% of the total coal thickness, respectively. The cumulative maximum thickness of the semi-dull coal in the Machang exploration area is 3.9 m (Well 0802); however, several boreholes have no semi-dull coal in the blocks.

Semi-bright coals are relatively developed in the study area (Figure 15). The four wells containing more than 70% semi-bright coal are Well 0401 (70.87%), Well 0403 (72.56%), and Well 0804 (77.52%) in the southern block and Well 5603 (70.18%) in the central block. The southern block contains full semi-bright coal drilling (Well 1601). The average thickness of the semi-bright coals is 2.11 m, accounting for 35.41% of $T_c$. The average thicknesses of semi-bright coal in the southern, central, and northern blocks are 1.97, 2.36, and 1.21 m, accounting for 34.40, 37.87, and 20.52% of the total coal thickness, respectively. The $M_c$ of semi-bright coal in the exploration area is 5.2 m (Wells 3602 and 5603); semi-bright coals are absent in some boreholes.

Bright coal is the most developed in the Machang exploration area (Figure 16). The wells with bright coal contents of more...
than 80% are Well 0601 (85.89%) and Well 0401 (88.94%) in the southern block and Well 10801 (100%) in the northern block. The Ac of bright coal in the exploration area is 2.13 m, accounting for 35.68% of the total 21 coal samples. The average thicknesses of bright coal in the southern, central, and northern blocks are 2.04, 2.09, and 3.31 m, accounting for 35.61, 33.57, and 56.29% of Tc, respectively. The Mc of bright coal is 6.55 m, which appears in Well 4803 in the central block; bright coal is absent in several wells. Thick bright coal is primarily distributed close to faults and folds (e.g., F0004, 4403, and 5205 wells). The thickness of bright coal tends to gradually decrease with increasing distance from the faults (Figure 16), suggesting that stronger tectonic movement promotes the formation of more deformed coals and bright coals.21

5. DISCUSSION

5.1. Effectiveness of Logging Curves in Identifying Coal Macrolithotypes and the Influence of Ash Yield. The proposed key division values of different logging curves show that coal macrolithotypes determined by field observations in the Machang exploration area are consistent with the identification of the loggings. It should be noted that the nine wells (12% of the total wells: 0805, 1203, 1603, 3602, 5203, 7601, 10001, 10801, and 11601) contained significant differences that could be directly related to abnormal coal ash yields in the boreholes. A coal seam with a similar material foundation is the basic condition for identifying coal macrolithotypes using logging curves;21 thus, extremely high or low ash contents can greatly influence the changes in the logging curve response. In the study area, the average ash content on air-dried basis covering the entire drilling boreholes is 15.2%, and the coals with higher ash content generally have higher density37 corresponding to lower GGL logging values that tend to denote dull coal macrolithotypes. Conversely, the coal with lower ash content corresponds to a higher GGL logging value, which results in the identified coal macrolithotypes tending toward bright coal. For example, the ash production of coals in Well 3602 (19.6%) is higher than that of the whole study region (15.2%). Field observations reveal a bright coal macrolithotype at coal depths between 1163.15 and 1168.35 m. However, logging data indicates a semi-bright coal macrolithotype for the same interval (Figure 17). In Well 10001, the ash yield of coals (11.2%) is lower than that of the whole study region (15.2%). Field observations indicate a dull coal macrolithotype, whereas logging identification yields dull and semi-dull coals (Figure 18). Therefore, identifying coal macrolithotypes only using cutoff values determined by logging data is inappropriate for wells with extremely high or low ash yields. However, ash yield commonly increases from bright to dull coals (Table 1), which is relatively easy for field description. In response to this phenomenon, field description results should be used instead of logging identification for coal macrolithotypes.

5.2. Effects of Macerals on Coal Macrolithotype Distribution. Submacerals and their assemblage in coals are represented by coal facies, which largely represent the original genetic types and water table fluctuations in peatlands.38 Various coal facies indices consisting of the tissue preservation index (TPI), gelification index (GI), and vegetation index (VI), and
groundwater index (GWI) are usually adopted. However, due to their limitations, it is not recommended to use these coal facies indices to analyze the peat depositional environments. In this study, the ICCP group (vitrinite, inertinite, and liptinite) and minerals were used to determine the effects of macerals on coal macrolithotype distribution. As shown in Table 1, the average vitrinite, inertinite, liptinite, and mineral contents of bright, semi-bright, semi-dull and dull coals are 86.05, 12.32, 0.81, and 0.81%; 80.06, 17.15, 2.13, and 0.66%; 77.50, 19.01, 2.57, and 0.92%; 72.23, 24.16, 2.15, and 1.46%, respectively. Therefore, from bright to dull coals, there is a decreasing trend for the vitrinite content but an increasing trend for the inertinite content. In terms of liptinite and mineral contents, a relatively complex rule is observed during various macrolithotypes. The

Figure 16. Distribution of bright coal thickness in the Shanxi 2 coal in the deep Jiaozuo coalfield.

Figure 17. Field description and logging interpretation of macrolithotype and parting in Well 3602; with keys same as Figure 8.
average of liptinite and mineral contents of bright (semi-bright) coals and dull (semi-dull) coals is 1.30, 2.40, 0.76, and 1.14%, respectively. However, relative to vitrinite and inertinite, the studied coals have low contents of liptinite and minerals (Table 1). It is impossible to form different macrolithotypes just depending on low liptinite and mineral contents. Thus, the semi-bright and bright coals are usually vitrinite rich, whereas the semi-dull and dull coals are primarily inertinite rich. Vitrinite, including telinite/collotelinite and corpogelinite/gelinite with non-debris as well as vitrodetrinite/collodetrinite, mainly comes from the gelification of wood components with multiple non-fire degradation pathways. As the leading components of inertinite, fusinite and semifusinite mainly come from the wildfire of woods, the burning of degraded woody tissue, and the charring of premaceral/maceral huminite/vitrinite. Generally, bright and semi-bright coals are typically characterized by high vitrinite and low inertinite, whereas dull and semi-dull coals are characterized by low vitrinite and high inertinite (Table 1). These internal relationships indicate that the distribution of coal macrolithotypes is fundamentally controlled by environmental changes in the peat swamp and is less affected by other factors such as coalification and structural conditions in the same coalfield.

5.3. Pore Structure Characteristics for Various Coal Macrolithotypes. The $S_{BET}$ and $V_{BJH}$ of the 13 Shanxi coal specimens (five bright coals, three semi-bright coals, three semi-dull coals, and two dull coals) in the deep Jiaozuo coalfield are shown in Table 1. The average $S_{BET}$ and $V_{BJH}$ of bright, semi-bright, semi-dull, and dull coals are 0.740, 0.395, 0.294, and 0.504 m$^2$/g and 1.567 x 10$^{-3}$, 0.648 x 10$^{-3}$, 0.603 x 10$^{-3}$, and 0.718 x 10$^{-3}$ cm$^3$/g, respectively (Table 1). We compiled several coal sample characteristics. First, $S_{BET}$ is positively correlated with $V_{BJH}$ in the coal seams; thus, coal with a higher $S_{BET}$ value usually corresponds to higher $V_{BJH}$. Second, the $S_{BET}$ and $V_{BJH}$ of bright coal are the highest, followed by those of dull and semi-bright coals, and these parameters of semi-dull coal are relatively low. The most possible reason is that the vitrinite in coals has more micropore content compared with other macerals, so it has higher $S_{BET}$ and $V_{BJH}$. The micropore content and methane adsorption capacity of inertinite in coals are generally lower than those of vitrinite with the same volume. However, the pore volume and methane adsorption capacity of dull coal can exceed those of bright coal when lower amounts of fusinite or semifusinite filled with minerals. Third, the $S_{BET}$ and $V_{BJH}$ of semi-bright coal are slightly higher than those of semi-dull coal, indicating that the $V_{BJH}$ and $S_{BET}$ of vitrinite are higher than those of inertinite with the same volume. The pore structures of different coal macrolithotypes change greatly. Even for the same coal macrolithotype (e.g., bright coal), the $S_{BET}$ of No. 2 sample was 0.085 m$^2$/g, whereas that of coal sample No. 13, it was 1.723 m$^2$/g (a difference of more than 20 times). Therefore, factors other than the coal macrolithotype (e.g., degree of metamorphism, pore filling, primary structure, and later structure) can also affect coal pore structures.

6. CONCLUSIONS

(1) The GGL and LLD logging values decreased from bright to dull coals, whereas the GR logging value increased. The cutoff values for various macrolithotypes in the deep Jiaozuo Coalfield were determined. The GGL and LLD values in semi-bright and semi-dull coals need to be specifically analyzed because of similar coal macerals.

(2) The vertical coal macrolithotypes in the Machang exploration region are mostly composed of three to six sublayers. The coal macrolithotypes close to the roof and floor are dominated by semi-dull/dull coals, whereas those in the central coal seam contain semi-bright/bright coals. The horizontal distribution of coal macrolithotypes in the Machang exploration area is dominated by bright and semi-bright coals, followed by semi-dull and dull coals, which is attributed to the dominance of vitrinite.

(3) Extremely high or low ash content in coal seriously affects the logging identification results. Coal with higher ash content corresponds to a lower GGL logging value and tends to be identified as dull coal, whereas coal with lower ash content corresponds to a higher GGL logging value and tends to be identified as bright coal.

(4) The $S_{BET}$ and $V_{BJH}$ of bright coal are the highest, followed by dull, semi-bright, and semi-dull coals. However, the macrolithotype is not a decisive factor controlling the coal pore structure. The semi-bright and bright coals are
usually vitrinite rich, whereas the semi-dull and dull coals are primarily inertinite rich. The changes in coal macrolithotypes are determined by the peatland sedimentary environment.

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**Notes**

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