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Research Article

Research on Coal Bed Methane (Gas) Occurrence Controlled by Geological Tectonics in the Southern Margin of North China Plate: A Case Study of the Pingdingshan Coalfield, China

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The geological structure is complex in the plate margin zone, and the occurrence of coal bed methane (CBM) is nonuniform with an obvious zoning phenomenon. It plays an important role to reveal the spatial distribution of CBM and its influence factors in plate margin zone for CBM exploitation and gas disaster prevention in coal mines. Based on the data of gas emission during mining, CBM content, and gas pressure in the Pingdingshan Coalfield, lying on the south edge of North China plate, the distribution characteristics of CBM and its influence factors using theories of CBM (gas) geology and statistical analysis method are investigated. The research area is divided into four CBM occurrence belts. There are its own CBM occurrence feature and control structural type in each CBM belt. Likou syncline is the structure that controls the overall distribution of CBM. NW-trending fold-fault belt, Guodishan fault, and Jiaxian fault are the structures that control the CBM occurrence in CBM belt IV, CBM belt II, and CBM belt I, respectively. And the difference in structural types is the main factor of CBM zoning.

1. Introduction

CBM (gas) is generated from and stored in the coal seam . It is not only a kind of disastrous gas for coal mining but also a kind of clean energy. The law of CBM (gas) occurrence and its influence factors are important bases for the exploitation of CBM and the prevention of gas disaster in the coal mine. Lots of researches have been done on the correlation between CBM (gas) occurrence and its influence factors such as geological tectonic, coal rank, coal seam thickness, overburden depth of coalbed, tectonic stress, and wall rock. Geological tectonic is a basic and important factor of them, which controls not only the formation and evolution of coal-bearing basins and coal-bearing strata but also the generation, preservation, and accumulation of CBM (gas).

Creedy (1988) pointed out that the geological tectonic is the main influencing factor for the occurrence and distribution of CBM (gas), which controls the characteristics of CBM occurrence and distribution [1]. Gayer and Harri (1996) put forward seven geological factors controlling CBM rich, such as tectonic, overburden depth of coal seam, coal rank, the thickness of coalbed, CBM (gas) content, and hydrogeology [2]; geological tectonic is a basic factor of them [3]. Bibler et al. pointed out that the tectonic movement affects not only the generation conditions of CBM (gas) but also the preservation conditions of it when studying worldwide coal mine methane emissions [4]. Frodsham et al. believed that the coal seam is compressed and sheared under tectonic action, the coal seam was destroyed, and the deformed coal, which is favorable for CBM (gas) preservation and provides a carrier for CBM (gas) enrichment, was developed [5, 6]. Yang found that there is a close relation between faults and gas emission in the Jiaoxi Mine of the Jiaozuo mining area [7]. Cao and Peng pointed out that the deformed coal area formed along the coal seam fault is a high gas accumulation area [8]. Zhang et al. found [9, 10] that the multiple tectonic evolutions of coal-bearing strata and the geological conditions formed by it are important geological factors affecting CBM generation, migration, preservation, and coal-gas outburst. Tectonic compression and shear activities will cause deformation and damage of coal seam, and it is conducive to form deformed coal and closed environment, which is apt to preserve CBM (gas). Tectonic extension, rifting activities, and tectonic uplift will make a large amount of CBM (gas) released. Jia et al. analyzed the tectonic control law of coalbed gas occurrence in Guizhou, Liaoning, Yunnan provinces, divided the different coalbed gas zones, and believed that the geological structure and its evolution controlled the characteristics of coal seam gas zones [11–13]. In summary, the current CBM (gas) occurrence is caused by many factors, but geological tectonics is a basic and key factor. The compressive and compress-shear geological tectonics zones are easy to have a gas outburst and enrich CBM (gas); extensional and rifted geological tectonics are easy to release CBM and often lead to low CBM (gas) content in those regions. The CBM (gas) occurrence is stepwise controlled by geological structure, which caused CBM (gas) to exhibit partition and zonation [9, 10, 14].

There are seven geological eras coal-bearing strata in China. The coal-bearing strata in different geological times experienced different tectonic movements; the degree of the coal-bearing strata deformed and displaced by compression, extension, and shear is different. The development degree of geological structure and the conditions of CBM (gas) generation, migration, and preservation are greatly different. For example, Permo-Carboniferous coal-bearing strata, formed early, mainly experienced the actions of Indosinian, Yanshan, and Himalayan tectonic movements and the present tectonic stress field. Generally, there are high CBM (gas) content and gas pressure and serious coal-gas outburst in the coal seam of Permo-Carboniferous. And the coal-bearing strata formed in different geological times in China are located in different geotectonic positions, with different degrees of plate tectonism and different regional geological tectonic evolution background, which makes the sedimentary environment, in situ stress field, and temperature field different, thus making the generation and preservation conditions of CBM (gas) different. Despite the different positions of the same mining area, CBM (gas) occurrence has also obvious differences. The occurrence of CBM (gas) is nonuniform, and there is an obvious zonation phenomenon. According to the actual situation of coal mine gas and regional geological structure in China, Zhang et al. (2013) put forward 10 geological structure controlling types for the coal mine gas (CBM) occurrence in China, and the whole coalfield in China was divided into 29 areas [15]. The coal seams in the south edge of North China plate are classified as high (CBM) gas and serious coal-gas outburst area [15]. Pingdingshan Coalfield is located in this area [16], 40 km along the east-west direction and 20 km along the north-south direction, with a total area of 650 km^2 [17]. It is an important coal production base of China. But it has complex geologic structures, high CBM (gas) content and gas pressure, and serious risk of coal-gas outburst [14]; the law of CBM (gas) occurrence and its control factors are yet not clarified, which seriously affects the production safety of coal mine. With the development of deep mining in recent years, the gas extraction and CBM development are more and more difficult, and the risks of coal-gas compound dynamic disasters are increasingly aggravating [18, 19]. More studies on the relationship between CBM (gas) occurrence and geological structure should be done. Based on the actual measured CBM (gas) data and geological data in the Pingdingshan Coalfield, this study investigated CBM (gas) occurrence laws and its control factors and predicted CBM (gas) distribution in deep areas, which offered significant guidance for CBM development and control of gas disasters in coal mine.

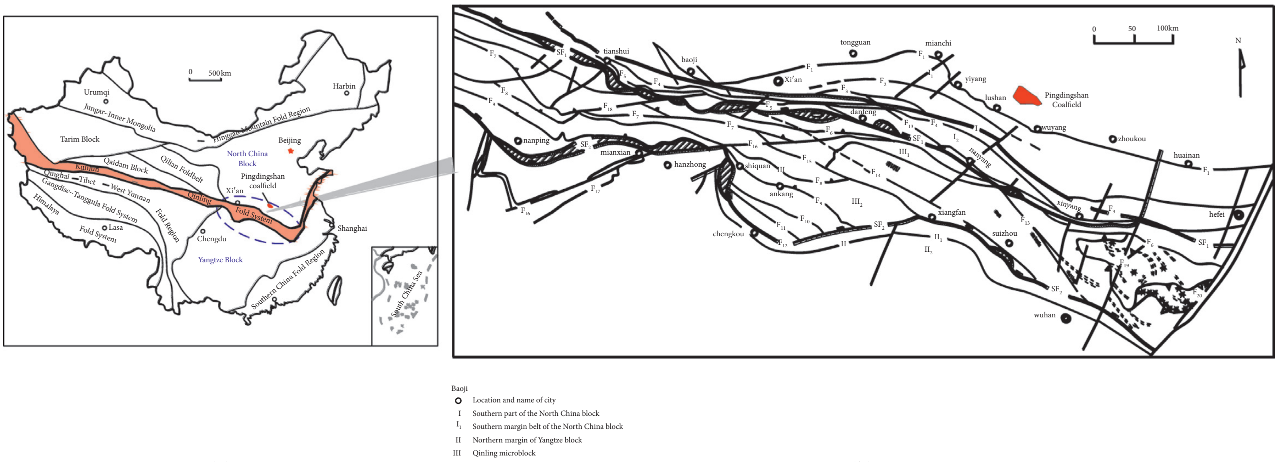
2. Geological Setting

The Pingdingshan Coalfield lies on the south edge of the North China plate and the north side of the northern boundary faults F_1 of the Qinling orogenic belt [20]. It is a typical representative of all coalfields on the south edge of the North China plate and is also controlled by the Qinling orogenic belt (Figure 1).

Likou syncline is a main tectonic in Pingdingshan Coalfield, which is stretched toward the NW–SE direction (Figure 2(a)). The axis of the syncline crosses the whole coalfield from southeast to northwest and its two wings are basically symmetric (Figure 2(b)). The syncline is relatively convergent and closed in the southeast and wide and gentle in the northwest. There are a series of WNW- trending and NW-trending fold structures and fault structures parallel to the Likou syncline axis on the two wings and the periphery of the coalfield. There are also some NEN-trending and NE-trending faults along with the NW-trending structure. In the eastern part of the coalfield, fold structures are especially developed. From south to north, there are mainly Niuzhuang syncline, Guozhuang anticline, Baishishan anticline, Lingwushan syncline, and Xiangjia anticline [14]. The southern boundary of the coalfield is a coal seam outcrop, and the northern, western, and eastern boundaries are Xiangjia fault, Jiaxian fault, and Luogang fault, respectively (Figure 2(a)). These boundaries' faults with large angles and high fall make Pingdingshan Coalfield a separate horst structure unit. A complete set of Carboniferous-Permian coal-bearing strata was deposited in Pingdingshan Coalfield. It is a multiseam coalfield with a total thickness of more than 30 meters. D, E, F, and G coal formations are the main minable coal seams with about 15–18 m coal thickness (Figure 2(c)). The research area lies on the SW wing of Likou syncline in the Pingdingshan Coalfield (Figure 2(a)).

3. Characteristics of CBM Occurrence

From the actual situation of coal mining such as gas emission and the measured data of CBM (gas) parameters including CBM content (from [21]) and gas pressure (Table 1), there are obvious differences in CBM content, gas



(a) (b)

FIGURE 1: The geotectonic location of Pingdingshan Coalfield with (a) geotectonic units of China and geographical location of Pingdingshan Coalfield and (b) tectonic units of Qinling orogenic belt and geographical location of Pingdingshan Coalfield.

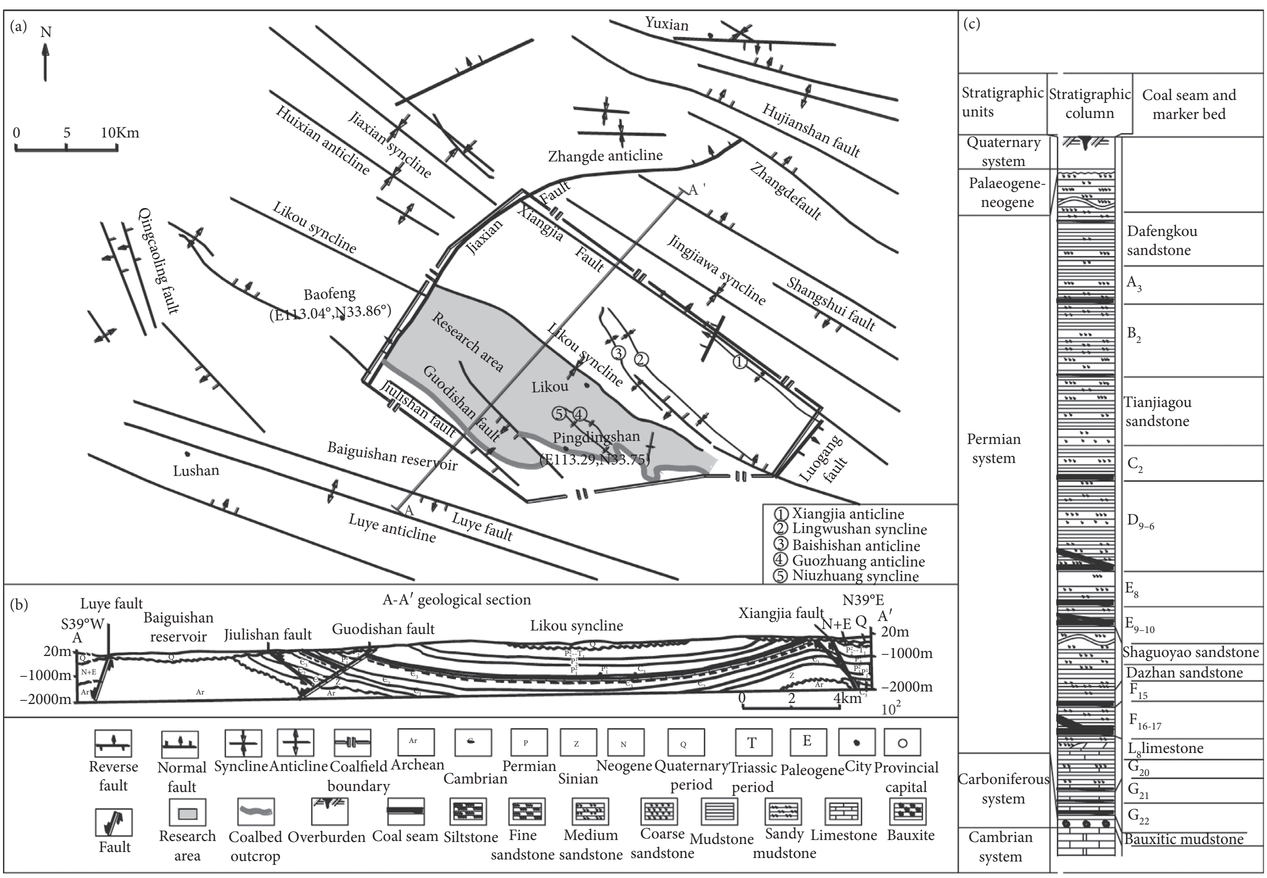


FIGURE 2: Geological setting and the position of the research area.

pressure, and gas emission among the western, middle, and eastern parts of the research area. CBM occurrence shows zonation characteristics. The research area is divided into four CBM occurrence belts. At the same burial depth, CBM content, gas pressure, and gas emission generally increase firstly, then decrease, and increase again from west to east (Figures 3 and 4, Tables 2 and 3).

CBM belt I is located in the west of Pingdingshan Coalfield and mainly includes Xsh Mine and the west of No.11 Mine. CBM belt II is also located in the west next to

Table 1: The representative gas pressure of the research area in coal seam group F.

Number	Gas pressure (MPa)	Burial depth (m)	Number	Gas pressure (MPa)	Burial depth (m)	Number	Gas pressure (MPa)	Burial depth (m)
1	0.7	970	36	1.69	1148	71	2.9	831
2	0.57	985	37	2.1	1039	72	1.07	475
3	0.35	923	38	2.5	1106	73	1.15	525
4	0.22	1020	39	2.6	1039	74	2.06	575
5	0.57	1026	40	1.5	1060	75	2	1117
6	0.42	988	41	1.37	1060	76	3.2	1185
7	0.5	1090	42	2.5	1056	77	2.7	1132
8	0.35	1080	43	2.15	1056	78	2.6	795
9	0.45	1100	44	2.5	1079	79	1.7	490
10	0.44	978	45	2.2	1148	80	2.06	490
11	0.25	917	46	0.3	756	81	1	494
12	0.4	959	47	0.5	900	82	1.5	504
13	0.27	955	48	0.36	790	83	1.8	642
14	1.4	848	49	0.5	747	84	1.7	642
15	1.55	870	50	1.35	792	85	2.1	765
16	1.6	901	51	1.1	890	86	2.85	1080
17	2.2	863	52	0.5	881	87	2.05	1100
18	1.6	956	53	0.5	846	88	2.3	1100
19	1.9	953	54	0.85	943	89	1.68	1000
20	1.3	952	55	1.18	935	90	1.78	1045
21	3.2	890	56	2.6	1163	91	1.2	795
22	2.1	900	57	2.1	1163	92	1.7	790
23	1.6	716	58	1.1	986.2	93	2.1	680
24	1.45	612	59	0.7	630	94	1.13	525.4
25	0.99	427	60	1.2	738	95	1.89	490
26	1.15	435	61	1.45	433	96	1.81	533
27	0.9	470	62	2.4	843	97	1.65	533
28	1.6	550	63	1.2	738	98	1.89	624
29	1.7	597	64	2.95	1000	99	1.61	533
30	0.68	600	65	2.4	1072	100	1.7	780
31	0.38	369	66	2.4	843	101	1.85	780
32	1.35	612	67	2.6	1148	102	2	808
33	1.85	693	68	1.1	475	103	1.25	605
34	2.7	985	69	1.5	620	104	1.4	545
35	1.07	1148	70	2.62	993			

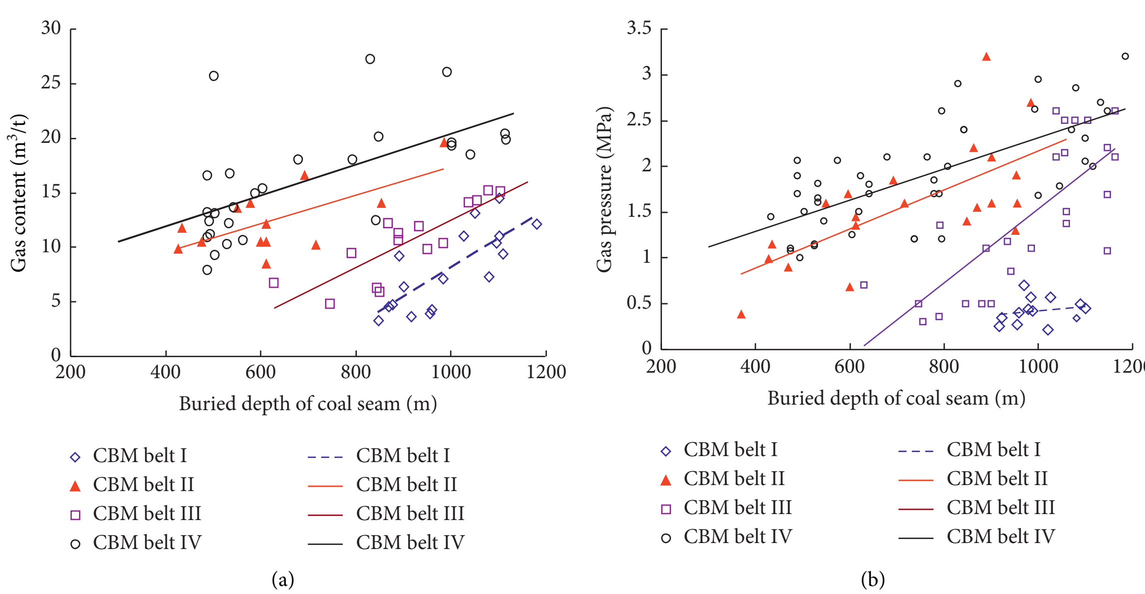


Figure 3: Difference of CBM (gas) occurrence among different CBM belts in coal seam group F showing (a) CBM (gas) content and (b) gas pressure, and these CBM (gas) data were measured actually underground coal mine.

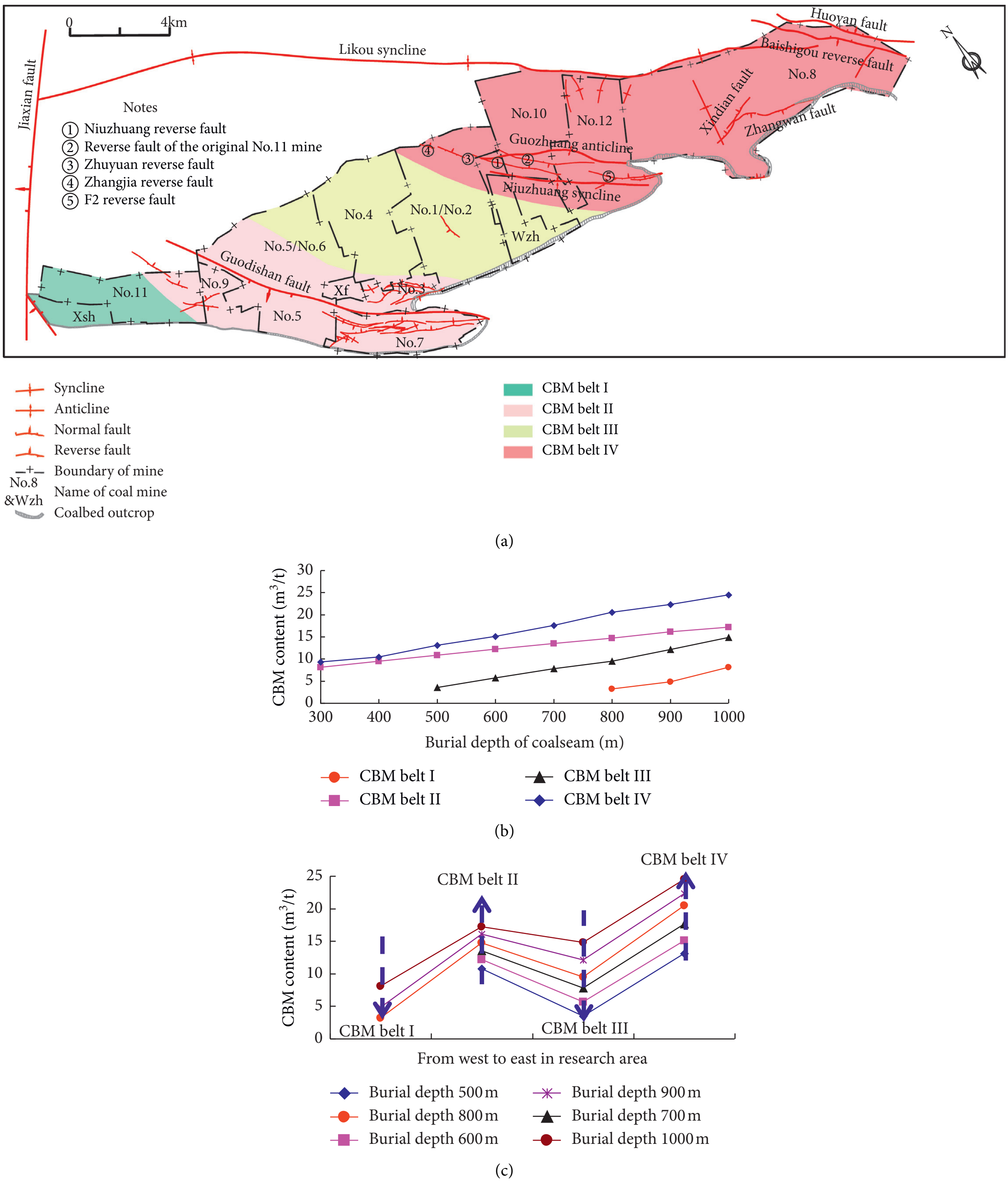


Figure 4: The division of CBM belts and the distribution of CBM (gas) content of the research area in coal seam group F showing (a) the division of CBM belts and ((b), (c)) the difference and change of CBM (gas) content among different CBM belts. Figures (b) and (c) were prepared according to the relationship between CBM content and burial depth (Table 3).

CBM belt I and mainly includes the east of No. 11 Mine, No. 9 Mine, the west of No. 5 (No. 6) Mine, No. 7 Mine, and No. 3 Mine. CBM belt III lies in the middle and mainly comprises No. 4 Mine, most part in the west of No. 1 (No. 2) Mine, Wzh Mine, and a small part of the east of No. 5/No. 6 Mine. CBM belt IV lies in the eastern part, No. 10, No. 12, and No. 8 mines and a small part of the east of No. 1 (No. 2). Mine are mainly distributed in this belt.

It shows that there is an overall trend of CBM contents and gas pressures increasing with the increase of the burial depth in the same CBM belt from Figures 3 and 4(b) and Table 2; in particular, there is a great difference of those

Table 2: Statistics and analysis of CBM (gas) content of the research area in coal seam group F.

CBM belts	Range of CBM content/m^3/t (min ~max/avg)	Depth range of CBM content measurement/m (min ~max/avg)	Relationship between CBM content (W/m^3/t) and burial depth (H/m)
CBM belt I	3.32~14.47/8.01	848 ~1180/996.8	$W = 0.0271H - 19.043$ $(750 < H < 1200)$
CBM belt II	8.49~19.58/12.44	427~985/626.7	$W = 0.0131H + 4.2609$ $(300 < H < 1100)$
CBM belt III	4.77~15.13/10.49	630~1106/911.2	$W = 0.0218H - 9.3485$ $(500 < H < 1100)$
CBM belt IV	7.87~27.2/16.00	489~1117/690.5	$W = 0.0142H + 6.1924$ $(200 < H < 1200)$

Table 3: Statistics and analysis of gas pressure of the research area in coal seam group F.

CBM belts	Range of gas pressure number	Range of gas pressure (MPa) (min ~max/avg)	Depth range of gas pressure measurement (m) (min ~max/avg)
CBM belt I	1~13	0.22~0.70/0.42	917 ~1100/999.3
CBM belt II	14~34	0.38~3.20/1.58	427~985/723.7
CBM belt III	35~59	0.3~2.6/1.43	630~1163/974.4
CBM belt IV	60~104	1.0~3.20/1.89	433~1185/755.9

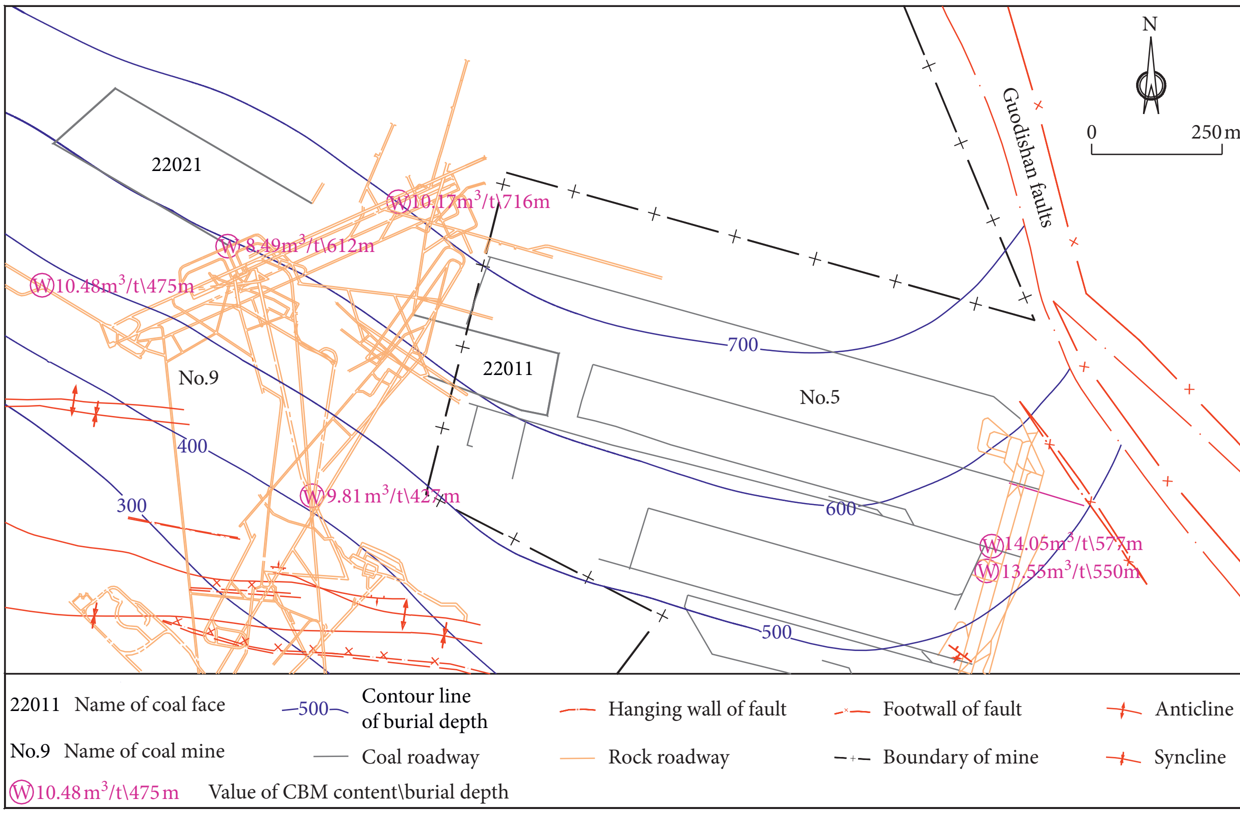
among CBM belt I, CBM belt II, CBM belt III, and CBM belt IV. At the same burial depth, CBM contents and gas pressures in CBM belt IV are the highest, followed by CBM belt II. CBM contents and gas pressures of CBM belt I are the lowest. The CBM contents and pressures of CBM belt III are between those of CBM belt II and those of CBM belt I. Each CBM belt shows its own characteristics. Taking the coal seam group F as an instance, the details are as follows.

In the CBM belt I, the overburden depth of measurement points of CBM contents is 848 ~1180 m with an average of 996.8 m. The gas content is 3.32~14.47 m^3/t with an average of 8.01 m^3/t, which is less than 10 m^3/t within the range of burial depth less than 1000 m. The gas pressure is below 0.7 MPa at the burial depth of not more than 1,000 m. The CBM content and gas pressure are the lowest in this coalfield. But the gas weathering zone of the coalbed is the deepest; it is about 750 m. Xsh Coal Mine is in this gas weathering zone; gas emissions are generally lower than 2 m^3/t during mining. The CBM content generally increases with the increase of burial depth; their correlation is apparent under 750 m depth.

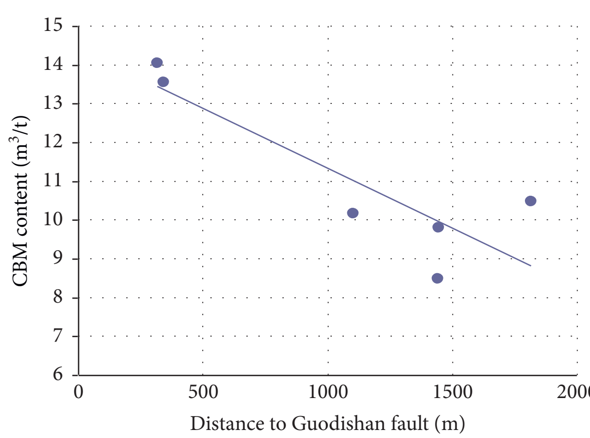
In the CBM belt II, the overburden depth of measurement points of CBM contents is 427~985 m with an average of 626.7 m. The CMB content is 8.49~19.58 m^3/t with an average of 12.44 m^3/t, which is mostly 10–15 m^3/t, and the gas pressure is mostly 1.2–2.0 MPa with an average of 1.58 MPa, which are generally higher than those of the CBM belt I and the CBM belt III and lower than those of the CBM belt IV at the same burial depth. The gas weathering zone of the coalbed is shallow; it is about 300 m. The CBM content generally increases with the increase of burial depth under the depth of coalbed gas weathering zone, but it tends to be relatively dispersed. In addition, the CBM content and gas emissions during mining tend to increase near Guodishan faults (Figure 5). It can be seen clearly from Figures 5(a) and 5(b) that the CBM content increases obviously with the decrease of the distance from the Guodishan fault. The 22021 working face and the 22011 working face lie in the same burial depth about 500 m (Figure 5(a)). The 22011 working face is closer to the Guodishan fault than the 22021 working face. According to the data of gas emission during mining, the gas emission of 22011 working face is significantly larger than that of 22021 working face. As shown in Figure 5(c), the relative gas emission of the 22011 working face is 9.96~14.16 m^3/t, and that of the 22021 working face is 5.69~8.61 m^3/t.

In the CBM belt III, the burial depth of measurement points of CBM contents is 630~1106 m with an average of 911.2 m. The coal seam demonstrates 4.77~15.13 m^3/t of gas content with an average of 10.49 m^3/t. The gas pressure is 0.3~2.60 MPa with an average of 1.43 MPa. It is mostly 0.4~1.5 MPa at the burial depth of not more than 1,100 m. However, gas pressure increases greatly and reaches 1.69~2.6 MPa under the burial depth of 1,100 m. And the gas weathering zone of the coalbed is deeper; it is around 500 m. The CBM content increases with the increase of burial depth under 500 m depth with good correlation.

In the CBM belt IV, the overburden depth of measurement points of CBM contents is 489~1117 m with an average of 690.5 m. The CBM (gas) content ranges from 7.87 m^3/to 27.2 m^3/t with an average of 16.0 m^3/t, which is mostly 10~20 m^3/t and even about 30 m^3/t. The gas pressure is mostly 1~3 MPa. The gas weathering zone of the coalbed is very shallow, which is approximately 200 m. The CBM content generally increases with the increase of burial depth under the burial depth of 200 m, but the trend is also

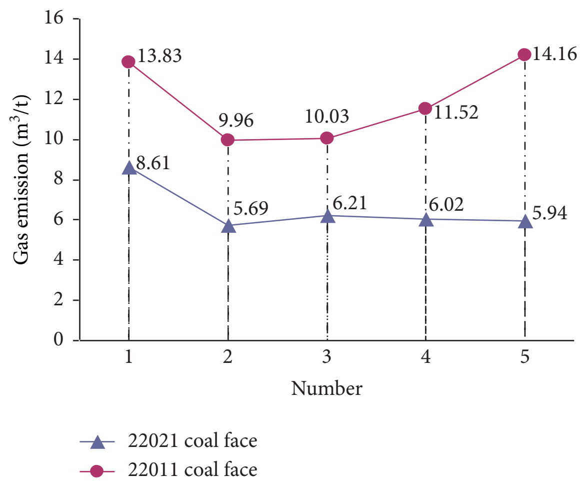


(a)



(b)

Figure 5: Continued.



(c)

Figure 5: An example of the variation of CBM content and gas emission of coal seam group F with the distance from Guodishan fault in CBM belt II, showing (a) the structural position of CBM content and coal face near Guodishan fault, (b) the variation of CBM content with the distance from Guodishan fault, and (c) comparison of gas emission between 22021 coal face and 22011 coal face.

relatively scattered. In addition, the CBM content and gas emission during mining increase near the syncline axis or far away from the anticline axis in this belt (Figures 6 and 7).

In addition, the gas content, gas pressure, and gas emission during mining tend to increase near the NW-trending and WNW-trending fault in this coalfield. For instance, the gas content and gas emission in No. 5 Coal Mine and No. 9 Coal Mine near Guodishan fault are higher than those in the middle and western areas far away Guodishan fault at the same burial depth (Figure 5).

4. Discussion

4.1. Evolution of Tectonics and Its Influences. The current tectonic framework and type, CBM occurrence, and the distribution of deformed coal are the results of tectonic evolution. Under the action of tectonic movement, coal-bearing strata were deformed and displaced by compression, extension, and shear; open and closed faults, folds, and other properties structures were formed, and coal structure was destroyed. And tectonic movement can cause the relative uplift and decline of coal seams. All of those changed the conditions of CBM generation, migration, and preservation in coal seams. The scale, scope, and tectonic stress field of tectonic movement in different periods are different. Due to the different tectonic positions of different areas, coal mining areas, and coal mines, the action intensity of tectonic movement on them is different. Therefore, the present tectonic pattern, CBM occurrence, and deformed coal in different areas, coal mining areas, and coal mines are different, or even very different.

The Pingdingshan Coalfield lies in the south edge belt of the North China plate and also the north side of the thrust and nappe tectonics at the north margin of Qinling orogenic belt [14, 16] (Figure 1). The Pingdingshan Coalfield is reformed by the North China plate and has been controlled and reformed by the Qinling orogenic belt for a long time. Since the formation of the Carboniferous-Permian coal-bearing strata, the Pingdingshan Coalfield has undergone multistage tectonic movements such as the Indosinian, Yanshanian, Sichuan, North China, Himalayan, and Neotectonic periods [21, 22] (Figure 8). The multiphase tectonic movements affected importantly CBM (gas) occurrence conditions such as tectonic pattern and deformed coal in Pingdingshan Coalfield.

According to the study on the tectonic evolution of Pingdingshan Coalfield in [21], the tectonic movements in various periods have the following main effects on structural formations, coal deformation, CBM formation, and storage in Pingdingshan Coalfield [22–26]. (1) The Pindingshan Coalfield is located at the plate margin, and meanwhile, it is also subjected to long-term squeezing in the south-north direction by the Qinling orogenic belt. The special tectonic location determines the basic features of gas geology in the Pingdingshan Coalfield. The basic features of gas geology are complex geological structures, well-developed deformed coal, and high CBM content. (2) In the Pingdingshan Coalfield, a great amount of coalbed gas was generated during the Indosinian-Yanshan period; the coal-bearing strata experienced severe deformation or displacement during the Sichuan period, which was also the major period for a deformed coal formation; the coalbed gas was mainly released when the NE-trending normal faults were formed during the Sichuan period, and part of the NW-trending reverse faults was transferred to normal faults; the Pingdingshan Coalfield was uplifted in the North China period. (3) The NW- and WNW-trending structures were subjected to squeezing in a longer duration and more intensive activities, compared to the NE–NEN-trending structures. The NW-trending and WNW-trending structures of the whole coalfield are more developed than those of the NE–NEN-trending structures, the deformed coal nearby is more developed, and the conditions of CMB (gas) preservation are better.

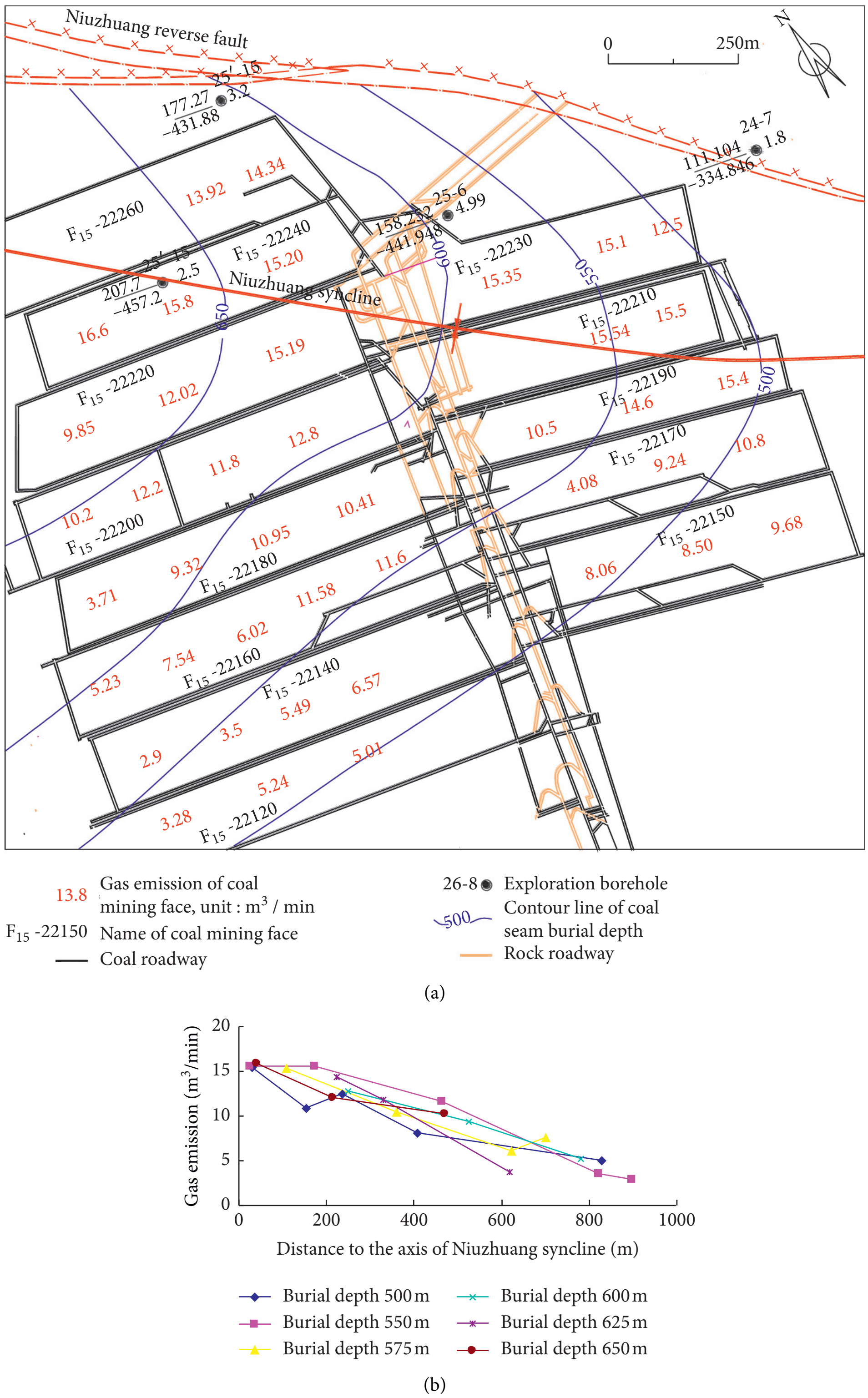
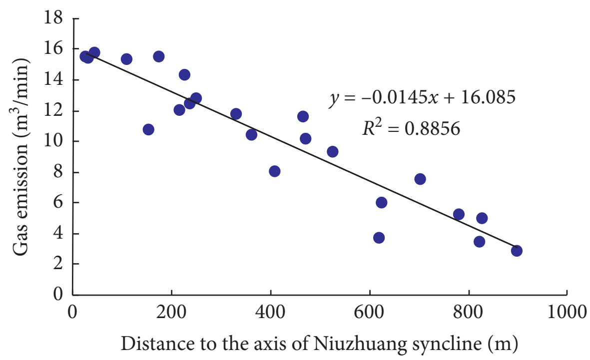
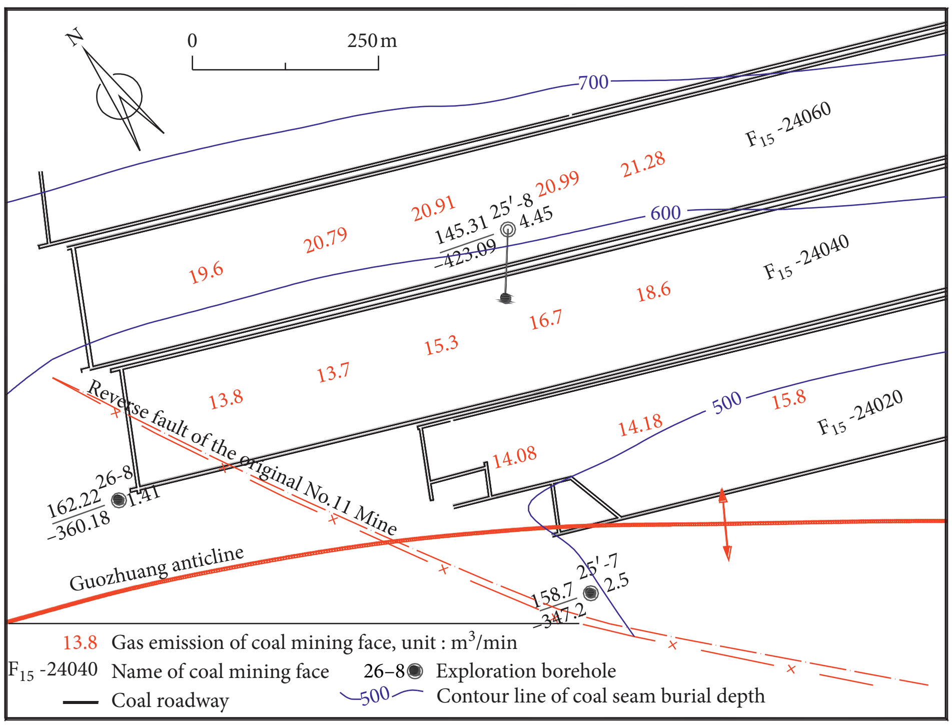


Figure 6: Continued.

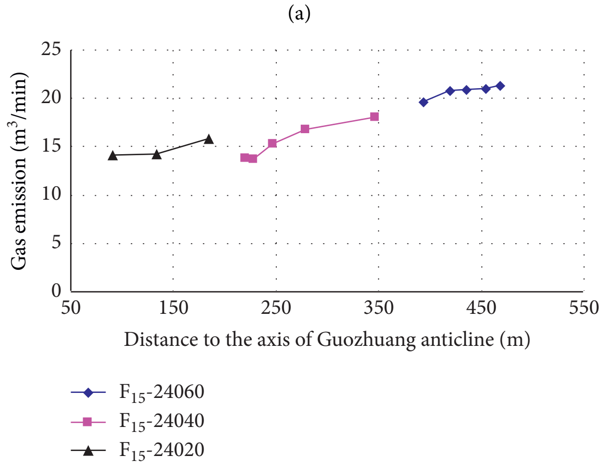


(c)

Figure 6: The variation of gas emission of coalbed F15 with the distance from Niuzhuang syncline in CBM belt IV.



(a)



(b)

Figure 7: The variation of gas emission of coalbed F15 with the distance from Guozhuang anticline in CBM belt IV.

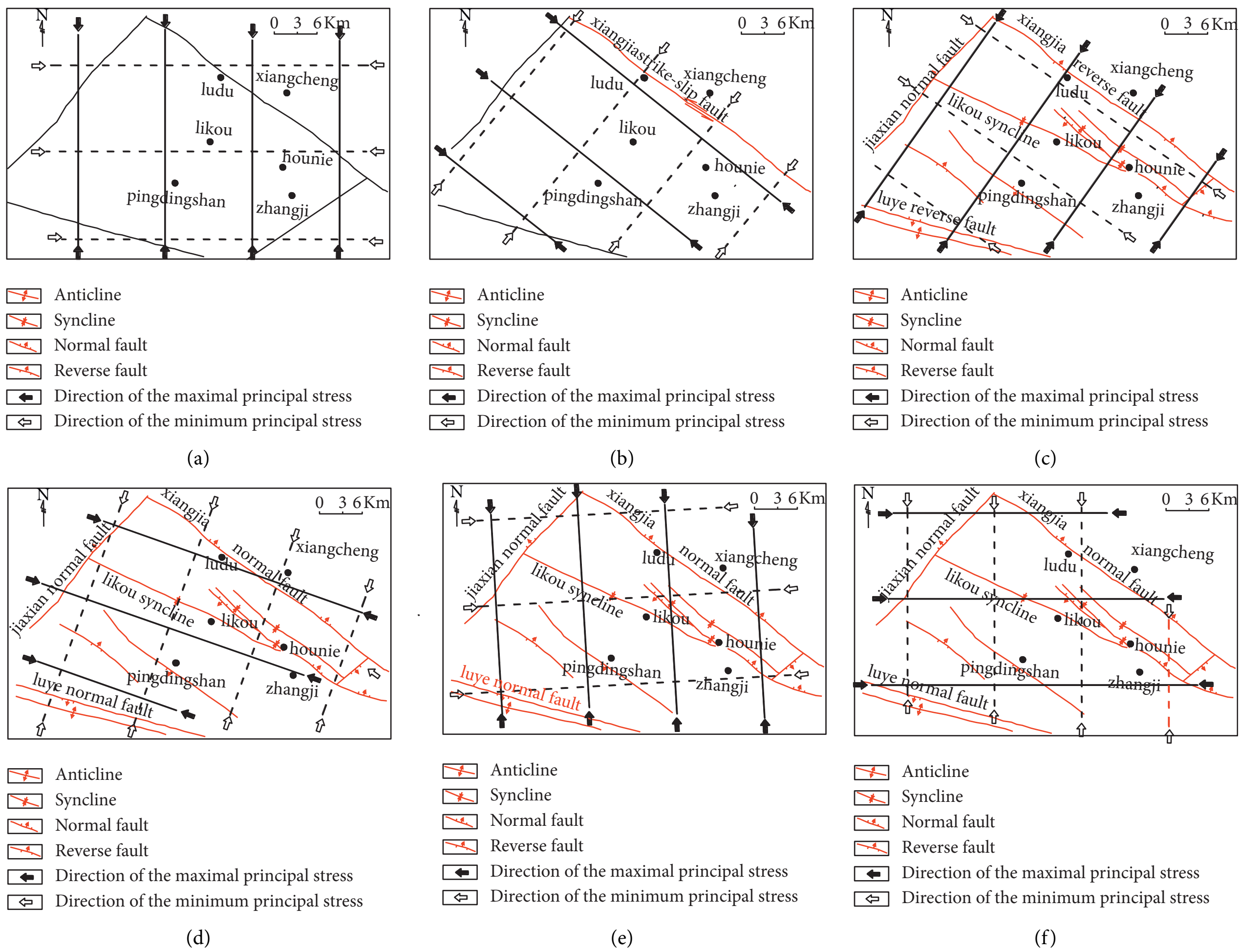


Figure 8: The evolution of the tectonic of Pingdingshan Coalfield in geological history. (a) Indosinian. (b) Yanshanian. (c) Sichuan period. (d) North China period. (e) Himalaya period. (f) Neotectonic Period.

4.2. Tectonic Controlling Law for CBM Occurrence

4.2.1. Tectonic Characteristics of CBM Belts. Under the action of tectonic stresses in various periods, a series of NW-trending and WNW-trending folds and faults were formed in Pingdingshan Coalfield, which were accompanied by NE–NEN-trending faults. Likou syncline is the main control tectonic. But the characteristics of structures in different CBM belts are obviously different (Table 4).

CBM belt I is located in the west of the research area, the wide and gentle area of the Likou syncline. It lies between the Jiaxian fault and the Guodishan fault, near the Jiaxian fault, far away from the Guodishan fault and the axis of the Likou syncline. The controlling structure is the Jiaxian fault. Faults and folds are undeveloped. The geological structure is simple. The structural control type is NE fault structural control type.

CBM belt II is also located in the west of the research area, the wide and gentle area of Likou syncline in the NW direction. It is on both sides of the Guodishan fault, far from the Likou syncline axis, near Guodishan faults, next to CBM belt I in the west. The controlling structure is Guodishan faults. NW- and WNW-trending faults are very developed. It belongs to a complex tectonic zonation. The structural control type is the NW fault structural control type.

CBM belt III is in the middle of the research area. It is in the transition zone from the wide and gentle area in the NW direction to the convergence area in the SE direction. It is far from Guodishan faults and the NW-trending fold-fault belt. This fold-fault belt is composed of Likou syncline, F_2 reverse fault, Zhangjia reverse fault, Zhuyuan reverse fault, reverse fault of the original No. 11 Mine, Niuzhuang reverse fault, Guozhuang anticline, and Niuzhuang syncline. The geological structure is relatively simple, with no large controlling structures in this belt. The structural control type is the burial depth control type.

CBM belt IV lies in the eastern part of the research area, the convergence, and the closed area of the Likou syncline in the SE direction. It is near the Likou syncline axis. NW- and WNW-trending folds and reverse faults are well developed. Folds are particularly developed. And NE-trending structures such as Xindian fault as well as composite structures formed by NW-trending and NE–NEN-trending structures such as Jiaozan syncline are also developed. Therefore, this belt belongs to the most complex tectonic zone in the

Table 4: The characteristics of tectonic distribution and control in different CBM belts.

Name of CBM belt	Tectonic location	Distance from the Likou syncline axis	Controlling structures	Geological structure and its Complexity
CBM belt I	In the wide and gentle area of Likou syncline, near Jiaxian faults	Far	Jiaxian faults	Simple
CBM belt II	In the wide and gentle area of Likou syncline, near Guodishan faults	Far	Guodishan faults	NW-trending fault structures are developed; the geological structure is more complex
CBM belt III	In the transition zone from the convergence area to the wide and gentle area	Between CBM belt II and CBM belt IV	Burial depth	Relatively simple
CBM belt IV	In the convergence area of Likou syncline	Near	Likou syncline and NW- and WNW- trending fold-fault belt	Fold structures and reverse faults are developed; the geological structure is the most complex

research area. Likou syncline and NW- and WNW-trending fold-fault belts are the main controlling structures. The structural control type is the fold structural control type.

4.2.2. Effects of Tectonic Types on CBM Occurrence. Based on the above analysis, four CBM belts in the research area have shown dissimilar tectonic types that have different roles for CBM preservation. This has resulted in the difference in CBM (gas) preservation conditions of each CBM belt in the coal seam.

In detail, the NE-trending Jiaxian fault is a boundary fault and mostly exhibited tension during its evolution process; a great amount of coalbed gas was escaped. The area near the Jiaxian fault is far away from the Likou syncline axis, the structure is simple, and the layer-sliding structure of the coal seam almost cannot be found. Deformed coal is not developed (Figure 9); it can be found only near the faults. Tectonic stress was consumed and released during fault formation. The tectonic stress is small in this area near the Jiaxian fault [21] (Figure 10). All these lead to simple structure conditions and very poor CBM preservation conditions. So, the CBM belt I controlled by the Jiaxian fault shows lower CBM content and gas pressure, deeper gas weathering zone of coalbed, and a good correlation between CBM content and burial depth.

It can be concluded from the evolution of tectonics in Pingdingshan Coalfield that the Guodishan fault was a reverse fault in the early stage, and it became a normal fault after inversion of the stress field in the later stage [21]. There are many NW-trending secondary faults on both sides of this fault, especially in the hanging wall. Its hanging wall is the upthrown side of the reverse fault formed during the Sichuan period and, in addition, is the downthrown side of the normal fault formed during the North China period. The coal seam is seriously damaged by rubbing, and the thickness of the coal seam changes greatly. As a result, in this area near the Guodishan fault, especially the hanging wall, the structure is very complex, deformed coal is very developed, and its thickness changes greatly (Figure 9). The closer to the Guodishan fault, the more complex the structure is, and the more developed the deformed coal is. These faults including the Guodishan fault were mostly subjected to compression during their evolution process. Guodishan fault and its secondary faults are closed faults, which are unfavorable for CBM release. The closer to the Guodishan fault, the more developed the microfracture and the larger the CBM preservation space. As we know, deformed coal is characterized by low strength, strong CBM adsorption capacity, and fast desorption speed [27–29]. So, the CBM belt II controlled by the Guodishan fault shows that CBM content and gas pressure are higher, the coalbed gas weathering zone is shallower, and the CBM content and gas emissions during mining tend to increase near the Guodishan fault. Because of the complexity of gas-geological conditions, the distribution of CBM content with burial depth is relatively scattered.

The geological tectonics is relatively simple in the CBM belt III. The coal seams are less subjected to strong tectonic compression and shear failure. Deformed coal is not developed (Figure 9). CBM is mainly controlled by the overburden depth, so the correlation between CBM content and burial depth is good. And this area is closer to the Likou syncline axis. The tectonic stress is relatively higher [21] (Figure 10). In situ stress greatly affects the permeability of coalbed; compressional stress decreases the permeability of coalbed and inhibits the migration and diffusion of CBM [30, 31]. It is conducive to save CBM and easily form CBM enrichment areas in compressional stress areas. All of these make that the CBM in the shallow escapes greatly, and the CBM in the deep is relatively well preserved in this area. So, the gas weathering zone of the coalbed is at greater depth; the CBM content and gas pressure are relatively higher at under the depth of 1100 m. And the mines in this area have transferred to mines prone to coal-gas outburst with increasing mining depth. Nevertheless, coal-gas outbursts are less severe.

CBM belt IV lies in the convergence area of the Likou syncline. The development of fold structures and the closest to the axis of Likou syncline are its typical feature. This type of structure is easy to form CBM enrichment area. Firstly, this type of structure was formed under the actions of strong thrust-nappe tectonics and rock masses bent and deformed without fracture, which maintains the continuous integrity of the rock mass, showing a closed state throughout. Tectonic stresses of every period remained in the subsequent tectonic evolutions without effective release. It is easy to

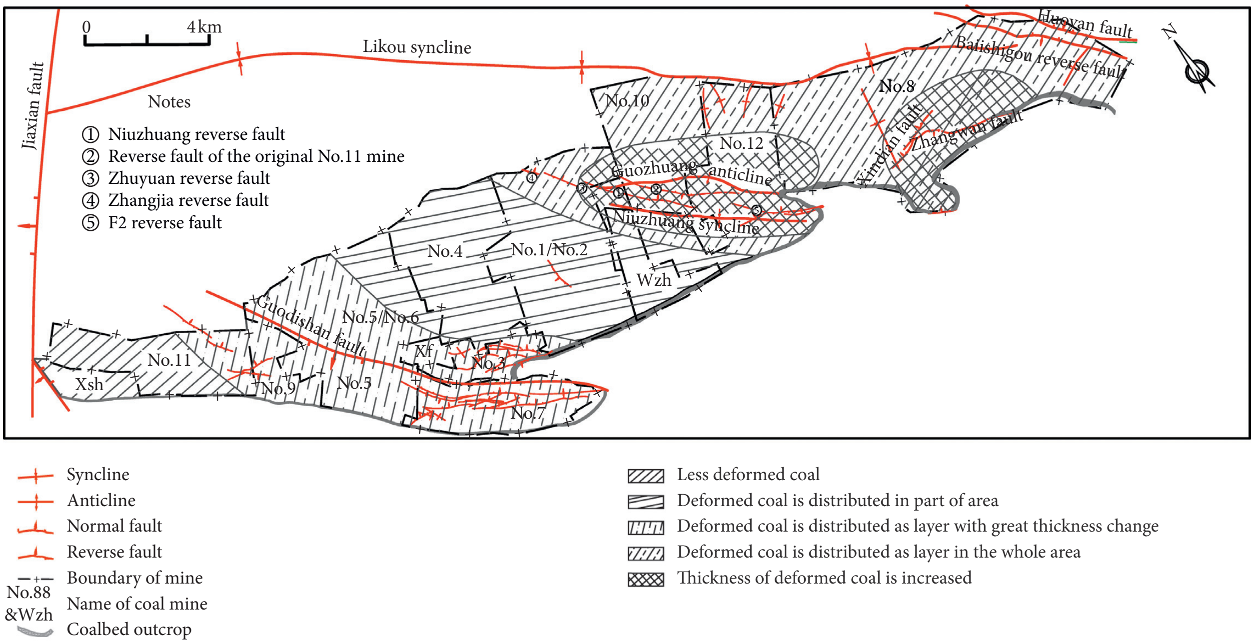


Figure 9: Distribution of deformed coal in the research area, which was prepared according to field investigation.

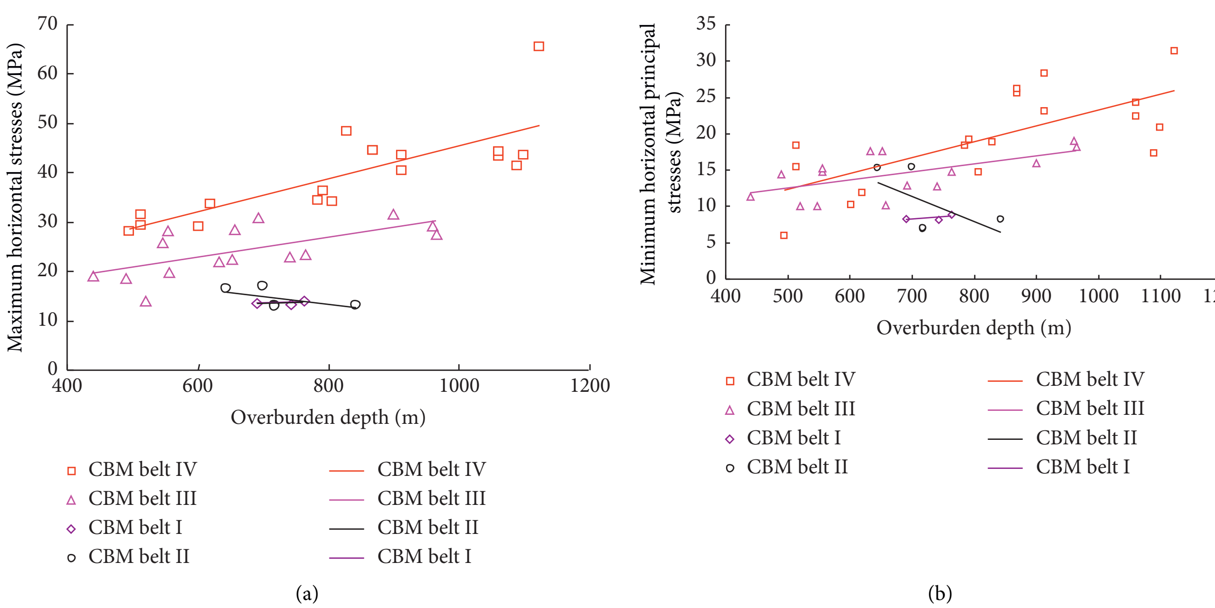


Figure 10: Difference of in situ stresses in the four CBM belts, showing (a) maximum horizontal principal stresses and (b) minimum horizontal principal stresses.

form a high-stress zone in the area of fold structure, which is a favorable condition for CBM preservation. In situ stress measurements show that the maximum horizontal stress in this area is generally 30–50 MPa with a maximum of 65.5 MPa, which is the largest in this research area (Figure 10). Secondly, during the formation of this type of structure, coal seams as the weaker layers were prone to sliding and deformed coal was formed in layers [32, 33]. In the whole area, deformed coal is distributed as a layer (Figure 9), which provides a larger space for CBM adsorption and preservation [21, 27, 28]. According to field observation and interpretation of deformed coal by logging curve (Figures 11 and 12), the thickness of deformed coal is generally 1.0 m–2.0 m (Figure 13). Thicker deformed coal was formed in the compound structure area, the wing of the anticline, and the axis of the syncline. For instance, at the NW-trending Niuzhuang syncline, Guozhuang anticline, and former No.11 Mine thrust fault or compound fold area,

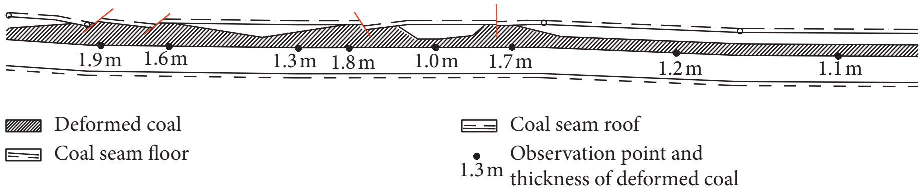


FIGURE 11: The thickness of deformed coal of C coal seam by field observation in No.8 Coal Mine.

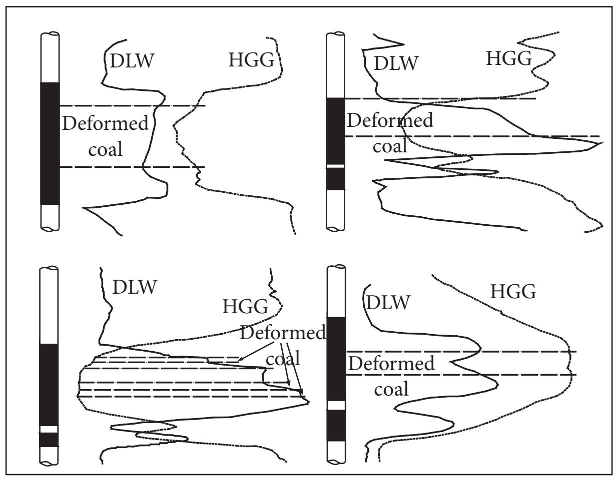


FIGURE 12: Typical example of interpretation for deformed coal by logging curve.

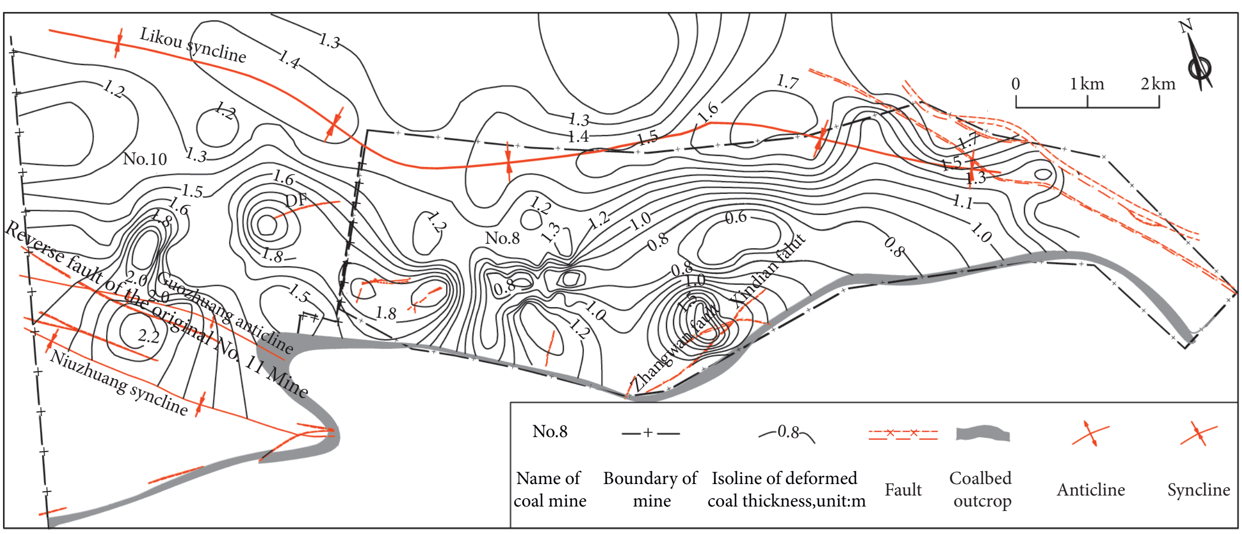


FIGURE 13: Distribution of deformed coal thickness of coal seam group E in the east of research area, which was prepared according to field observation and interpretation of deformed coal by logging curve.

the deformed coal is about 2.0 m thick. It is 1.5–1.8 m thick at the north wing of the Guozhuang anticline and 1.5 m at the axis of the Likou syncline (Figure 13). Thirdly, coal seams were prone to rheology during the formation of the tectonic structure. As a result, thick coal seams were formed which provides a rich material basis for the formation of CBM and a large adsorption space for CBM preservation. For example, the E coal seam in the No. 10 Mine at the north wing of Guozhuang anticline is 5-6 m thick (Figure 14). Finally, this area is near the Likou syncline axis, the burial depth of coal seams is deep, and the overlying bedrock of coal seams is thick. CBM migration to the surface is difficult.

On the whole, the difference of structural types in the east, middle, and west of Pingdingshan Coalfield is the main

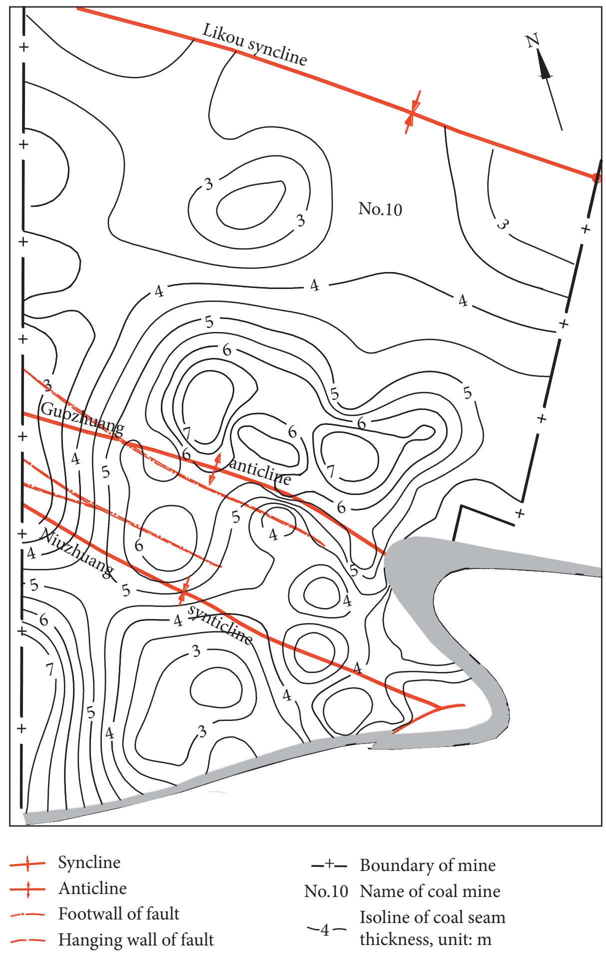


Figure 14: Contour of the thickness of coal seam E in No. 10 Coal Mine.

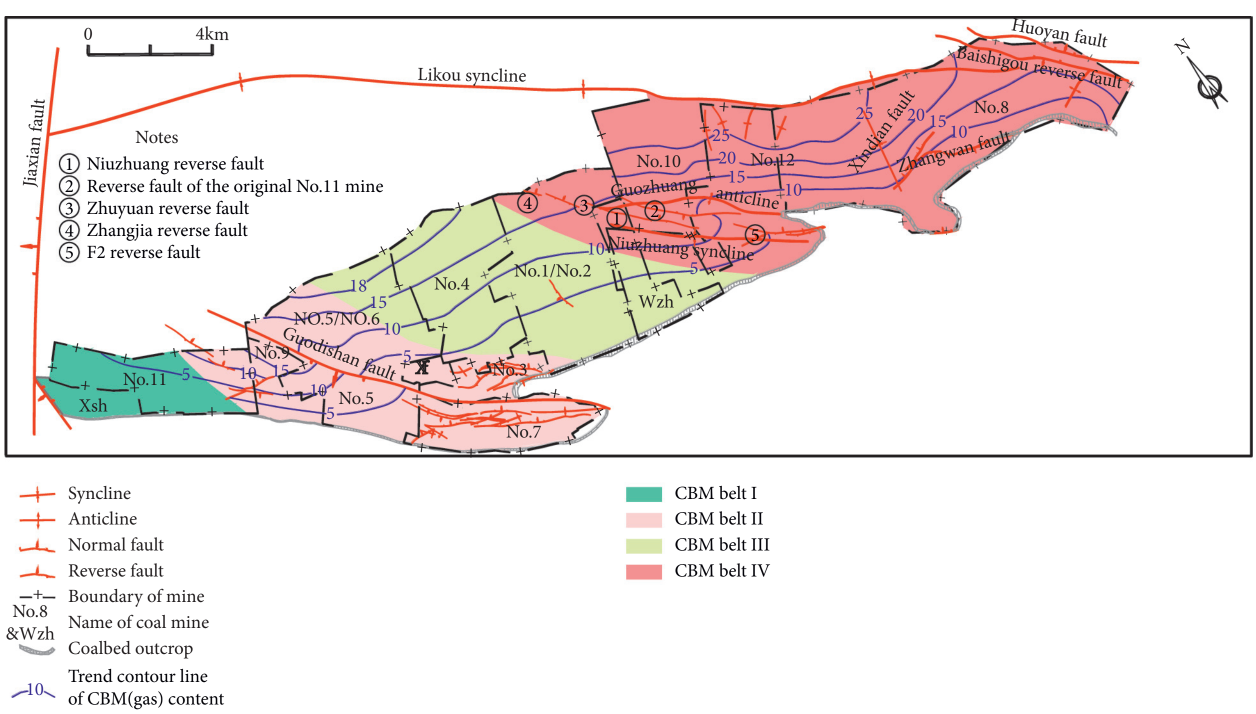


Figure 15: Trend isoline of CBM content of coal seam group F in the research area.

factor of CBM zoning. Likou syncline is the structure that controls the overall distribution of CBM; the CBM content in the east is obviously larger than that in the west. Guodishan fault, Jiaxian fault, and NW-trending fold-fault belt are the structures that control the local CBM occurrence in the research area.

4.2.3. Prediction of CBM Occurrence. According to tectonic controlling law for CBM occurrence and the relationship between CBM content and burial depth in each CBM belt (Table 2), isoline of CBM content was compiled (Figure 15). The prediction of CBM (gas) content for the unmined area in the deep is an important basis for the exploitation planning of CBM and the prevention and control of coal mine gas disaster. The map of CBM content isoline is also an important reference for the evaluation and development of CBM resources in abandoned mines in the future.

5. Conclusions

(1) Pindingshan Coalfield is located in the plate margin, and meanwhile, it is also subjected to long-term squeezing in the SN direction by the Qinling orogenic belt. The basic features of gas geology in this coalfield are complex geological structures, well-developed deformed coal, and high CBM content.

(2) CBM occurrence shows zonation characteristics in the Pindingshan Coalfield. The research area is divided into four CBM occurrence belts. At the same burial depth, CBM belt IV demonstrates the highest CBM contents, followed by CBM belt II. The CBM contents of CBM belt I are the lowest. The CBM contents of CBM belt III are between those of CBM belt II and those of CBM belt I. And each CBM belt shows its own characteristics.

(3) The difference of structural types in the east, middle, and west of Pingdingshan Coalfield is the main factor of CBM zoning. Likou syncline is the structure that controls the overall distribution of CBM. The CBM content in the east is obviously larger than that in the west. Guodishan fault, Jiaxian fault, and NW-trending fold-fault belt are the structures that control the local CBM occurrence in this research area.

(4) CBM content has an overall trend of increasing with the increase of burial depth in the same CBM occurrence belt. Due to the difference of structural types, the variation trend and correlation of CBM content with burial depth are apparently different in different CBM belts. The correlation is apparent in CBM belt I and CBM belt III with a simple structure. The distribution of CBM content with burial depth is relatively scattered in CBM belt II and CBM belt IV with a complex structure.

Data Availability

The data used to support the findings of this study are included within the supplemental information file(s).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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