

## Article

# Multiple-Level Tectonic Control of Coalbed Methane Occurrence in the Huaibei Coalfield of Anhui Province, China

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**Abstract:** The Huaibei coalfield is an important coal base and one of the hot spots of coalbed methane development in China. Therefore, a detailed understanding of gas occurrence in the Huaibei coalfield is of great significance. This paper analyzes the gas occurrence from the perspective of multiple-level tectonic control, i.e., the regional tectonic level, the coalfield tectonic level, the mining area tectonic level, and the coal mine tectonic level. This study deduces that gas occurrence in the Huaibei coalfield is characterized by multiple-level tectonic control. At the regional level, the Huaibei coalfield is located in the southeast margin of the North China plate, affected by the tectonic evolution of the North China plate and by the evolution of the Dabie–Tanlu–Sulu orogenic belt. Therefore, the regional geological tectonic is complex, leading to the high gas content and serious gas hazard. At the coalfield level, gas occurrence in the Huaibei coalfield is controlled by east–west faults, NNE faults, and the Xuzhou–Suzhou arc nappe tectonic, which results in the highest gas occurrence in the Suxian mining area, followed by the Linhuan mining area and the Suixiao mining area, while the lowest amount of gas occurs in the Guoyang mining area. At the mining area level, considering the Suxian mining area as an example, the gas occurrence is controlled by the distance from the Tancheng–Lujiang fault zone and the intensity of tectonic compression, i.e., coal mine gas in the east is the highest, followed by coal mines in the south, while coal mine gas in the west is the lowest. At the coal mine level, gas occurrence is controlled by the buried depth of the coal seam, the tensional normal fault, magmatic activity, and uplift and erosion of strata. Finally, the findings of this study may help in the prevention of gas hazard and the exploration and development of coalbed methane in the Huaibei coalfield and other coalfields of similar geological characteristics.

**Keywords:** Huaibei coalfield; tectonic evolution; gas occurrence; multiple-level tectonic control; coalbed methane

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## 1. Introduction

Gas explosions and coal and gas outbursts are potential hazards in high-gas coal mines [1,2]. Methane is the main component of coal mine gas, which is a clean and efficient energy source [3,4]. China is seriously affected by coal mine gas, and it is also actively engaged in the development and utilization of coalbed methane [5–7]. It is, therefore, important to further investigate the occurrence characteristics and gas distribution patterns of coal mines.

In the long-term study of gas geology, it is well recognized that the generation, migration, and occurrence of a certain area's coal mine gas are controlled by the geotectonic evolution of this area [8–10]. The multiple-level tectonic control of gas occurrence is proposed [11]. A macroscopic study of the multiple-level tectonic control of gas occurrence in China reveals that there are 29 areas of coal mine gas occurrence, including 16 high- and outburst-gas areas and 13 low-gas areas [12]. There are also some studies based on the

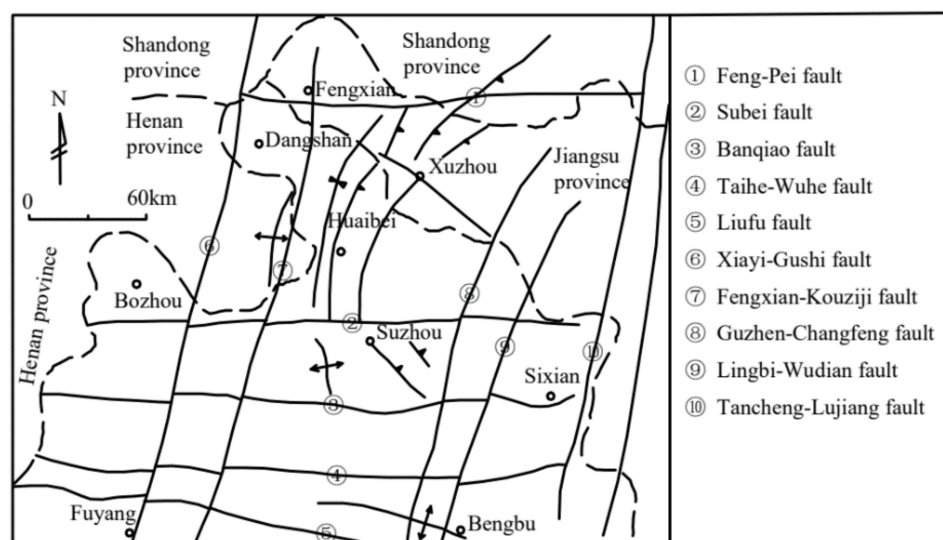
multiple-level tectonic control of gas occurrence from the perspective of a certain coalfield, mining area, or coal mine. It is important to mention that in existing studies, multiple-level tectonic control may be expressed as “tectonic-level control” [12], “tectonic level-by-level control” [13], “stepwise tectonic control” [14,15], “tectonic gradual control” [16], and “step by step control” [17].

The Huaibei coalfield is rich in coal and coalbed methane resources. It features thick coal seams with a moderate depth and a relatively high gas content [18]. Therefore, the Huaibei coalfield is an important coal base in China and faces serious safety challenges in mitigating gas risk during coal mining operation [19,20]. As this coalfield is rich in coalbed methane resources [21,22], it is a hot spot for the development of coalbed methane resources. The coalfield has been explored and developed for its coal resources since 1955, and a number of surface test boreholes have been created in several pilot studies of coalbed methane development. A wealth of data has been obtained on the coalfield geology, gas geology and coalbed methane resources of the Huaibei coalfield. These data have substantially improved the understanding of the occurrence and distribution of coalbed methane. In this paper, the Huaibei coalfield is considered a target area in order to study the gas occurrence from the perspective of multiple-level tectonic control.

## 2. Geological Background

Anhui Province is located in eastern China. It is part of the Yangtze River Delta region, with a well-developed economy and a strong energy demand. Its west, north, and east are bound by Henan, Shandong, and Jiangsu Provinces [23]. The Huaibei coalfield is located in the northern part of Anhui Province and spreads across Huaibei City, Suzhou City, and Bozhou City of Anhui Province, with a coal-bearing area of approximately 4100 km<sup>2</sup> [24]. In the Huaibei coalfield, two large coal-producing enterprises mainly exist: the Huaibei Mining (Group) Co., Ltd., headquartered in Huaibei City of Anhui Province, China, and Wanbei Coal-electricity Group Co., Ltd., headquartered in Suzhou City of Anhui Province, China. In addition, at least 23 underground coal mines have been developed [18].

The Huaibei coalfield is in the southeastern margin of the North China plate. It belongs to Xusu depression in the south–central part of the Luxi-Xuhuai uplift area [25,26]. Regionally, the Huaibei coalfield is located between the nearly east–west Feng–Pei uplift and the Bengbu uplift and lies adjacent to the He-Huai subsidence area on the west and the Tancheng–Lujiang fault zone on the east [26,27]. The Huaibei coalfield is in north–south orientation. Its fault structure has a grid structure pattern. From north to south, the main east–west orientation faults are the Feng–Pei fault, the Subei fault, and the Banqiao fault. From east to west, the main north–south orientation faults are the Guzhen–Changfeng fault, the Fengxian–Kouziji fault, and the Xiayi–Gushi fault, as shown in Figure 1. According to the characteristics of tectonic development, the Huaibei coalfield can be subdivided into the Suixiao, Linhuan, Suxian, and Guoyang mining areas [23,24,27]. The Suixiao mining area is located north of the Subei fault, while the Suxian, Linhuan, and Guoyang mining areas are located between the Subei fault and the Banqiao fault. The Nanping fault is the boundary between the Suxian and Linhuan mining areas, while the Fengxian–Kouziji fault is the boundary between the Linhuan and Guoyang mining areas.



**Figure 1.** Tectonic outline map of the Huaibei coalfield. Modified from [28].

The strata in this study area in ascending order consists of the Archean, Qingbaikou system and Sinian, Cambrian and Ordovician, Carboniferous and Permian, Triassic, Jurassic and Cretaceous, Paleogene, Neogene, and Quaternary formations [23,26,27]. The Carboniferous and Permian are the coal-bearing formations, including in ascending order, the Benxi, Taiyuan, Shanxi, Lower Shihezi, Upper Shihezi, and Sunjiagou formations. The coal-bearing strata has a thickness of nearly 920 m. It is formed by shallow marine deposition, shore coastal deposition, fluvial delta deposition, and alluvial plain deposition [29]. The Benxi and Taiyuan formations contain several thin coal seams that are not minable, the Shanxi, Lower Shihezi, and Upper Shihezi formations are major coal-bearing strata, while the Sunjiagou Formation contains no coal seams. In total, 25 coal seams exist in the Huaibei coalfield. Among them, 12 coal seams are minable, with an average total thickness of almost 14.25 m, and the main minable coal seams are nos. 3<sub>2</sub>, 7<sub>2</sub>, 8<sub>1</sub>, 8<sub>2</sub>, and 10<sub>2</sub> [18,23,30].

### 3. Multiple-Level Tectonic Control of Gas Occurrence

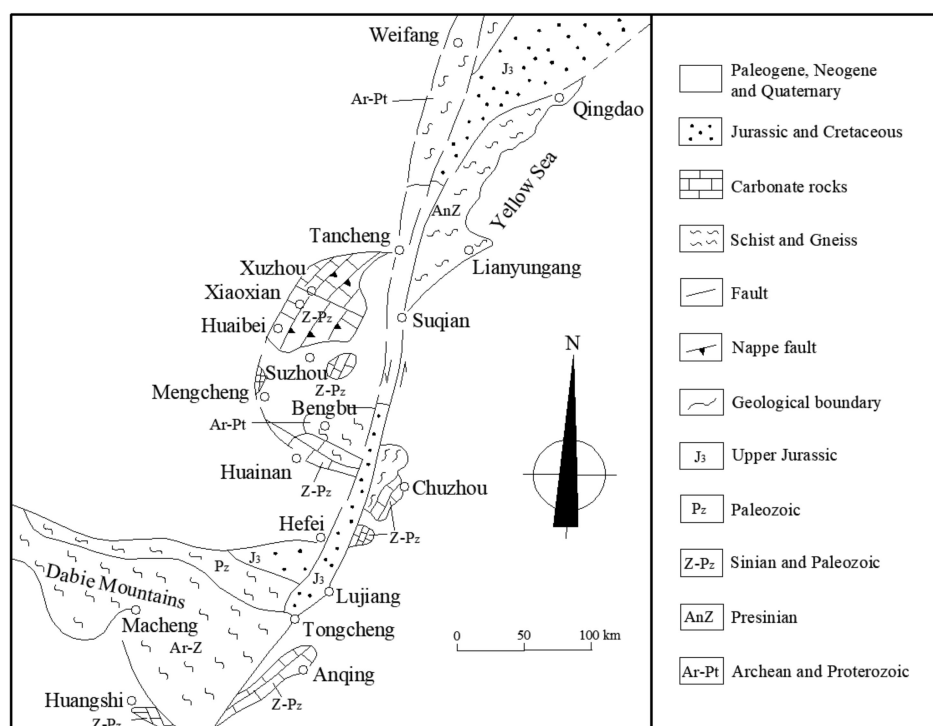
The multiple-level tectonic control of gas occurrence in the Huaibei coalfield is analyzed at four levels: the regional tectonic level, the coalfield tectonic level, the mining area tectonic level, and the coal mine tectonic level.

#### 3.1. Regional Tectonic Level

The basement of the coal-bearing strata in the Huaibei coalfield is complete and continuous, with a flat terrain and no large tectonic differentiation in this area. The whole crust subsides in Late Paleozoic. In addition, deposition occurs on basin basement, forming continuous and stable coal accumulation in Carboniferous Permian [31,32]. After the formation of coal-bearing strata, the evolution of coal seams' buried depth and temperature in the Huaibei coalfield can be subdivided into three major stages: Triassic to Middle Jurassic, Late Jurassic to Cretaceous, and Paleogene onward. From Triassic to Middle Jurassic, the buried depth of the Permian strata rapidly increased and reached almost 3000 m, with a maximum temperature range of 140–180 °C. From Late Jurassic to Cretaceous, the Permian strata uplifted, the overlying strata suffered from erosion, and the maximum erosion thickness reached 1800–2650 m. From Paleogene onward, the deposition in the area continued and the temperature of the coal-bearing formation was kept between 27 and 50 °C for a period of time [33,34]. The coal seam temperature was mainly controlled by its buried depth of the coal seam. In this case, the deep burial metamorphism of coal is important to the coalification process. In addition, the Yanshanian tectonic-thermal event superimposed magmatic thermal metamorphism on the coal seams in the Huaibei coalfield, which led to an increase in coal rank to coking coal, and even natural coke in some areas [35–37].

From the perspective of plate tectonics, since the formation of the Carboniferous Permian coal-bearing strata, the North China plate where the Huaibei coalfield is located, was mainly pushed by the Siberian plate from north to south and by the Yangtze block from south to north during the Indosinian period, forming wide and flat folds and faults in nearly east–west orientation. The North China plate was then mainly pushed by the subduction and collision of the Pacific Kula plate during the Yanshanian period, which formed a series of large-scale uplift and depression in NNE and NE directions, accompanied by intense magmatism. On the west side of the Tancheng–Lujiang fault zone, the Xuzhou–Suzhou arc nappe tectonic was formed by the subduction and collision of the Yangtze plate to the North China plate [11]. In summary, the tectonic evolution of the Huaibei coalfield has gone through three stages: the east–west trending tectonic development stage in the Indosinian period (257–205 Ma), the NEE trending tectonic development stage in the Yanshanian period (205–65 Ma), and the extensional tectonic development stage in the Himalayan period (65 Ma–) [38].

The Huaibei coalfield is located in the southeast margin of the North China plate. It lies adjacent to the Tancheng–Lujiang fault zone on the east, and therefore it is affected by the tectonic evolution of the North China plate and the evolution of the Dabie–Tanlu–Sulu orogenic belt. Consequently, the geological tectonic of the Huaibei coalfield is complex, the magmatic activity is frequent, and the faults and folds are well developed [26,39]. The tectonic in the Huaibei coalfield is controlled by east–west faults, NNE faults, and the Xuzhou–Suzhou arc nappe tectonic. The fault structure of the whole coalfield presents a grid structure pattern, and the NNE trending faults formed in the Yanshanian period transformed the east–west trending faults in the Indosinian period. Under the influence of the Dabie orogenic belt and the Tancheng–Lujiang fault zone, the Huaibei coalfield generally shows the tectonic pattern of pushing in the east part and sinking in the west part. More precisely, the east part is the Xuzhou–Suzhou arc nappe tectonic, while the west part is the Guoyang–Linhuan fault depression belt [26,40], as shown in Figure 2.



**Figure 2.** Geological background of the Xuzhou–Suzhou arc nappe tectonic. Modified from [41,42].

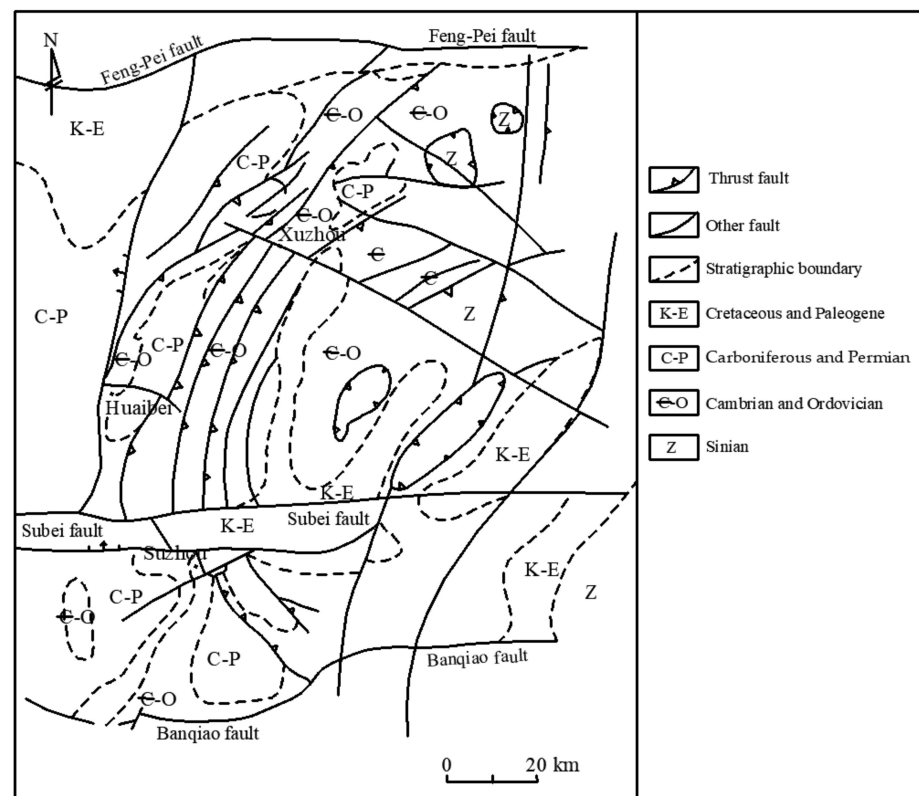
The regional tectonic evolution history controls the gas occurrence in the Huaibei coalfield. The complex regional geological tectonic leads to the high gas content and serious

gas hazard in the Huaibei coalfield [12,43,44]. Li and Wang (2009) mention that all the 14 coal mines in Huaibei Mining (Group) Co., Ltd. are of high content. In addition, 7 of them, namely Luling, Haizi, Qinan, Zhuxianzhuang, Shitai, Taoyuan, and Tongting mines, are prone to coal and gas outbursts [43]. Since the development of coal resources in the Huaibei coalfield, 33 outburst incidences have occurred, with a total coal ejection of 11,339 t and gas emission of 1,404,000 m<sup>3</sup> [43]. Zhang and Wu (2013) mention that the Huaibei coalfield has 13 coal- and gas-outburst-prone coal mines and 9 high-gas coal mines. Moreover, more than 140 incidences of coal and gas outbursts have occurred. The largest outburst in the Huaibei coalfield occurred at the Luling coal mine, with a coal ejection of 10,500 t and gas emission of 1,230,000 m<sup>3</sup> [12].

### 3.2. Coalfield Tectonic Level

As previously mentioned, the Huaibei coalfield is controlled by the Xuzhou–Suzhou arc nappe tectonic (cf Figure 3). Therefore, the stress of the arc structure mainly controls the distribution characteristics of gas enrichment in the coalfield. The stress of the arc structure has two states, divided by the neutral plane of the arc structure. The stress state is compressive in the inward arc direction and tensile in the outward arc direction. In general, the curvature of the inner arc zone is greater than that of the outer arc. Therefore, the stress of the inner arc zone is concentrated and the compression is serious, which results in the development of more reverse faults. Thus, the gas content in the middle part of the arc is higher than that in the two wings of the arc, and the gas content in the inner arc zone is greater than that in the outer zone [45]. The Suxian mining area, which is located on the inner side of the arc structure and close to the Tancheng–Lujiang fault zone, is of high stress concentration due to compression. It has many reverse faults, and it is conducive to the accumulation and preservation of coal seam gas. Therefore, the Suxian mining area has a high gas content and faces serious gas hazard in coalmining operations [38]. The Linhuan mining area, which is located in the middle of the arc structure and slightly far away from the Tancheng–Lujiang fault zone, is in the area of transformation from compressive stress to tensile stress and has many tensile normal faults. This area is relatively conducive to the migration and release of coal mine gas. Therefore, although the Linhuan mining area has a high gas content, the gas hazard risk in the area is lower than that in the Suxian mining area. Although the Suixiao mining area is also located in the middle of the arc structure, it is on the wing of the arc structure rather than at the center of the arc structure. Therefore, it is in the area of tensile stress, and many tensile normal faults are developed. This area is relatively unfavorable to the accumulation and preservation of coal seam gas. Therefore, the Suixiao mining area has generally a low gas content. The Guoyang mining area is located on the outside of the arc structure and farthest from the Tancheng–Lujiang fault zone. Therefore, the influence of the Xuzhou–Suzhou arc nappe tectonic has largely disappeared. Thus, the Guoyang mining area has the lowest gas content in the Huaibei coalfield.

Besides the control of the Xuzhou–Suzhou arc nappe tectonic, the uneven subsidence of the Huaibei coalfield also affects the distribution characteristics of coal seam gas. The uneven subsidence of the Huaibei coalfield that occurred in the Himalayan period causes subsidence and sedimentation in Linhuan and Suxian mining areas located in the south of the Subei fault and the east of the Fengxian–Kouziji fault, which provides favorable conditions for gas preservation. The uneven subsidence has also caused uplift and erosion in the Suixiao mining area in the north of the Subei fault and the Guoyang mining area in the west of the Fengxian–Kouziji fault, which provides favorable conditions for gas migration and release and therefore results in low gas contents in the areas [25].



**Figure 3.** Geological map of the Xuzhou–Suzhou arc nappe tectonic. Modified from [46].

Thus, the gas distribution in the Huaibei coalfield presents a distribution pattern of “high in the south and low in the north,” “high in the east and low in the west,” and “the highest in the southeast” [25,40]. “High in the south and low in the north” denotes that the gas content and the gas hazard in the Suxian mining area and the Linhuan mining area in the south of the Subei fault are greater than those of the Suixiao mining area in the north of the Subei fault. “High in the east and low in the west” denotes that there are 3 mining areas in the south of the Subei fault: the Suxian, Linhuan, and Guoyang mining areas. The gas content and the gas hazard in the Suxian mining area in the east are the highest, followed by those in the Linhuan mining area in the middle, while the Guoyang mining area in the west has the lowest gas content and gas hazard risk. “The highest in the southeast” denotes that among the four mining areas in the study area, the gas content and the gas hazard in the Suxian mining area in the southeast of the Huaibei coalfield are the highest.

Previous studies have confirmed this understanding, as shown in Table 1. For instance, Zhou and Wang (2000) report that the gas content in the east of the Suxian mining area is the highest, averaging at more than  $8 \text{ m}^3/\text{t}$ . This is followed by the gas content in the south of the Suxian mining area, while the gas content in the Guoyang mining area is the lowest, averaging at less than  $4 \text{ m}^3/\text{t}$ . The average gas contents of no. 8 coal seam in the Suxiang, Linhuan, Suixiao, and Guoyang mining areas are  $7.3$ ,  $6.1$ ,  $5.2$ , and  $3.4 \text{ m}^3/\text{t}$ , respectively [47]. Qu et al. (2008) report that the gas content of the Suixiao mining area north of the Subei fault is only  $2\text{--}12 \text{ m}^3/\text{t}$ , which is far less than that of mining areas in the south of the Subei fault. In addition, from the west to the east of the Huaibei coalfield, the gas content in the Guoyang mining area is  $2\text{--}8 \text{ m}^3/\text{t}$ , which is less than the  $6\text{--}16 \text{ m}^3/\text{t}$  in the Linhuan mining area and the  $6\text{--}24 \text{ m}^3/\text{t}$  in the Suxian mining area [25]. Wang (2015) reports that the gas contents of the Suxian mining area and the Linhuan mining area are, respectively,  $12\text{--}15 \text{ m}^3/\text{t}$  and  $8\text{--}12 \text{ m}^3/\text{t}$ , which is higher than the  $8\text{--}10 \text{ m}^3/\text{t}$  in the Suixiao mining area and less than the  $8 \text{ m}^3/\text{t}$  in the Guoyang mining area [45]. Hu et al. (2014) report that 75.8% outburst incidences occurred in the Suxian mining area, 21.2% in the Linhuan mining area, 3.0% in the Suixiao mining area, and none in the Guoyang mining

area as no active coal production exists in this area at the time of reporting. Among the incidences, the Luling coal mine in the Suxian mining area is the most serious, and the number of outburst incidences accounts for 66.7% of the total in the Huaibei coalfield [40].

**Table 1.** The gas characteristics of the Huaibei coalfield.

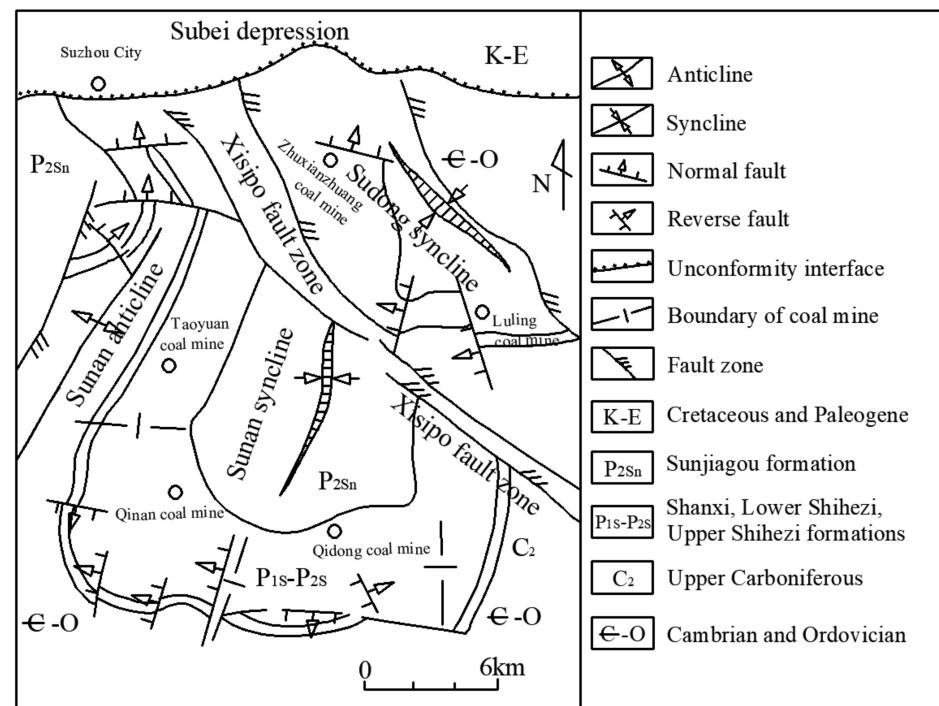
Characteristic	Suxian Mining Area	Linhuan Mining Area	Suixiao Mining Area	Guoyang Mining Area	Source
Average gas content of no. 8 coal seam ( $\text{m}^3/\text{t}$ )	7.3	6.1	5.2	3.4	[47]
Gas content ( $\text{m}^3/\text{t}$ )	6–24	6–16	2–12	2–8	[25]
Gas content ( $\text{m}^3/\text{t}$ )	12–15	8–12	8–10	<8	[45]
Outburst incidence (%)	75.8	21.2	3.0	0.0	[40]

### 3.3. Mining Area Tectonic Level

This section analyzes the gas occurrence in these four mining areas from the perspective of the mining area tectonic level.

#### 3.3.1. Suxian Mining Area

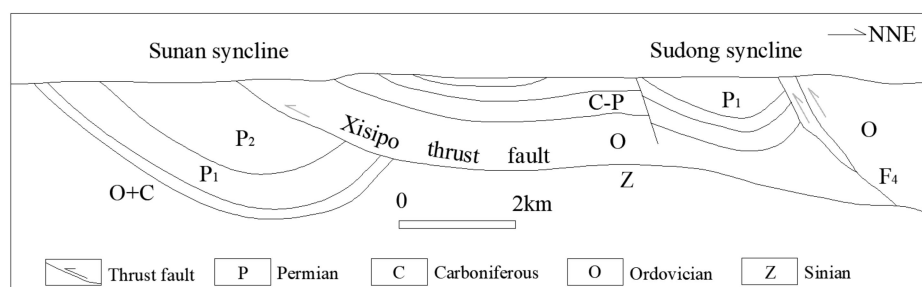
The main coal mines in the Suxian mining area include the Luling coal mine and the Zhuxianzhuang coal mine in the east, the Taoyuan coal mine, the Qinan coal mine and the Qidong coal mine in the south, and the Qianyingzi coal mine and the Zouzhuang coal mine in the west (cf Figure 4). The gas hazards these coal mines pose are serious. However, the characteristics of coal seam gas occurrence and the risk of coal and gas outburst are different for specific coal mines due to their different tectonic positions in the Suxian mining area.



**Figure 4.** Tectonic outline map in the Suxian mining area. Modified from [38].

As for the Sudong syncline in the east of the mining area, it is in the hanging wall of the NW trending the Xisipo thrust fault (cf Figure 5). In addition, the tectonic compression and shear deformation are strong, and therefore the tectonic coals in coal seams are well developed, with large thickness and continuous distribution, which is the main reason why

the Luling coal mine and the Zhuxianzhuang coal mine in the Sudong syncline are highly prone to coal and gas outburst [48,49].



**Figure 5.** Geological section of the Xisipo thrust fault and its surrounding area. Modified from [50].

As for the Sunan syncline in the south of the mining area, it is in the footwall (i.e., a passive moving wall) of the NW trending Xisipo thrust fault (cf Figure 5). The tectonic compression and shear deformation are smaller than those of the Sudong syncline in the hanging wall. The south end of the Sunan syncline is close to the east–west direction’s Bengbu uplift, and the east–west tectonics are relatively well developed, such as the Weimiao fault, which creates good conditions for gas release [3,51]. Therefore, the risk of coal and gas outburst at Taoyuan, Qinan, and Qidong coal mines in the Sunan syncline is smaller than that at the Luling and Zhuxianzhuang coal mines in the Sudong syncline.

As for the Sunan anticline in the west of the mining area, the Qianyingzi and Zouzhuang coal mines are on the west wing of the Sunan anticline. The tectonic compression and shear deformation of this location are further smaller than those of the Sudong syncline and the Sunan syncline. Furthermore, this location is divided by two high-angle normal faults (i.e., the Nanping normal fault and the Shuangduiji normal fault), which is conducive to gas release. In the long process of geological evolution, a large amount of coal seam gas has been released. Therefore, the risk of coal and gas outburst is much smaller than that of the Sudong syncline and the Sunan syncline [52,53].

### 3.3.2. Linhuan Mining Area

Affected by the superposition of multi-stage tectonic movements, many faults have been formed in the Linhuan mining area. The openness of these faults is fairly good, which is conducive to the release of coal seam gas, resulting in a significant reduction in gas content compared with the adjacent Suxian mining area. There are more than 10 coal mines in the Linhuan mining area, i.e., Haizi, Linhuan, Tongting, Zhangyoufang, Wugou, Jiegou, Xutuan, Renlou, Suntuan, and Yangliu coal mines, many of them distributed around the Tongting anticline. At the core of the Tongting anticline, due to the uplift of coal-bearing strata, the coal seams suffer from weathering and erosion, which forms gas release channels. The gas of coal seams the nearby weathering area can continuously release through the channels, thus reducing the gas pressure and gas content of these coal seams. Therefore, in general, the gas content of coal seams around the Tongting anticline is small [54].

However, the northwest area of the Tongting anticline where the Tongting coal mine, the Linhuan coal mine, and the Haizi coal mine are located is the superimposed intersection of the Tongting anticline formed in the early Yanshan period and the Yuandian syncline, the Qingtuan anticline, and the Haizi syncline formed in the Indosinian period. Consequently, the compressive stress is concentrated in this area. Moreover, in this area, the magmatic intrusion is serious. Due to the concentrated stress and serious magmatic intrusion, the coal seam structure is damaged and tectonic coal and even a soft layer in coal seams are developed. Thus, this is an area having a high gas pressure and gas content of coal seam, is a potential gas hazard, and could lead to serious coal and gas outburst in the Linhuan mining area [55]. For instance, the Haizi coal mine is a coal-and-gas-outburst coal mine, its maximum absolute gas emission rate is 55.80 m<sup>3</sup>/min, and its maximum relative gas

emission rate is  $28.79 \text{ m}^3/\text{t}$ . In addition, Xutuan and Renlou coal mines are located in the southeast edge of the Linhuan mining area. They are in the transition zone from the Suxian mining area, dominated by a compressive fault, to the Linhuan mining area, dominated by a tensile fault. It is also a stress concentration zone, which is conducive to gas accumulation and preservation. Thus, the gas pressure of the main coal seams at Xutuan and Renlou coal mines is greater than that in the middle and west of the Linhuan mining area. In addition, the coal seam here has a certain risk of coal and gas outburst. For instance, the Xutaun coal mine is a coal-and-gas-outburst coal mine, its maximum absolute gas emission rate is  $58.34 \text{ m}^3/\text{min}$ , and its maximum relative gas emission rate is  $15.82 \text{ m}^3/\text{t}$ .

### 3.3.3. Suixiao Mining Area

The Suixiao mining area is the earliest mining area in the history of coal resources development in the Huaibei coalfield. More than 10 coal mines are distributed around Zhahe syncline, i.e., the Yangzhuang, Zhuzhuang, Zhangzhuang, Daihe, Shitai, Shuoli, Yuanzhuang, Shenzhuang, Mengzhuang, and Maoyingzi coal mines [56]. The Suixiao mining area is located at the north of the Subei fault, which is relatively far from the Bengbu uplift. Therefore, it is less affected by the Bengbu uplift and is mainly controlled by the Xuzhou–Suzhou arc nappe tectonic. The Suixiao mining area is located in the wing of the arc structure rather than at the center of the arc structure. Therefore, it is relatively unfavorable to the accumulation and preservation of coal seam gas. In addition, the uneven subsidence of the Huaibei coalfield that occurred in the Himalayan period causes uplift and erosion of Triassic strata in the Suixiao mining area, which provides favorable conditions for gas migration and release. Therefore, the gas content in the Suixiao mining area is relatively low and several low gas coal mines exist [57]. These coal mines in the west of the Suixiao mining area, such as the Baishan coal mine, Liuqiao no. 1 coal mine, and the Hengyuan coal mine, are all low-gas coal mines due to the strong weathering and erosion of the coal seams.

When coal seams are located in the conditions of complex tectonic, strong tectonic compression, or deep burial depth, they may have high gas contents and even have the risks of coal and gas outburst. The magmatic activity may lead to secondary hydrocarbon generation, which results in uneven gas distribution in the area and sudden enrichment of gas in parts of the area. This location extruded by magmatic activity can be easily enriched by coal seam gas, and it is prone to coal and gas outbursts in mining activities. For instance, in general, the Maoyingzi coal mine has a low gas content and a low risk of coal and gas outburst. Its maximum absolute gas emission rate is only  $4.9 \text{ m}^3/\text{min}$ , and its maximum relative gas emission rate is only  $6.4 \text{ m}^3/\text{t}$ . However, there exists the risk of coal and gas outburst in the zones affected by magmatic intrusion and the zones with stress concentration, and an incidence of coal and gas outburst did occur in the mine [57].

### 3.3.4. Guoyang Mining Area

The Guoyang mining area is located on the west of the Linhuan mining area, bound by the Subei fault in the north, the Banqiao fault in the south, the Xiayi–Gushi fault in the west, and the Fengxian–Kouziji fault in the east. The Guoyang mining area is the most recently explored and developed among the four mining areas in the Huaibei coalfield. In the reported year [58], there were only two coal mines in the Guoyang mining area (Guobei and Liudian), while the others were at exploration stages. Compared with other mining areas in the Huaibei coalfield, the Guoyang mining area is the farthest away from the Tancheng–Lujiang fault zone and has been far away from the tectonic active zone on the plate edge. Therefore, most of the tectonic stress formed by the strong rock deformation at the plate edge has been diminished in the area [59]. In addition, the fault tectonic in the Guoyang mining area is relatively well developed and the main faults in the area are the east–west trending and north–south trending normal faults, which result in poor continuity of coal bearing strata and easy gas release. Therefore, the gas content and the gas hazard in this area are far less than those at the other three mining areas in the Huaibei coalfield [60].

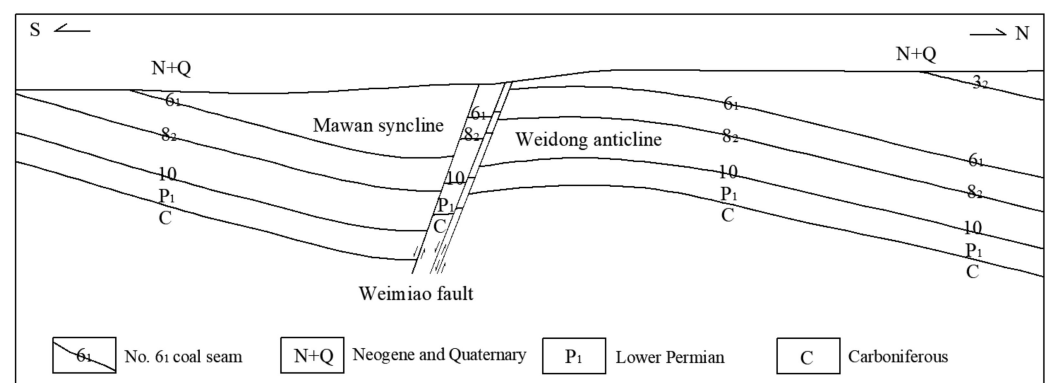
However, it is important to mention that in the zones having a high gas content, the risk of coal and gas outburst may occur under the condition of an increased coal seam buried depth, complex tectonic, magmatic intrusion, and high compressive stress [61].

### 3.4. Coal Mine Tectonic Level

There are many coal mines in each of the mining areas. A total of four coal mines, selected respectively from each of the four mining areas, are used in this study.

#### 3.4.1. Qidong Coal Mine in the Suxian Mining Area

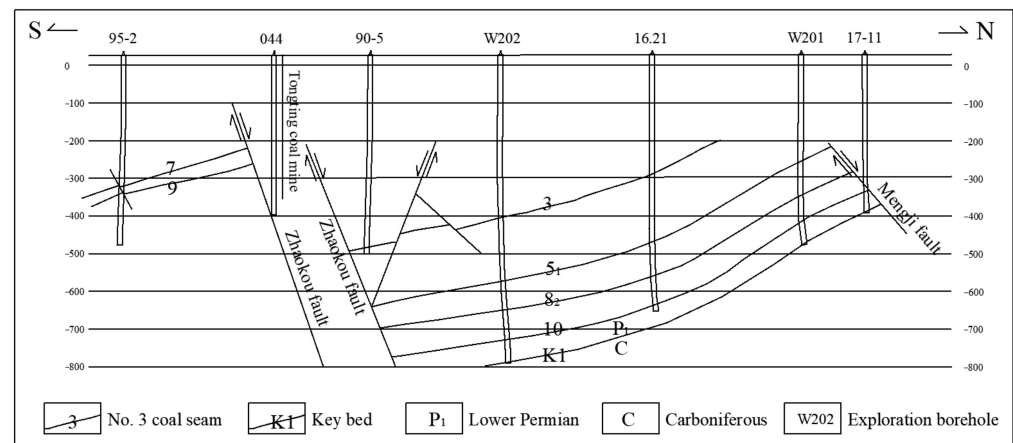
There are two distinct characteristics of the tectonic control of the Qidong coal mine in terms of gas occurrence. The first is the differentiation between the north part and the south part of this coal mine. The Weimiao fault in the east–west direction is a major controlling fault of the Qidong coal mine, which divides it into a north part and a south part. The Mawan syncline and the Weidong anticline, with an axial nearly east–west direction, are developed around the Weimiao fault, as shown in Figure 6. Due to the fact that the Weimiao fault is a tensional normal fault system, it provides a good channel for gas release. In addition, a large part of the coal-bearing strata in the core of the Mawan syncline and the Weidong anticline has been eroded, making gas release favorable. Therefore, it is deduced that the gas content in the north part is 2–3 times higher than that in the south part at the same burial depth [62]. The second is the effect of the burial depth. For a given coal seam, the gas content and the risk of coal and gas outburst increase with the burial depth of the coal seam [62,63].



**Figure 6.** Geological section of no. 24 exploration line at the Qidong coal mine. Simplified from [64].

#### 3.4.2. Tongting Coal Mine in the Linhuan Mining Area

The Zhaokou fault and the Mengji fault are two large normal faults at the boundary of the Tongting coal mine. The coal seams are cut and controlled by the Mengji fault in the shallow part and the Zhaokou fault in the deep part, as shown in Figure 7. Consequently, the occurrence characteristics of coal seam gas are largely controlled by these two faults. It is widely accepted in gas geology that the gas content and pressure in coal seams increase with the increase in the burial depth of coal seams. In addition, the gas emission and the risk of coal and gas outburst will be high when the seams are mined. However, an abnormal phenomenon occurs at the Tongting coal mine. That is, with the increase in the coal seam burial depth, the gas content, the gas pressure, and the gas emission first increase and then decrease [65,66], which is mainly due to the fact that the distribution of the coal seam gas is controlled by the Zhaokou fault in the deep part. The Zhaokou fault is a tensional normal fault in the deep part of this coal mine, which is characterized by a large fault drop, a wide fracture zone, and extended distance. During the long geological time, this normal fault has become a good channel for gas release, which results in a reduction in the gas content in the coal seams around the Zhaokou fault.



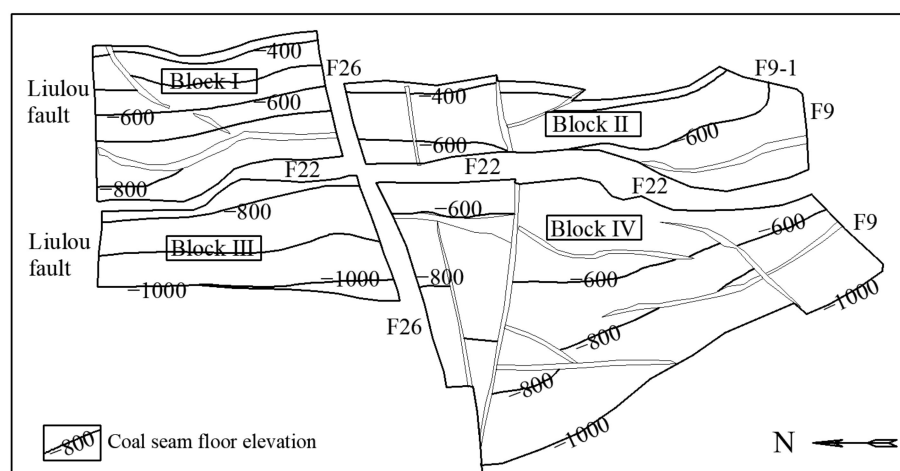
**Figure 7.** Geological section of no. w20 exploration line at the Tongting coal mine. Simplified from [67].

### 3.4.3. Qianling Coal Mine in the Suixiao Mining Area

Several coal and gas outbursts have occurred at the Qianling coal mine due to its complex geological tectonic [68]. The magmatic intrusion is serious in this coal mine. The magmatic rock has been found in 27 of a total 32 exploration boreholes. Based on the statistics of gas emissions of the working faces at the Qianling coal mine, it is deduced that the gas emission from the working faces affected by magmatic intrusion is greater than that from the unaffected working faces, and so is the risk of coal and gas outburst. This is due to the secondary hydrocarbon generation of the coal seam by magmatic intrusion at a high temperature and the overlying sill of the coal seam, which prevents gas from escaping from the coal seam [69].

### 3.4.4. Guobei Coal Mine in the Guoyang Mining Area

The overall tectonic of the Guobei coal mine is a monocline with nearly north–south strike and a near-west inclination. The south boundary is the F9 fault and the F9-1 fault, while the north boundary is the Liulou fault. Two intersecting faults (F22 and F26) divide this coal mine into four blocks, as shown in Figure 8. The tectonic characteristics in this coal mine are that the faults are mainly developed, while the folds are not well developed and the magmatic activities are not serious. The five normal faults are most important: F9, F9-1, Liulou, F22, and F26. In addition, 54 faults, i.e., 51 normal faults and 3 reverse faults, are found in this coal mine. These tensional normal faults provide favorable conditions for gas migration and gas release, which results in low gas pressure, low gas content, low gas emission, and low risk of coal and gas outburst [70,71]. In addition, the uplift and erosion of the Triassic strata that occurred in the Himalayan period also provide favorable conditions for gas migration and release. The data of geological exploration and coal mine construction confirm this understanding. The data of geological exploration reveal that the gas pressure (elevation from  $-442.10$  to  $-806.40$  m) of this coal mine is  $0.20$ – $0.60$  MPa, the gas content (elevation from  $-439.62$  to  $-878.71$  m) is  $0.01$ – $6.96$  m<sup>3</sup>/t, the relative gas emission rate (elevation from  $-457.56$  to  $-685.00$  m) is  $0.38$ – $4.54$  m<sup>3</sup>/t, and the absolute gas emission rate (elevation from  $-457.56$  to  $-685.00$  m) is  $0.37$ – $5.72$  m<sup>3</sup>/min. The data in the coal mine construction reveal that the gas pressure in nos. 8<sub>1</sub> and 8<sub>2</sub> coal seams at the main shaft and the auxiliary shaft is  $0.96$  Mpa and  $0.85$  Mpa, respectively. In addition, the gas contents in nos. 8<sub>1</sub> and 8<sub>2</sub> coal seams at the main shaft are respectively  $5.81$  m<sup>3</sup>/t and  $5.23$  m<sup>3</sup>/t, and the gas content in no. 8<sub>1</sub> coal seam at the auxiliary shaft is  $4.32$  m<sup>3</sup>/t [71]. The coal seams generally have a low gas content. However, the gas content of the seams may increase with the increase in the buried depth of the seam and tectonic complexity.



**Figure 8.** Tectonic map of no. 8 coal seam at the Guobei coal mine. Modified from [72].

Although these four coal mines considered in this study may not represent all the characteristics of all the coal mines in the Huaibei coalfield, the above analysis shows that in general, the gas occurrence characteristics are largely controlled by the buried depth of the coal seam, the tensional normal fault, magmatic activity, as well as the uplift and erosion of strata.

#### 4. Discussion

Whether it is for the prevention and control of gas hazard or for the development of coalbed methane resources, the Huaibei coalfield is one of the areas for intensive study in China. However, these studies lack a systematic approach on gas occurrence in the Huaibei coalfield from the perspective of multiple-level tectonic control. Since the discovery of coal resources in the Huaibei coalfield in 1955, rich data have accumulated on regional geology, coalfield geology, and gas geology after a large period of coal resource exploration, coal mine construction and operation, and coalbed methane drainage [26,36,73]. This provides a solid foundation for the study of the multiple-level tectonic control of gas occurrence in the Huaibei coalfield. Based on the previous research results and the analysis of the rich data, this paper studied the multiple-level tectonic control of coal mine gas occurrence in the Huaibei coalfield from four levels: the regional level, the coalfield level, the mining area level, and the coal mine level.

Several geological factors affect the occurrence of coal seam gas. For instance, the coal maceral and coal rank may affect the generation of gas. The permeability of the coal seam and the hydrogeological condition of the coal mine may affect the migration of gas. The burial depth of the coal seam and the porosity of surrounding rock strata may affect the preservation of gas. The development characteristics and the evolution history of geological tectonic are important factors controlling the generation, migration, and preservation of gas [12,38,39]. The multiple-level tectonic control of gas occurrence in the Huaibei coalfield is helpful to understand the gas distribution characteristics at the regional level, the coalfield level, the mining area level, and the coal mine level. It is also useful in the prevention and control of gas hazard in coal mines and in the selection of favorable belts for coalbed methane development.

The Huaibei coalfield is one of the key areas of coal resource prospecting in Anhui Province [74,75]. In order to ensure sustainable and stable coal production, improve the guarantee capacity of coal resources, and promote the development of coalbed methane, it is required to continue the exploration and development of coal resources, coalbed methane resources, and related scientific studies. This study provides a reference for the future exploration and development in the Huaibei coalfield and for other coalfields or mining areas having a similar geological tectonic evolution history or gas geological occurrence. Finally, any new geological data related to the Huaibei coalfield or the research results of

other coalfields or mining areas will also help to enrich and improve the understanding of the Huaibei coalfield.

## 5. Conclusions

Gas occurrence in the Huaibei coalfield is characterized by multiple-level tectonic control, as well as a tectonic level controls gas occurrence in a certain range. At the regional level, the Huaibei coalfield is located at the southeast margin of the North China plate. It is affected by the tectonic evolution of the North China plate and by the evolution of the Dabie–Tanlu–Sulu orogenic belt. Therefore, the regional geological tectonic is complex, which leads to a high gas content and serious gas hazard in the Huaibei coalfield. At the coalfield level, gas occurrence in the Huaibei coalfield is controlled by east–west faults, NNE faults, and the Xuzhou–Suzhou arc nappe tectonic, which results in the overall pattern of gas distribution. In other words, the Suxian mining area has the highest gas content, followed by the Linhuan mining area, the Suixiao mining area, and the Guoyang mining area. At the tectonic level of mining areas, considering the Suxian mining area as an example, the gas distribution of the coal mines is controlled by the distance from the Tancheng–Luijiang fault zone and the intensity of tectonic compression. That is, the highest gas content occurs in mines in the east, followed by mines in the south, and mines in the west. At the tectonic level of coal mines, the gas occurrence characteristics in each mining area are different, which shows the tectonic control characteristics as the buried depth of coal seams, the tensional normal fault, magmatic activity, and uplift and erosion of strata.

This study provides a reference for the subsequent exploration and development of coal and coalbed methane resources and the prevention and control of gas hazard in the Huaibei coalfield. It may also provide a reference for studies on other coalfields or mining areas having the same geological characteristics.

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