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Research paper

Controlling effect of palaeo-tectonic stress field on gas occurrence

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Abstract: The paleo-tectonic stress field was hereby inverted by using the stereographic projection method through field and underground observations of conjugate shear joints. On the basis of analyzing and studying the characteristics of gas occurrence in mining areas, the control effect of paleo-tectonic stress field on gas occurrence was discussed from three aspects of gas generation, preservation environment and gas migration. The results show that: (1) During the Indosinian and early-middle Yanshan period, the coal seam was buried deep, and the temperature and pressure conditions were suitable for massive gas generation, especially during the Indosinian period featuring massive gas generation and weak gas migration; (2) During the late Yanshan period, the metamorphic evolution rate of coal seams accelerated, secondary hydrocarbon generation occurred in the coal seams, and a large amount of gas was generated. Meanwhile, the gas migration was enhanced. The gas generation amount was much larger than the emission amount, therefore, making it still a period of massive gas generation in general; (3) During the Himalayan period, the coal measure stratum was in the uplift stage, and a large number of geological structures were developed in the stratum. The tectonic stress field in this period caused the escape of massive coal seam gas. Multi-stage tectonic stress field acted on coal measures strata in turn, resulting in gas generation in coal seam and gas migration at the same time. Besides, gas occurrence is the superposition effect of gas generation, preservation conditions, and gas migration in coal seam.

Keywords: Paleo-tectonic stress field, gas occurrence, fault, fold, mining area in the east of Pingdingshan

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1. Introduction

China is the country with the most coal and gas outburst accidents. So far, more than 15,000 outburst accidents have occurred [1, 2]. During 2012–2021, a total of 57 outburst accidents happened in China, and a total of 354 people died in CAGO accidents. The accident brought great pain to the miners, as well as huge economic losses and casualties to the society, imposing a rather serious impact on the entire social environment [3–5], also a negative impact on the international image of China. Gas is the main factor causing casualties in outburst accidents [6–8], and an outburst power source as well. Exploration on the gas occurrence law and its causes in mining areas is extremely important for preventing coal and gas outburst accidents [9–11]. The law of gas occurrence is the basis of formulating efficient gas disaster prevention measures. In areas with high gas content and pressure, technical measures such as gas drainage, pressure relief and permeability enhancement need to be taken. By studying the law of gas occurrence, coal mines can take targeted gas prevention measures to improve the economic and safety benefits of mines. Gas content are generally high in all mines in the Eastern Pingdingshan mining area, but the distribution is uneven. Only by clarifying the causes of gas imbalance can the law of gas occurrence be more accurately studied. However, less research on the causes of unbalanced gas occurrence has been reported, which is generally considered to be caused by geological structures, but geological structures only form differentiated gas preservation conditions and flow channels. Gas migration requires dynamic conditions, which is the paleo-tectonic stress field, and the geological structure is also formed by the paleo-tectonic stress field. In this case, it is necessary to conduct a more comprehensive study on the process of the paleo-tectonic stress field controlling the occurrence of gas in mining areas. By collecting the data of mine gas content and pressure, combined with actual test data and gas geological data, the gas occurrence law was hereby studied. On this basis, reasons for the unbalanced gas occurrence in the study mining area were correspondingly analyzed. The paleo-tectonic stress field is the most critical factor, which mainly controls the gas occurrence in the mining area by affecting the gas generation, preservation conditions and gas migration.

2. The gas occurrence law

2.1. Gas content and gas pressure distribution characteristics

Pingdingshan No. 8, No. 10, No. 12 and Shoushan No. 1 mines are all outburst mines. Herein, considerable original gas content and pressure data of the Ji Coal Seam were tested on site, so that the accuracy of the data was ensured. A total of 120 groups of gas content and 92 groups of gas pressure were tested for the Ji Coal Seam. Based on these data, the original gas content and gas pressure contour map of the Ji Coal Seam in the Eastern Pingdingshan mining area is drawn, as shown in Fig. 1 and Fig. 2.

The maximum gas content of the Ji Coal Seam in No. 8, No. 10, No. 12 and Shoushan No. 1 mines is above 24 m^3/t, and the maximum gas pressure is 2.5 MPa. However, the maximum gas content is only 16 m^3/t, the maximum gas pressure is only 0.74 MPa, and

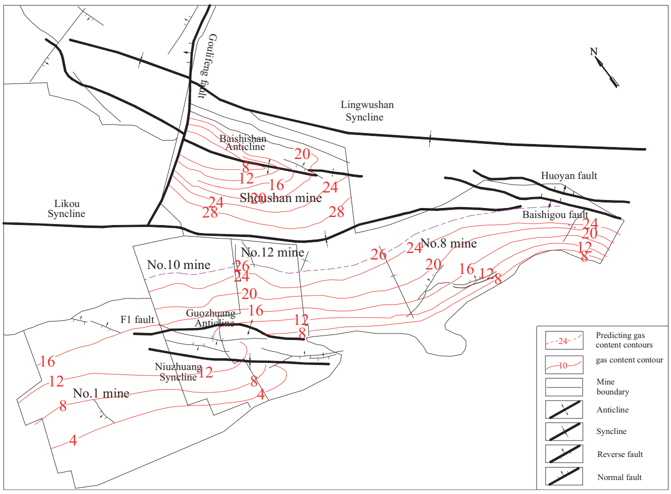


Fig. 1. Contour map of the gas content of the Ji Coal Seam in the Eastern Pingdingshan mining area (unit of the gas content in the figure: m^3/t)

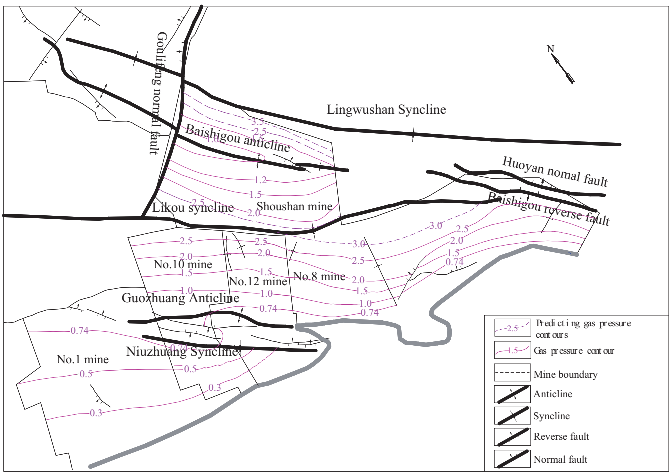


Fig. 2. Gas pressure contour map of the Ji Coal Seam in the Eastern Pingdingshan mining area (unit of the gas pressure in the figure: MPa)

the gas pressure in most areas is between 0.3–0.5 MPa in No. 1 mine which is adjacent to No. 10 mine (Fig. 1 and Fig. 2). No. 1 mine is a non-outburst mine, and the other four mines are outburst mines. The gas content and gas pressure in the outburst mine are much higher than those in the non-outburst mine, so the gas occurrence presents an obvious zoning trend. The gas content and gas pressure are the largest in the area of the Lingwushan syncline axis, and the lowest in the Baishishan anticline axis area, indicating the impact of the geological structure on gas occurrence.

2.2. Gas occurrence anomaly in geological structure areas

2.2.1. Characteristics of gas occurrence in fault areas

The extrusion direction of the modern tectonic stress field in the study mining area was the NEE direction. The stress field acted on the NW and NWW trending faults, and the fault sealing gas effect was favorable. Therefore, the gas emission from the working face near this type of fault generally increased. On the contrary, the NE and NEE-trending faults exhibited tensile properties, which was conducive to gas escape. The main faults in the mine, such as the Baishigou reverse fault and the Niuzhuang reverse fault, were NW-trending faults formed during the Yanshan period. The gas content and gas pressure in the fault-affected area were significantly higher than those not in the surrounding structure area. In particular, the gas content near the Baishigou reverse fault was as high as 24 m^3/t and 26 m^3/t, much higher than that in the non-structural area.

2.2.2. Characteristics of gas occurrence in fold areas

The gas in the syncline axis generally increased, while that in the anticline axis generally decreased. The gas content in the axis of the Niuzhuang and Lingwushan syncline were 14 and 24 m^3/t, respectively, while the gas content in the axis of the Guozhuang and Baishishan anticline was 6 and 7 m^3/t (Fig. 3). The gas content in the axis of the anticline was much lower than that of the axis of the syncline. Among them, due to the shallow burial depth and the existence of coal seam outcrops in the Niuzhuang syncline, massive gas escaped, thereby resulting in a relatively low gas content. Besides, the gas content gradually decreased from the axis of the Niuzhuang syncline to the axis of the Guozhuang anticline, while that gradually increased and reached the maximum from the axis of the Guozhuang anticline to the axis of the Likou syncline, decreased gradually from the axis of the Likou syncline to the axis of the Baishishan anticline, and increased gradually from the axis of the Baishishan anticline to the axis of the Lingwushan syncline.

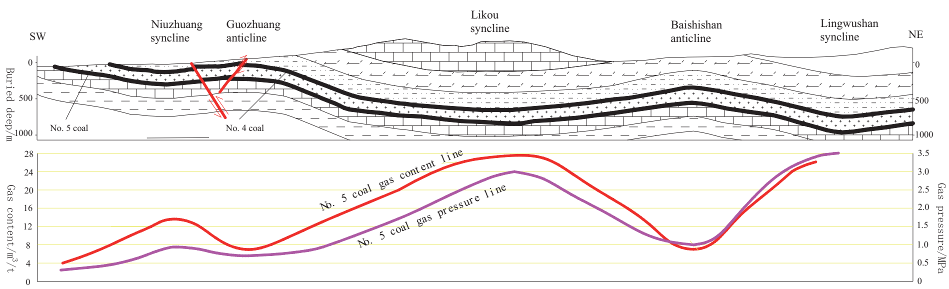


Fig. 3. Gas content and pressure distribution of the barrier folds in the research mining area

3. The characteristics of paleo-tectonic stress field

In the research mining area, 32 conjugate shear joint measurement points, including 26 field measurement points and 6 underground measurement points, were selected (Fig. 4 and Fig. 5). A total of 1415 shear joint data were collected, and then the paleo-tectonic stress experienced by the mining area after the Permian was inverted by using the stereographic projection method.

Fig. 4. Conjugate shear joint diagram of field test points

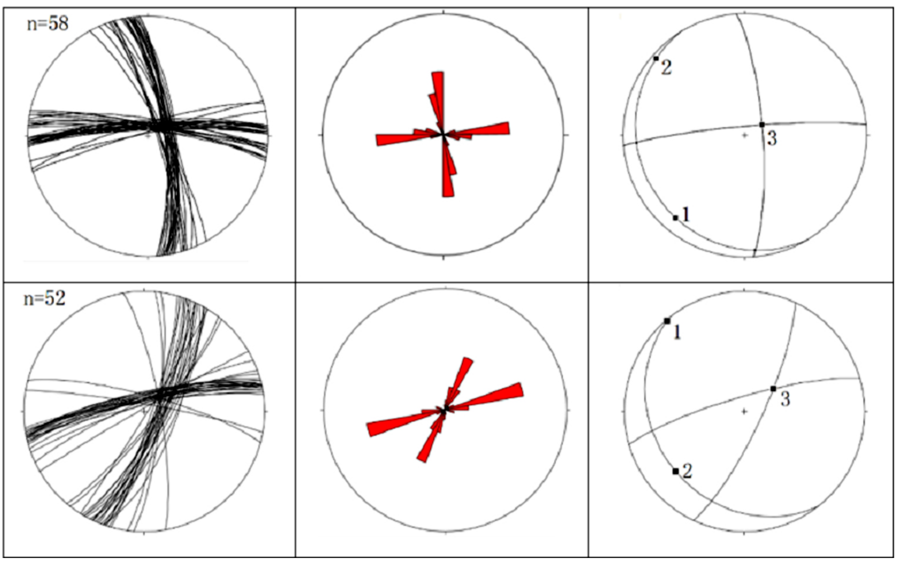
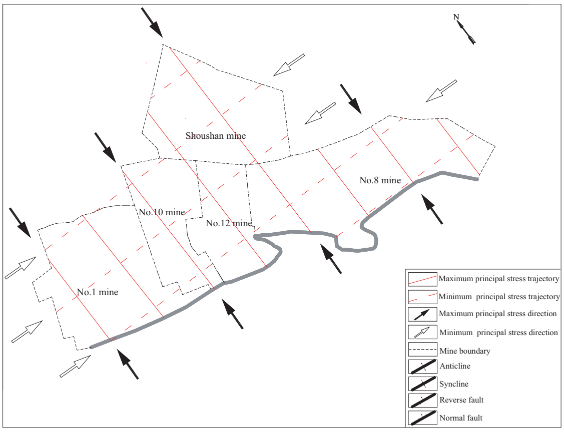
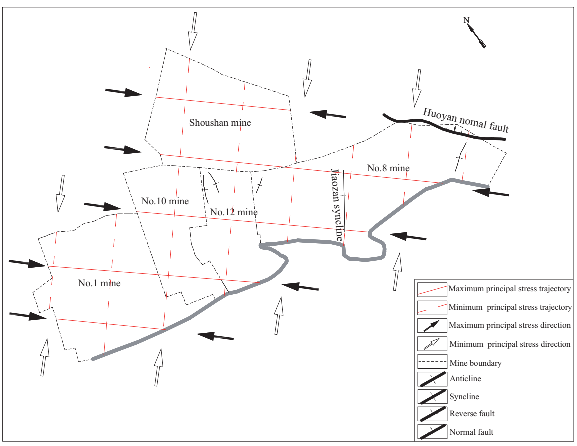


Fig. 5. Joint analysis diagram of some field measurement points

The Eastern Pingdingshan mining area mainly experienced four tectonic stress fields, i.e., Indosinian, early-mid Yanshan, late Yanshan and Himalayan. The direction of the maximum principal stress in the Indosinian period was nearly NS (Fig. 6a); The direction of the maximum principal stress in the early and middle Yanshan tectonic stress field was near NW, the stress field intensity is larger (Fig. 6b); The direction of the maximum principal stress in the late Yanshan period was nearly NE, the stress field had the largest action intensity (Fig. 6c); The maximum principal stress direction of the tectonic stress field in Himalayan period was close to NNE direction, the action intensity was weaker than that in the late Yanshan period (Fig. 6d).



(a)



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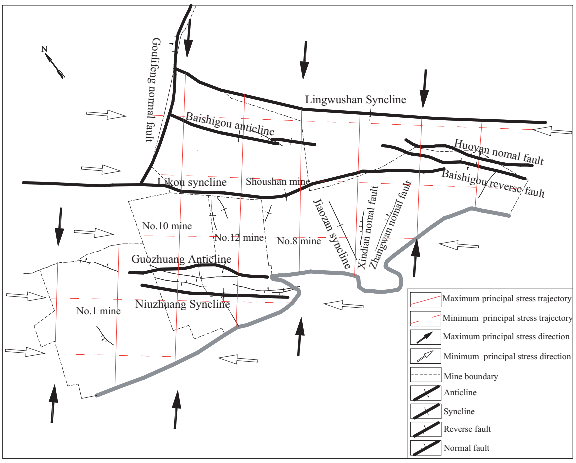
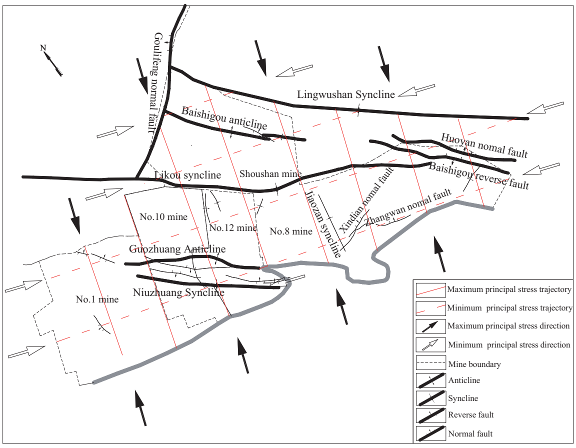


(c)



(d)

Fig. 6. The main tectonic stress field experienced after coal formation in the Eastern Pingdingshan mining area: a) Indosinian period, b) Early-middle Yanshanian period, c) Late Yanshanian period, d) Himalayan period

4. Research on the control effect of paleo-tectonic stress field on gas occurrence

The gas occurrence in the mining areas was the superposition effect of gas generation, preservation conditions, gas migration and accumulation, and these processes were closely related to the paleo-tectonic stress field. The paleo-tectonic stress field mainly affected the amount of gas generation through uplifted strata and dynamic metamorphism, affected the gas preservation conditions through the formation of geological structures, and affected the gas migration through the stress-driven mechanism.

4.1. Effect of paleo-tectonic stress field on gas generation

The dynamic response mechanism dominated by the paleo-tectonic stress field was the main factor for the diversity of coal seam hydrocarbon generation [12–14]. The Ji Coal Seam was formed during the Permian period [15], and at the end of the Triassic period, the burial depth reached its maximum, i.e., about 2200 m, and the coal seam temperature was above 125°C, forming the most favorable gas generation conditions in its evolution process (Table 1). The Indosinian tectonic stress field was weak in the study area, mainly manifesting as a certain uplift of the coal-measure strata. Actually, the coal seam had been in a high temperature and high pressure environment for a long time, and the coal was mainly gas coal. The gas coal had a strong hydrocarbon generation ability. Therefore, massive gas was generated during this period. The coal seam gas preservation conditions were good, and this period was favorable for coal seam gas generation.

Table 1. Recovery of thermal evolution history in the Pingdingshan mining area

Geological age	Tectonic movement stage	Buried depth (m)	Geothermal field (°)	Heating temperature (°)	Coal rank R_0, max%
N–Q	Himalayan period	800	4°	44	1.32
E		300		36	1.32
J_3–K	Middle and late Yanshan period	800	8°	155	1.32
J_1–J_2	Early Yanshan period	1650	4°	94	0.73
T	Indosinian period	2105	4°	104.2	0.68
P_3	Hercynian	1005	4°	60.2	0.37
P_2		155	4°	26.2	0.22

During the early-mid Yanshanian period, the coal seams were dominated by gas-fat coal and fat coal. The tectonic stress field in the early and mid-Yanshan period had a stronger effect on the Pingdingshan coal-measure strata than that in the Indosinian period. Large-scale structural deformation caused a lot of frictional heat, and the coal seam was buried at a depth of about 2,200 m during this period (Table 1). Moreover, the temperature was high, which is beneficial to gas generation.

During the late Yanshan period, a large amount of frictional heat was generated (Table 1). The results of the thermal evolution history of Pingdingshan showed that the coal seam temperature was around 155° in this period, secondary hydrocarbon generation occurred, and massive gas was generated. The degree of coal seam metamorphism increased sharply, mainly in fat coal, and the gas storage capacity of coal reservoir increased sharply. The late Yanshan period was the stage of massive gas generation in the coal seam.

During the Himalayan period, the temperature of the coal seam increased, and the pressure environment was relatively high. However, the coal seam was mostly fat coal, and the coalification process was terminated. In this case, there was less tectonic stress field and coal seam gas generation during this period (Fig. 7).

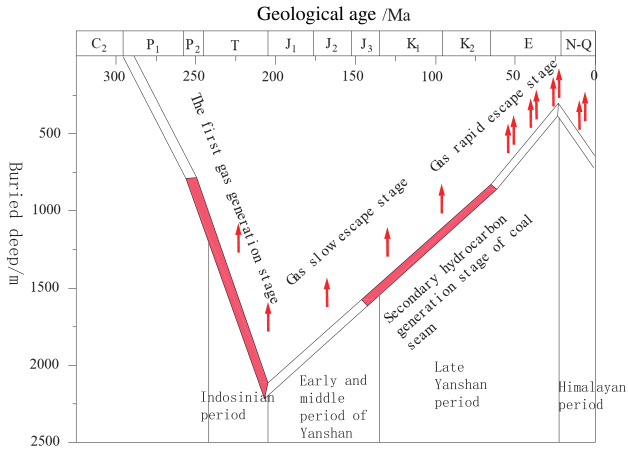


Fig. 7. Coal seam burial history and gas generation stage map in the study area

4.2. Effect of paleo-tectonic stress field on the gas preservation environment

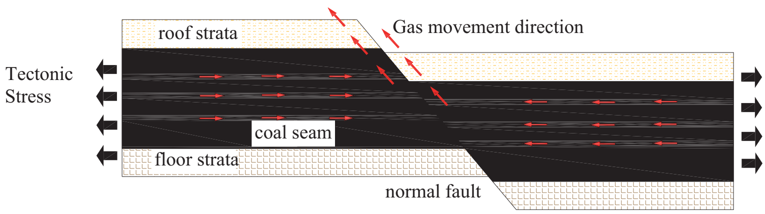
The gas preservation environment was mainly determined by the roof and floor of the coal seam as well as the geological structure. Some roof and floor strata were tight rock strata such as mudstone without tension faults, favorable for gas preservation. Syncline structures and reverse faults were formed by compressional tectonic stress fields. The compressional shear stress was concentrated in the area near the axis of the syncline and the fault plane of the reverse fault, where the tectonic coal was developed. The roof and floor rock formations were also in a compressive state, which had a good sealing effect on the gas, and the gas was not easy to escape. Anticlines were formed by compressional tectonic stress fields, and normal faults were formed by tensional tectonic stress fields. There often developed a large number of tensional joints in areas near the axis of anticlines and normal faults. Tensile fractures were usually developed in the roof and floor strata, and gas could easily escape along the coal-rock fractures. Such an environment was not conducive to gas preservation. The gas content and pressure in the axis of the Guozhuang anticlinein were low, with the lowest gas content being only 4 m^3/t. The anticline axis and normal fault areas were unfavorable for gas preservation.

4.3. Influence of tectonic stress field on gas migration

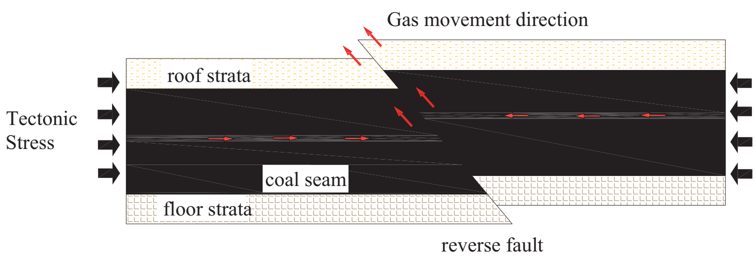
4.3.1. The affecting mechanism of tectonic stress field on gas migration

The paleo-tectonic stress field acted on the coal-measure strata, resulting in the development of faults and folds of different levels. Fracture planes in geological structures (as large as regional control faults, such as the Gou-Lifeng fault, and as small as fractures in coal seams) were good migration flow channels [16, 17]. The fracture surface was the low-stress area, and the gas in other high-stress areas migrated to the fracture surface [18–21]. Under the continuous action of the stress field, the fracture surfaces of different levels could be connected, and the gas continued to flow to the low-stress area along the connected flow channel. When the low-stress area was well sealed, gas accumulated in the low-stress area. The influence of the tectonic stress field on the seepage migration effect could be described from the following two aspects: (1) The structures such as faults and fissures of different scales generated by the tectonic stress field were the channels for gas seepage migration; (2) The paleo-tectonic stress drove the free gas to migrate from the high stress area to the low stress area.

The normal fault was formed by the tensional tectonic stress, the fault plane was in a state of tension, and extensional fractures were developed. The tectonic stress drove the gas to migrate from the upper and lower walls to the fault plane area, and massive gas finally escaped from the fault plane area (Fig. 8a). The fault plane of the reverse fault



(a)



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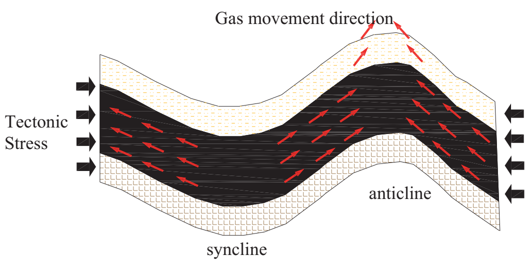

(c)

Fig. 8. Gas migration map in geological structure areas: a) Gas migration map in normal fault areas, b) Gas migration map in reverse fault area, c) Gas migration map in the fold region

had been in a compressive state for a long time. The permeability of the coal body was extremely low, which was not conducive to gas escape. However, the fault plane area was still a low-stress area, and a small amount of gas escaped from the fault plane. The gas content was usually larger in the foot wall of the reverse fault (Fig. 8b). For the syncline structure, the compressional shear stress was concentrated in the axial area, where the tectonic coal was developed. The gas flow channels such as fissures and fractures in the coal body were in a compressive state, and the coal body permeability decreased seriously. The tectonic stress drove the gas to migrate to the two wings with a lower stress; A large number of tension joints were often developed in the axial area of the anticline structure. Tectonic stress drove gas to migrate from the two wings of the anticline to the axis of the anticline, and massive gas was dissipated in the axis of the anticline (Fig. 8c).

4.3.2. Influence of tectonic stress field evolution on the occurrence of coal seam gas

In the Indosinian period, the vertical gas migration distance was long, and the escape time was short, thus resulting in good preservation of coalbed methane; The stress field was weak, the difference of coal seam pressure gradient in the horizontal direction was small, so the gas migration was generally weak. During this very period, the gas content increased more, but the gas occurrence in the mining area was relatively uniform.

In the early-mid Yanshan period, the metamorphic evolution of the coal seam was stagnant, and the amount of gas generated as well as the temperature and pressure of the coal seam was reduced. The strength of the tectonic stress was still small, and the development degree of cracks was larger. The gas migration in the horizontal direction was stronger than that in the Indosinian period, but the gas migration was still relatively weak on the whole. The tectonic stress field caused the gas saturation of coal seams to be lower, and the gas occurrence in the mining area was still relatively uniform during this period.

The tectonic stress field in the late Yanshan period exerted a strong effect on the studied mining area, and the main structure was basically formed during this period. Besides, the temperature of the coal reservoir increased sharply to about 155°, secondary hydrocarbon generation occurred, and the gas storage capacity of the coal seam increased dramatically. The stress in the horizontal direction drove massive gas to migrate to the lower stress area, and the horizontal migration effect was enhanced. The gas content and pressure were high in the axial area of the Likou and Lingwushan syncline, but small in the Baishishan and Guozhuang anticline. The stress in the wing region near the syncline axis was greater than that in the wing region near the anticline axis. Besides, the tectonic stress field drove the gas to migrate from the wing region near the syncline axis to the wing region near the anticline axis, and finally escaped through the anticline axis region. As a result, the gas occurrence decreased with the increase of the distance from the syncline axis, and increased with the increase of the distance from the anticline axis, as shown in Fig. 9.

In the Himalayan period, due to the decrease in temperature and pressure conditions, the evolution of coal quality was basically stagnant. The gas adsorption capacity of the coal reservoir was enhanced, and part of the free gas was converted into adsorbed gas, and the gas migration was strong in the horizontal direction. The structures were generally uplifted to a certain extent, and coal seams were outcropped in local areas of individual structures,

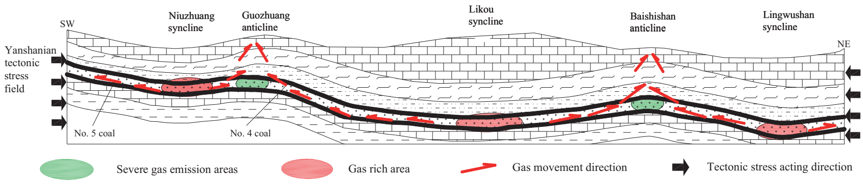

Fig. 9. Gas migration and enrichment map in the late Yanshanian period

thus resulting in coal seams partially located in the gas weathering zone. For example, in the Niuzhuang syncline, coal seam outcrops appeared in the edge region of the SW wing of the Niuzhuang syncline. As a result, the gas enriched in the syncline area was dissipated in large quantities, and the coal seam gas was greatly reduced; In general, the gas-enriched parts were still in the axial area of the controlling syncline except for the Niuzhuang syncline, and the low gas area was still in the axial area of the controlling anticline in the mining area. In this case, the tectonic stress in this period had a limited impact on the gas occurrence of the entire mining area, and the gas occurrence in local areas was mainly affected (Fig. 10).

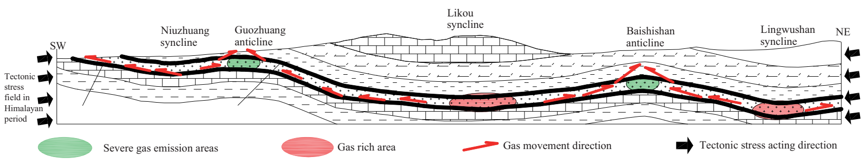

Fig. 10. Gas migration and enrichment map in the Himalayan period

5. Conclusions

The influence of the paleo-tectonic stress field on the gas occurrence in the Eastern Pingdingshan mining area could be divided into three key periods: (1) During the Indosinian and early-middle Yanshanian periods, the coal seam was buried deep, when, the temperature and pressure conditions were suitable for massive gas generation, especially the Indosinian period, which was the stage of massive gas generation and weak gas migration; (2) During the late Yanshan period, the metamorphic evolution rate of coal seams accelerated, secondary hydrocarbon generation occurred, and massive gas was generated. Meanwhile, a large number of geological structures were formed, and the gas migration was enhanced. Besides, the gas generation amount was much larger than the gas escape amount, making it still a period of massive gas generation in general; (3) During the Himalayan period, the coal measure stratum was in the uplift stage, and a large number of geological structures were developed in the stratum. This period was the stage of massive escape of coal seam gas.

Acknowledgements

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