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Coexistence and Development Model of Multi-Minerals Dominated by Multilayer Magma Intrusion: A Case Study of Huanghebei Coalfield in North China Basin

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ABSTRACT

The diversity of coal measure determines the occurrence state and spatial distribution complexity of mineral resources. Abundant resources have become an important part of geological resources and have attracted more and more attention. Coal measure and their overlying and underlying strata often coexist with various mineral resource types, and there is a certain relationship between their genesis and occurrence. In order to further enrich the theory of comprehensive exploration and coordinated development of multi-mineral resources, this paper takes the Huanghebei Coalfield as an example to systematically study the genesis mechanism and occurrence law of coal seam, coalbed methane, and coal-measure shale gas in Late Paleozoic and rich iron ore in Ordovician limestone underlie coal measure. The research is that: 1) The Late Paleozoic Carboniferous-Permian Marine facies, terrestrial facies, and transitional facies all developed in the coal-bearing area in the Huanghebei Coalfield, and the coal seams and mud shales developed well in Shanxi Formation and Taiyuan Formation. 2) Yanshanian magmatic intruded into Ordovician limestone. Contact metasomatism occurred between the ore-bearing hydrothermal fluids and the surrounding rocks, which led to skarn formation. The magnetite mineralization occurred in the metasomatism alteration process, and finally, the contact metasomatic iron deposit was formed; 3) Yanshanian magma intrusion has a significant impact on the generation of coal from coalbed methane and shale gas in the coal measures of Late Paleozoic. The magma carries a lot of heat by baking the coal seam and overlying shale, which is reflected explicitly in the increasing metamorphism degree of coal. Under the action of high temperature, the secondary gas of coal seam and coalbed methane increase sharply. The maturity and thermal evolution of organic matter in shale beds increased, and the shale gas entered a favorable range. The intrusion of magma greatly enhances the thermal evolution of organic matter in coal and shale, forming a variety of coals and promoting the generation and accumulation of coalbed methane and shale gas. At the same time, Mesozoic magmatic intrusion also controlled the formation of rich iron ores. According to the characteristics of mineral development and distribution in the study area, a multi-mineral development and distribution model of “coal - coalbed methane - shale gas - rich iron ore” coexists in the Huanghebei Coalfield, which is referred to as the “Huanghebei model”.

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1. Introduction

The diverse types of coal measure the mineral resource's complex occurrence and spatial distribution. Abundant resources have become an important part of geological resources and have attracted more and more attention (Li *et al*. [1]). There are not only many coal resources in coal measure, but also a lot of them are associated minerals with coal and other mineral resources in overlying and underlying strata of coal measure. With the increasing demand of the society for energy and the improvement of the utilization rate of resources, the research on these minerals is strengthened in the process of coal mining. The large sedimentary basins all over the world are basically the coexistence of a variety of energy and mineral resources. Although the forms are diverse and the degree of enrichment varies, their coexistence is not accidental, and there must be internal relations (Qin [2]). Efficient mining of mineral resources has always been a major problem human beings face, so it is crucial to explore the inner relationship of mineral resources and realize efficient mining from multiple perspectives.

Ning *et al*. [3] determined the types and occurrence strata of mineral resources from the aspects of sedimentary environment genetic properties and occurrence rules of the same basin. Cao *et al.* [4] divided coal measure mineral resources into three combined types: coal-energy minerals, coal-metal minerals, and coal-non-metallic minerals from the aspects of occurrence characteristics and genetic mechanism. For energy minerals that have been widely exploited, such as natural gas, coal and iron ore, and other non-renewable resources, the study of their mineralization mechanism and enrichment distribution rules is of great significance. The study laid a theoretical foundation for the simultaneous three-dimensional efficient and coordinated exploration and scientific prediction of multiple energy minerals in the basin (Liu *et al*. [5]). At the same time, it can also make up for the weak links in the research of multi-energy disciplines and comprehensive fields and enrich and develop the world energy geological theory (Qin [2]).

There are many mineral resources in the Carboniferous-Permian coal measures in the Huanghebei Coalfield, such as coal from coalbed methane shale gas (Wang *et al*. [6]). At the same time, rich iron ore is well developed in the underlying strata of coal measure; these energy minerals' coexistence in the coalfield is obvious. Previous studies have been carried out on the sedimentary environment characteristics of coal-bearing strata in Huanghebei Coalfield (Zhang [7]), which were based on the distribution of mine temperature, the occurrence of coalbed methane and its main controlling factors and conditions, potential evaluation of coal measure, hydrocarbon source rocks, and spatial distribution characteristics of intrusive magmatic rocks and their influence on coal seam coal quality. Few scholars put a variety of mineral resources in a system and study the causes of a variety of mineral resources system mechanisms. Based on the Yanshanian magmatic intrusion in Huanghebei Coalfield, this paper systematically studies the genetic mechanism and occurrence law of multi-mineral resources, effectively guiding the cooperative exploration and comprehensive exploration of related mineral resources from the fundamental mechanism.

2. The Geological Situation of the Huanghebei Coalfield

Huanghebei Coalfield is located in Dezhou City, Liaocheng City and Jinan City in Shandong Province, spanning Dong'e, Changqing, Qihe, Licheng, Gaotang, Yucheng, Jiyang and Zhangqiu (Figure **1**). The entire coalfield has 22 exploration areas, including Changqing, Zhaoguan, Qiuji, Pandian (Lv *et al*. [8]). The eastern part of the coalfield is the boundary between the Woniushan fault and Zhangqiu Coalfield, whereas the western part is the Liuji fault adjacent to the Yanggu-Chipping Coalfield. The southern part is the outcrop of the coal measure bottom, and the northern part is the Qiguang fault which is rich in coal resources (Li *et al*. [9]). Affected by the long-term uplift of the Luzhong Block uplift, the regional strata in the Huanghebei Coalfield generally show obvious gentle monoclinal structure. The strata strike N50˚E dip N40˚W and dip Angle 5~8˚ (Wang [10]; Zhang [11]). In the coalfield, secondary folds are developed, and a group of short-axial and axial NE anticlines are developed along the strata strike, all of which are small wavy undulations. The coalfield as a whole is a broad and gentle monocline in the NE strike of the strata, and there are broad and gentle folds in the NE.

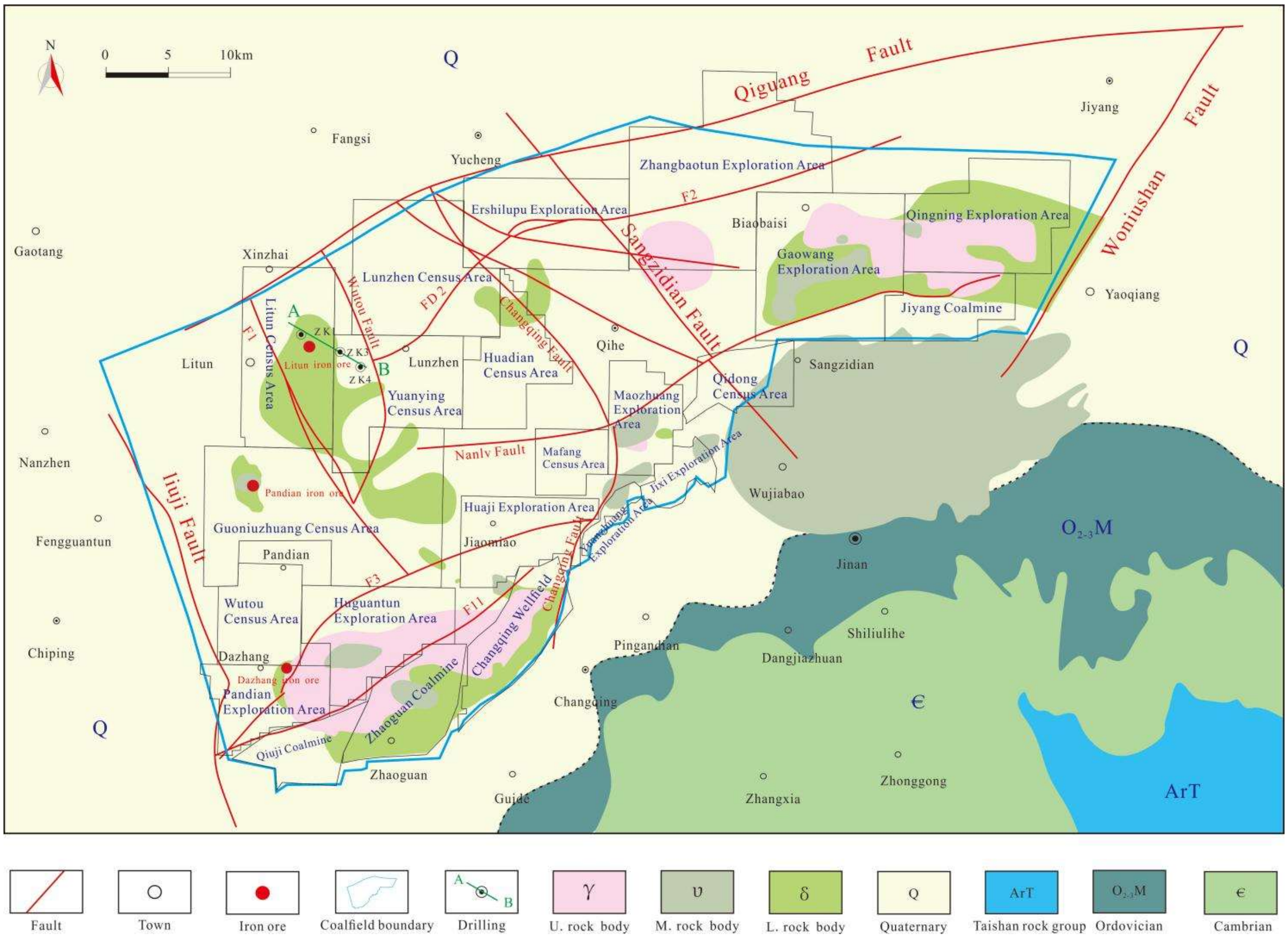

Figure 1: Distribution diagram of geological structure and rock mass in Huanghebei Coalfield.

The Huanghebei Coalfield is located in the North China stratigraphic area-Luxi stratigraphic division, and the coal-bearing rock series are mainly developed in the Carboniferous and Permian followed by The Benxi Formation Taiyuan Formation Shanxi Formation Lower Shihezi Formation and Upper Shihezi Formation from bottom to top (Sun *et al.* [12-14]). Only the Heishan Member and the Wanshan Member remain in the Huanghebei Coalfield due to denudation in the sedimentary process (Li *et al*. [9]). The Yanshanian movement has strong activity in this area and formed a structural pattern with fault depression and fault uplift as the main characteristics. In particular, the Late Yanshanian magmatic activity was the most intense during this period, mainly developed in the south and northeast of the coalfield. Three layers of magma mainly invade the stratum. The upper-level rock mass, the middle-level rock mass, and the lower-level rock mass are distributed to varying degrees in the coalfield. The upper-level rock mass is distributed in the Zhaoguan, Changqing, Qiuji exploration areas in the south of the coalfield, and Qingning Gaowang and Jiyang exploration areas in the east. The middle-level rock mass is mainly scattered in the Zhaoguan and Gaowang exploration areas of the coalfield, and the lower-level rock masses are distributed in Litun, Zhaoguan, Changqing, Gaowang, Qingning and Jiyang exploration areas. Magma intrusive rock masses are mainly intermediate-basic rocks, and the main rock type is gabbro (Zhu [15]). Acidic rocks are followed, most of which are diorite and granite, primarily distributed in the Carboniferous-Permian in the form of bedrock.

2. Sedimentary Environment and Coal Measure Development

2.1. Sedimentary Environment

The Late Paleozoic Carboniferous-Permian marine facies continental facies and transitional facies environments of the Huanghebei Coalfield all developed. Over time the surface sea basins gradually disappeared, and the seawater receded to the south. The difference between the north and south elevations was noticeable.

The epicontinental sea environment, transitional environment, and continental environment were roughly distributed from south to north on the plane (Chen *et al*. [16]). The main sedimentary systems developed in coal fields are the tidal flat sedimentary system barrier-lagoon, river-controlled shallow delta sedimentary system, and river-lake sedimentary system. Among them, the tidal flat deposition system and the barrier-lagoon deposition system are mainly developed in the Benxi Formation and the Taiyuan Formation, whereas the river-controlled shallow delta deposition system is developed in the Shanxi Formation. The river-lake composite deposition system is developed in the Lower and Upper Shihezi Formation, which is a continental deposit product of the environment (Zhou *et al.* [17]).

In the Benxi Period of the Late Carboniferous, with the sinking of the crust, seawater gradually invaded Shandong province, forming a vast epicontinental sea and developing a set of platform-lagoon facies-based sediments. As the water body became shallow, peat began to appear on the lagoon sediments. Coal accumulation and the formation of the unstable coal seam is a large epicontinental sea coal-accumulating basin (Han *et al*. [18]). The frequent advances and retreats of seawater in the Early Permian created favorable conditions for the accumulation of coal and shale. In the Taiyuan Period of the Early Permian, the Huanghebei Coalfield was mainly a lagoon-tidal flat sedimentary system with no barrier islands developed. Coal accumulation time was longer than that in the south with relatively stable coal seams; lagoon-tidal flats provide conditions for shale development. In the Shanxi Period of the Early Permian delta, plain-delta front deposits developed on the vast coastal plains lagoons and tidal flats. The lower part of the Shanxi Period was sea-land alternate sedimentation, and a large delta composite sedimentary system developed in the upper part. It is a set of transitional facies deposits from sea to land indicating that the overall sea level has dropped, the nature of sediments has begun to change, and land-based materials have begun to be deposited. The sedimentary environment from the land-sea alternate depositional environment transformed into a continental river-lake depositional environment. Until the Lower Shihezi Period, seawater exited North China, and river-lake facies deposition began to develop.

2.2. Coal seam Development and Distribution

The coal-bearing strata in the Huanghebei Coalfield are well developed, and they are distributed in both the Shanxi Formation and the Taiyuan Formation, among which 1-5 coal seams occur in Shanxi Formation and 6-14 coal seams in Taiyuan Formation. According to the distribution of coal seams in the seven exploration areas of Changqing, Zhaoguan, Qiuji, Jixi, Wutou, Yuanzhuang and Pandian, it can be seen that there are seven recoverable coal seams in the Huanghebei Coalfield (Table **1**). Among them, five coal seams can be mined in Changqing, Yuanzhuang and Jixi located in the lower member of Shanxi Formation with an average recoverable thickness of 0.81m. Coal seams 6, 7, and 8 are developed in the upper member of the Taiyuan Formation and are only partially recoverable with an average recoverable thickness between 0.95 and 1.07 m. Coal seam 10 is developed in the middle member of Taiyuan Formation with an average recoverable thickness of 0.87m which is not recoverable only in Jixi. Among all 7 recoverable coal seams, 11 and 13 are developed and stably recoverable in the whole coalfield, all located in the lower member of the coal-bearing stratum Taiyuan Formation with a thickness of more

Table 1: General situation of recoverable coal seams in Huanghebei Coalfield.

Coal Measures	Shanxi Formation	Taiyuan Formation					
	Lower Member	Upper Member			Middle Member	Lower Member	
Coal Seam	**5**	**6**	**7**	**8**	**10**	**11**	**13**
Recoverable situation	Changqing, Yuanzhuang Jixi recoverable	Jixi uncoverable	Wutou recoverable	Yuanzhuang recoverable	Jixi uncoverable	recoverable	recoverable
Recoverable thickness (m)	0~1.30	0~1.45	0~2.13	0.60~1.20	0~2.18	0~3.44	0.60~6.46
Average recoverable thickness (m)	0.81	1.04	1.07	0.95	0.87	1.45	2.76

than 1.45 m, and the average thickness of the coal seam is gradually increasing from top to bottom. Therefore, it can be seen that the distribution characteristics of the recoverable coal seams on the coal-bearing strata section are "thin upper and thicker underneath".

2.3. Development and Distribution of Mud Shale

The Late Paleozoic Carboniferous-Permian Shanxi Formation, Taiyuan Formation and Heishan Formation in the Huanghebei Coalfield developed thick shale strata. Thin mud shale is interbedded with coal seams, sandstone, and limestone. It is a complete set of continuously deposited gas reservoirs (Zhou *et al.* [17]). The mud shale sections of the Carboniferous-Permian Taiyuan Formation and Shanxi Formation are mainly distributed between 5 coals and 10 coals which are the target beds for shale gas research in this area. The thickness of the mud shale section of the target beds is about 52.8-97.1 m, with an average thickness of 84.8 m. The thickness of the shale layer in the coalfield has a certain regularity in the horizontal direction, and the thickness of the shale layer gradually decreases from north to south. The thickness of the Zhaoguan Coalmine and Changqing Wellfield in the south is mostly greater than 85 m, while the thickness of the Huaji exploration areas and Mafang census area in the southwest is smaller, mostly less than 60 m. The thickness of the gas-bearing zone in the Lunzhen census area, Litun census area in the northwest, and Gaowang exploration areas in the northeast is relatively large, mostly above 90 m (Figure **2**).

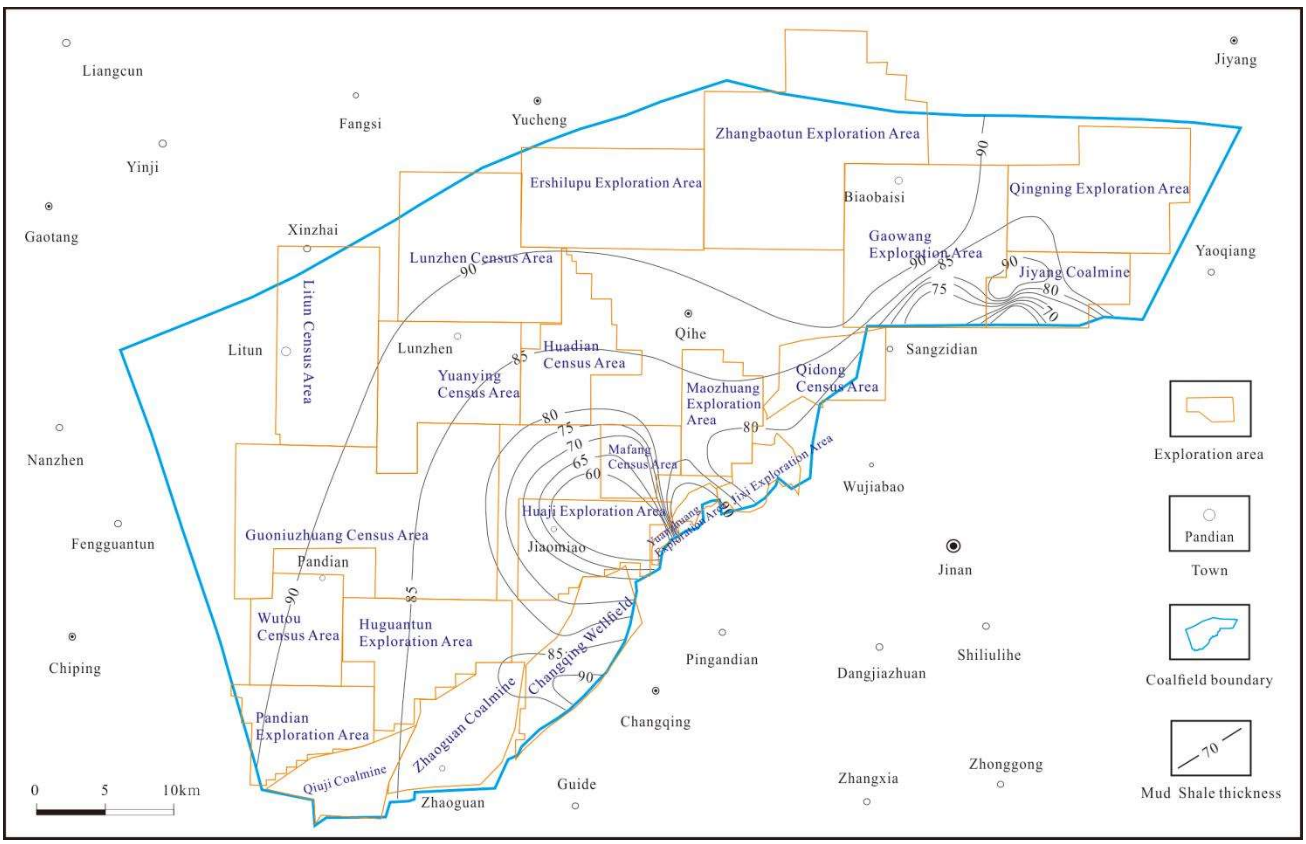

Figure 2: Contour map of the thickness of gas-bearing mud shale in Huanghebei Coalfield.

3. Magma Intrusion and Formation of Rich Iron Ore

3.1. Distribution Characteristics of Intrusive Magma Mass

The magmatic rocks in the Huanghebei Coalfield are widely distributed, and magmatic activities mainly occur in the Early Cretaceous in the Late Yanshanian mainly intrusive rocks, and magmatic rocks do not develop in other times (Figure **1**). The late Yanshanese intrusive rocks are widely distributed. They experienced different degrees of separation, crystallization magma mixing, and crustal contamination during their intrusions, which resulted in the formation of various intermediate-basic and intermediate-acid intrusive rocks in the shallow crust (Li *et al*. [19]; Xie *et al.* [20]). Magmatic intrusions are common in coal-bearing strata and coal seams, and magmatic intrusions are common in Shanxi Formation and Taiyuan Formation. There are mainly three layers developed; the upper and lower layers are acidic magmatic rocks, while the middle layer is medium-basic magmatic rocks. Magma is injected along the strata of Shanxi Formation and Taiyuan Formation or along weak sections, such as coal seams which are basically parallel to the strata of surrounding rock strata and are in the form of rock bed or rock cap (Liu and Guo [21]).

The acidic rock mass is distributed in the west of the coalfield, while the basic rock mass is distributed in the east of the coalfield. In the middle of the Changqing Wellfield, it overlapped, and the basic rock and the lower acidic rock seriously affected the coal seam in the coalfield (Liu [22]). The meso-basic rocks are mainly distributed in Jinan, and all belong to the Jinan sequence. The main rock types are diorites and gabbro, and a few are syenites and monzogranites. The sequence is distributed in Jinan and Qihe-Yucheng areas. The main body of the rock mass in the Jinan area is elliptically distributed near the east-west direction, while the main body of the rock mass in the Qihe-Yucheng area is distributed in the dumbbell-shaped direction. The basic magmatic rocks in the sequence are closely related to the mineralization of magnetite, and the rock mass edge Ordovician and Carboniferous-Permian contact zone are favorable parts for iron ore mineralization whose distribution not only controls the output of magnetite ore bodies but also may provide the source of iron ore mineralization materials.

3.2. Metallogenic Law of Rich Iron Ore

The formation of skarn-type iron ore is a complicated and long geological process (Chen and Zhang [23]). The subduction movement of the Pacific Plate to the Eurasian plate during the Yanshanian (Li and Suo *et al*. [24]) was the most important tectono-magmatic activity period in the eastern part of China, and a large number of Mesozoic intrusive rocks were formed whose lithology was diorite, gabbana, syenite, and a few granitoid and quartz diorite (Song *et al*. [25]). Skarn type iron ore in Huanghebei Coalfield is located to the west of Jinan-Jinling contact-metasomatic type iron ore metallogenic belt. This type of iron ore is closely related to the Majiagou Formation limestone and the Jinan gabbro sequence. Below the Quaternary overburden in the area are the Carboniferous-Permian and Ordovician strata. The carbonate rocks of the Majiagou Formation in Ordovician are the floor of coal-bearing strata and important ore-controlling surrounding rocks of contact-metasomatic iron ore. The Late Yanshanian Jinan intrusive rocks are the metallogenic parent rocks of contact metasomatic iron ore. The metallogenic epoch of contact metasomatic iron ore is generally close to the forming epoch of metallogenic geological bodies, so the forming epoch of metallogenic geological bodies can be used to represent the forming epoch of ore deposits. Zircon dating (LA-ICP-MS) data from the metallogenic geological bodies in this area indicate that (Wang *et al*. [26]; Gary [27]) the diagenetic ages of diorite in the metallogenic geological bodies of contact metasomatic iron ore in the Qihe-Yucheng area are (131.6±1.7) Ma and (130.0±2.3) Ma (Hao *et al*. [28]; Deng *et al*. [29-31]; Li *et al*. [32]; Xie *et al*. [20]).

The inference of geophysical data from the Huanghebei Coalfield and the exposure of a small number of drilling holes inferred the spatial distribution of the Litun rock mass, and skarn type rich iron ore was formed at the edge of the pluton. The intrusion is mainly located in the lower part of the Ordovician and Carboniferous. The uppermost intrusive layers are the Carboniferous-Permian Taiyuan and Shanxi Formations. It is now revealed that the iron-rich ore bodies are mainly located in the contact zone between the Carboniferous-Permian strata and the magmatic rocks. During the process of magma intrusion and placement, the rich ore hydrothermal fluid precipitates and undergoes hydrothermal metasomatism infiltration and filling and is enriched in structural spaces such as strata rock mass and the contact zone between the two to form iron ore bodies (Hao [28]). Preliminary analysis believes that the deep part of the rock mass is generally seen as a rock foundation and a certain scale of magmatic rock intruded into the Carboniferous-Permian strata in the form of a bed or dyke (Figure **3**).

3.3. Rich Iron Ore Mineralization Model

Skarn-type iron ore is generally characterized by complexity and multi-genesis. Different ore-forming environments and mechanisms mostly indicate that mineral sources and enrichment modes are different (Chen *et* *al*. [23]). The ore-forming period of skarn type iron ore (medium basic skarn type and medium acid skarn type) in Huanghebei Coalfield is the Late Yanshanian of Mesozoic (Zhou *et al.* [33]). During this period, magmatic activity was strong, and fault basins developed at the peak of lithosphere thinning in the North China Craton (Zhai [34]). Meanwhile, the output of bimodal magmatic rocks of the same period in eastern China also indicates that this period was in the background of extensional structure. In the background of tension, mantle-derived magma developed. There are also many gabbro and diabase dike intrusions in Qihe-Yucheng, which indicate the important contribution of mantle-derived magma. With the evolution of mantle-derived magma, meso-basic, ore-bearing magmatic rocks are formed in the process of magma rising. Ancient crustal materials may be added and intruded into the limestone strata of the Majiagou Formation of Ordovician. Ordovician Majiagou Group carbonate strata are widely distributed. The stratigraphic unit is the main research area of skarn type iron ore controlling surrounding rock (its lithology is limestone marble lithification limestone). Contact metasomatism occurs between ore-bearing hydrothermal fluids and surrounding rocks to form skarn, and magnetite mineralization occurs in the process of degenerated alteration, finally forming contact metasomatism type iron deposit.

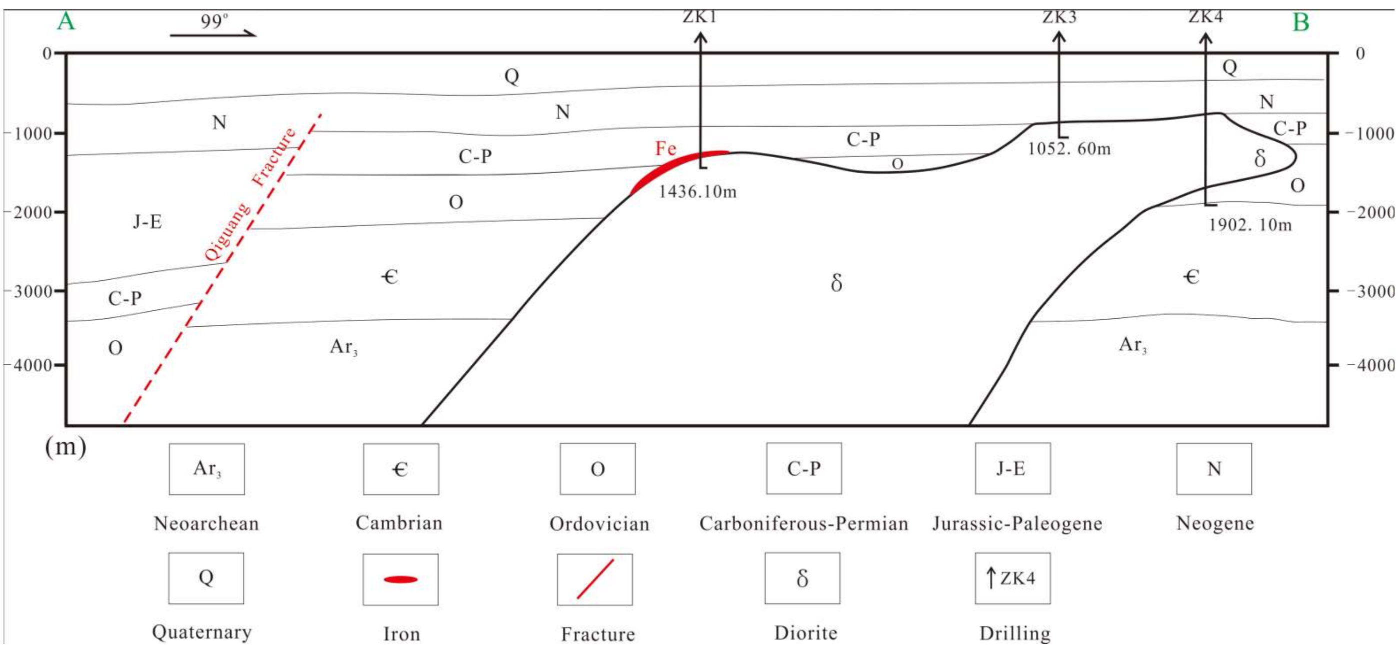

Figure 3: Near-east-west geological section of Litun rock mass exposed by borehole (Modified from Shen, 2020).

Qihe-Yucheng district contact metasomatic type iron ore geological prospecting model can be summarized as (1) The ore-forming geological body diorite may be the product of basic magmatic evolution differentiation diorite including the differentiation diorite porphyry and other diorite veins, and the basic rocks from gabbro diabase. The surrounding rock strata are mainly the Ordovician Majiagou Group and the Carboniferous-Permian Yumengou Group (Figure **4A**); (2) The metallogenic structural plane is mainly composed of contact zone structure, interlayer structure, fault zone structure, and karst cave structure, whereas the ore body is mainly produced in contact zone structure and weak interlayer zone (Figure **4B**). (3) The mineralization characteristics are manifested in the aspect of alteration zones from shallow to deep. It is a marble belt, outer skarn belt, ore body-inner skarn belt, altered diorite, diorite (Figure **4C**).

3.4. Distribution of Rich Iron Ore Resources

The results of iron ore exploration in the study area show that the occurrence form of the iron ore body is closely related to the structural form of a contact relationship between carbonate rock clastic rock stratum and diorite, among which the occurrence form of the contact zone is the most important way of iron ore occurrence in the area. The intrusive rocks in the iron ore-producing area mainly include Litun Pandian and Dazhang rock mass. The intrusive rocks are mainly intermediate-base rocks, and the lithology is diorite (Hao [35]). The location and shape of the ore body are obviously controlled by rock mass which indicates the close relationship between rock mass and rich iron ore mineralization. These rock masses control the output of rich iron ore bodies in the area and provide material sources for rich iron ore mineralization. The Litun and Pandian iron mines are buried deep, and the ore body is thicker, whereas the Dazhang iron mine is relatively shallow and thinner. The alteration and zonal characteristics of surrounding rock near the developed iron ore areas in Litun Pandian and Dazhang areas are obvious, and the color change of rock ore is obvious. The occurrence forms of iron ore are diverse. The iron ore grade is high; all are skarn type rich iron ore. The average grade of Dazhang iron ore is (TFe): 64.08% (MFe): 58.13%; The average grade of Litun iron ore is (TFe): 56.75% (MFe): 51.70%; The average grade of Pandian Iron ore is (TFe): 51.82% (MFe): 47.20 (Hao [28]).

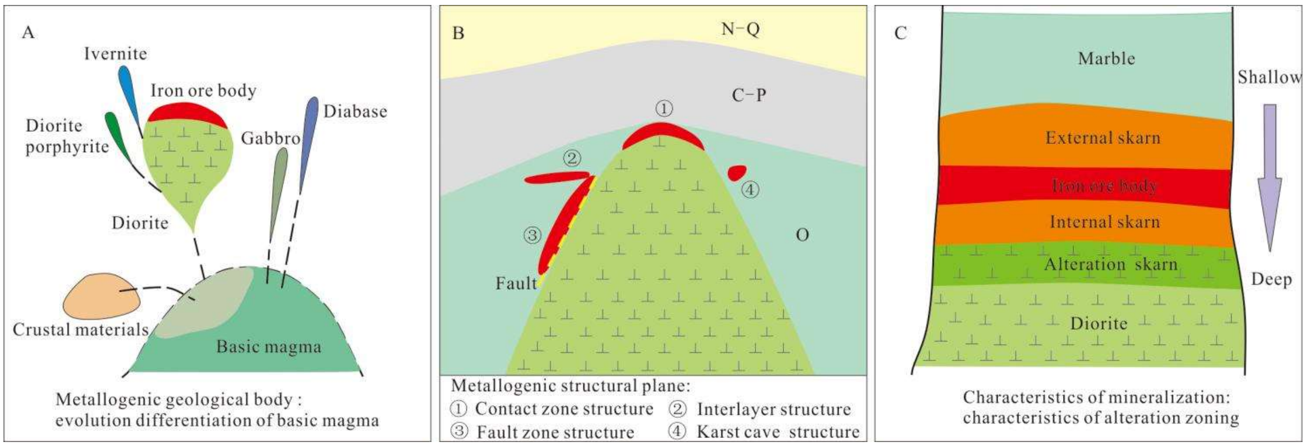

Figure 4: Schematic diagram of geological prospecting model for contact-metasomatic iron ore in Huanghebei Coalfield.

4. Metamorphism and Coal Measure Gas Generation

4.1. Metamorphism between Mud Shale and Coal Seam

The vitrinite reflectance (Ro %) is the most commonly used index to describe the maturity of post-Silurian sedimentary organic matter (Buchardt and Lewan [36]; Mukhopadhyay [37]; Taylor *et al*. [38]), and it increases with the increase in maturity (McCartney and Teichmüller [39]). The vitrinite reflectance data are often used to estimate the remaining oil and gas production potential, including conventional oil and gas (Hackley and Cardott [40]) as well as coal bed methane (Decc [41]) and shale gas (Smith *et al*. [42]. The coalification of organic matter in coal in geological history, that is, coal rank or thermal maturity, is usually measured by vitrinite reflectance (Smith *et al*. [42]). Based on the "Data Measurement Method of Vitrinite Reflectance of Sedimentary Rocks" (SY/T 5124-1995) (Li *et al*. [9] and according to the *People's Republic of China Coal Industry Standard Catalog* [43], the classification of coal grades is made. At the same time, according to the "Regulation of Shale Gas Resources/Reserves Estimation" (DZ/T 0254-2014), the degree of the thermal evolution of shale gas layers is classified.

In the Huanghebei Coalfield, due to the influence of tectonism and erosion factors, the buried depth of the coal seam is relatively small. However, because of its formation in the Carboniferous-Permian 250~350 million years ago, geological history suffered from long-term upper geothermal layer. The overburdened rock pressure caused by deep metamorphism has a relatively high overall metamorphic degree. Contact metamorphism occurs as a result of magma intrusion and direct contact with coal measure strata. Contact metamorphism plays a key role in the thermal maturation of organic matter (Bishop and Abbott [44]). Contact metamorphism is usually conduction-based contact metamorphism and occurs mainly in shallow areas.

The vitrinite reflectance and metamorphic stage of coal rock in the Huanghebei Coalfield are different in all exploration areas, and the vitrinite reflectance of coal rock varies between 0.613% and 6.351%. Due to the increase in coal ranks, the degree of metamorphism of 5 coal is relatively low in each exploration area belonging to the middle and high metamorphic stage, mainly including lean coal, fat coal, gas fat coal, and gas coal. Coal seams 7, 10, 11, and 13 are mostly affected by rock mass intrusions and are of medium to high metamorphism. They are mainly anthracite lean coal, lean coal, coking coal, fat coal, 1/3 coking coal, gas fat coal, and gas coal.

Among them, coal seams of 5, 7, 10, and 13 are mostly black glass luster gas coal and fat coal; 11 coal seam has a high degree of metamorphism, mainly brown soft bituminous coal and anthracite. Some 11 coal have been metamorphosed into light gray-gray black with slight metallic luster and relatively hard natural coke (Table **2**). In general, most coal seams close to rock mass turn into natural coke and form an irregular banded coal metamorphic zonal phenomenon from near to far, which is basically consistent with mass rock strike (Liu and Guo [7]). The change of coal class in the whole coalfield, especially the presence of natural coke, indicates that this period was affected by contact thermal metamorphism.

Table 2: Vitrinite reflectance (Ro, %) and coal types of coal rock in Huanghebei Coalfield.

Coal Seam		Changqing	Zhaoguan	Huguantun	Qiuji	Pandian	Maozhuang	Gaowang	Jiyang
5	Ro	0.798~2.259 1.528(2)						0.780~0.840 0.810(2)	0.82~1.01 0.915(2)
	coal types	meagre coal, fat coal, gas fat coal, gas coal, non-caking coal							
7	Ro	0.747~0.964 0.824(4)	1.774~3.089 2.264(6)	0.720~1.950 1.356(5)	0.660~0.900 0.737(6)	0.730~1.510 0.974(10)		0.830~0.910 0.865(4)	
	coal types	anthracite, meagre coal, coking coal, 1/3 coking coal, gas coal, 1/2 medium-caking coal, weakly caking coal, non-caking coal							
10	Ro	0.737~0.971 0.808(4)	0.775~4.389 2.339(9)	0.720~3.570 1.422(5)	0.613~4.520 1.617(9)	0.730~1.530 0.866(7)	1.23	0.90	0.85~1.74 1.138(4)
	coal types	anthracite, meagre coal, lean coal, coking coal, fat coal, 1/3 coking coal, gas fat coal, gas coal, 1/2 medium caking coal, weakly caking coal, non-caking coal							
11	Ro	0.722~6.351 3.203(20)	0.742~5.552 3.022(13)		0.620~4.237 1.179(12)	0.740~3.950 1.264(16)	1.000~1.250 1.130(2)	0.970~2.390 1.660(3)	0.91~1.70 1.305(2)
	coal types	natural coke, anthracite, meagre coal, lean coal, coking coal, fat coal, 1/3 coking coal, gas fat coal, gas coal, weakly caking coal							
13	Ro	0.701~2.378 0.924(11)	0.761~4.121 2.202(15)	0.710~4.930 2.488(12)	0.620~1.050 0.738(30)	0.730~3.31 1.217(34)	1.410~1.450 1.430(2)	0.930~5.870 2.456(7)	0.88~1.74 1.227(3)
	coal types	anthracite, meagre coal, meagre lean coal, coking coal, fat coal, 1/3 coking coal, gas fat coal, gas coal, 1/2 medium caking coal, weakly caking coal, non-caking coal							

According to the magma distribution in the Huanghebei Coalfield, the superposition of the three-layer magma intrusions is located in the Zhaoguan, Changqing and Gaowang regions. The thickness area and intrusions of magmatic rock in Zhaoguan Coalmine are all larger than the adjacent area, and there are basically three layers of intrusions in the coal measure strata of Shanxi Formation and Taiyuan Formation with strong activities. Intermediate-acid magma invades these sedimentary strata transforming coal seams into natural coke or high-rank coal (Lv *et al*. [7]). The upper-level magma intrudes into the 3rd and 4th coal seams in the lower member of Shanxi Formation, the middle-level magma mainly intrudes into the 5-9 coal seams in the middle and upper member of Taiyuan Formation, and the lower-level magma intrudes into the 11 and 13 coal seams in the lower member of Taiyuan Formation. Due to the different intensity and range of magmatic rock intrusion into each coal seam, its influence degree on coal seam coal quality and coal metamorphism is also different. From the distribution of coal types in Zhaoguan and Changqing Coalmine 5, 7, and 10 coals, it can be seen that coals at the high metamorphic stage are mainly distributed in the middle and deep part of the mine, which is basically consistent with the distribution range of three-layers magmatic rocks. It can be seen from the distribution of coal types in Zhaoguan Coalmine and Changqing Wellfield in the 11 and 13 coal seams that the lower group coal magmatic rock intrusion site is the center and the transition from natural coke to gas fertilizer coal in the coal metamorphism stage is obvious and the magmatic rock intrusion range is basically consistent with the change of coal metamorphism degree (Figure **5**).

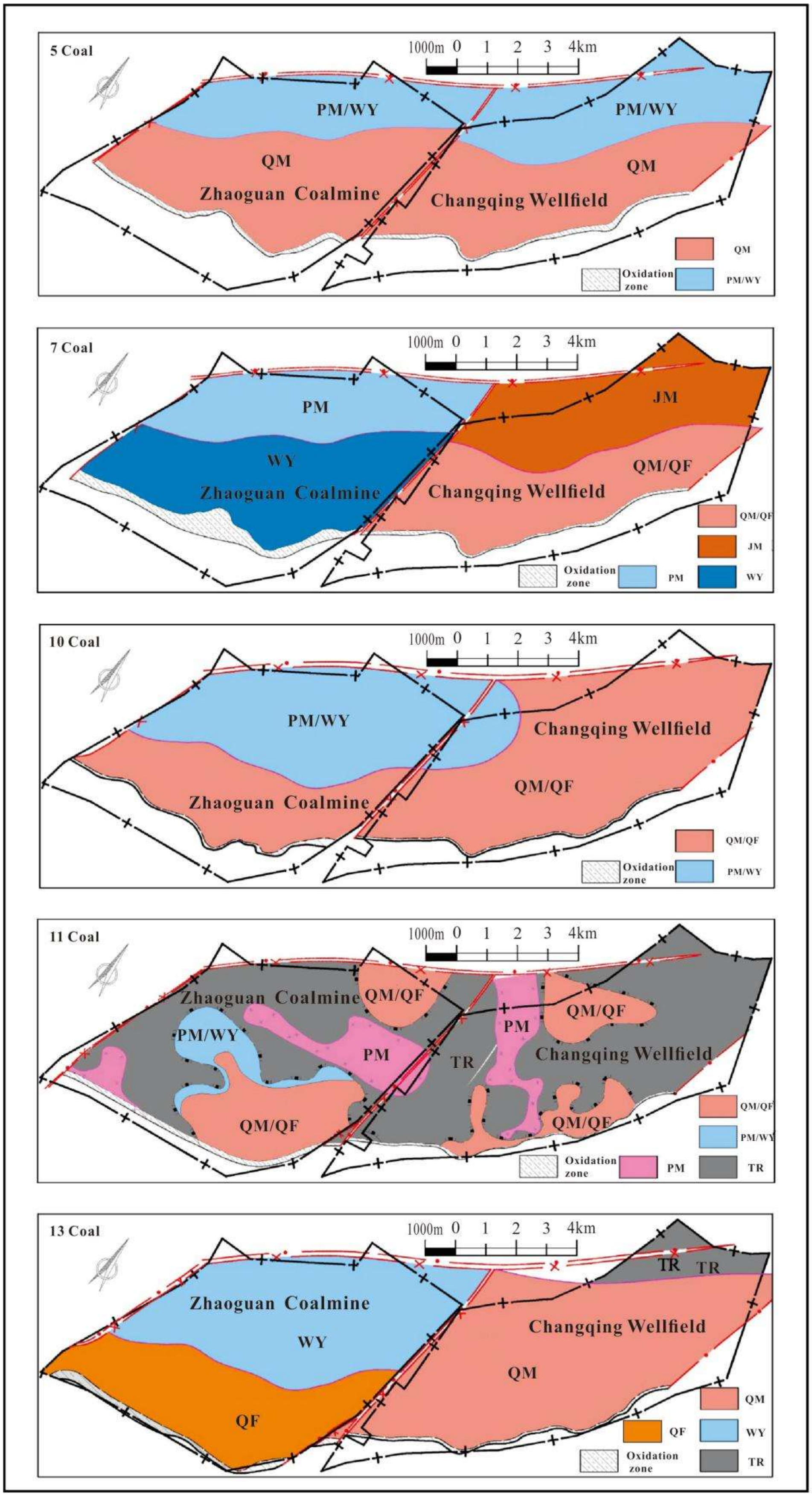

Figure 5: Schematic diagram of coal type distribution in coal seam in Zhaoguan Coalmine and Changqing Wellfield.

The intrusion of the middle-level magma destroys the structure of the carbonaceous mud shale, which shows that the maturity of organic matter in the mud shale layer increases, and the degree of thermal evolution increases (Figure **6**). The vitrinite reflectance of dark mudstone in Huanghebei Coalfield ranges from 0.72% to 1.25%, and its thermal evolution is mature, which is favorable for shale gas (Bai *et al*. [45]; Zhao *et al*. [46]. The maturity of organic matter in Qiuji and Zhaoguan Coalmines in the south of the working area is relatively low, and the vitrinite reflectance is mostly between 0.7% and 0.9%. The maturity of Zhangbaotun and Ershilipu exploration areas in the north is relatively high, and the vitrinite reflectance is between 1.0% and 1.2%, while the vitrinite reflectance of Jixi Jiyang and Qidong exploration areas is above 1.2%.

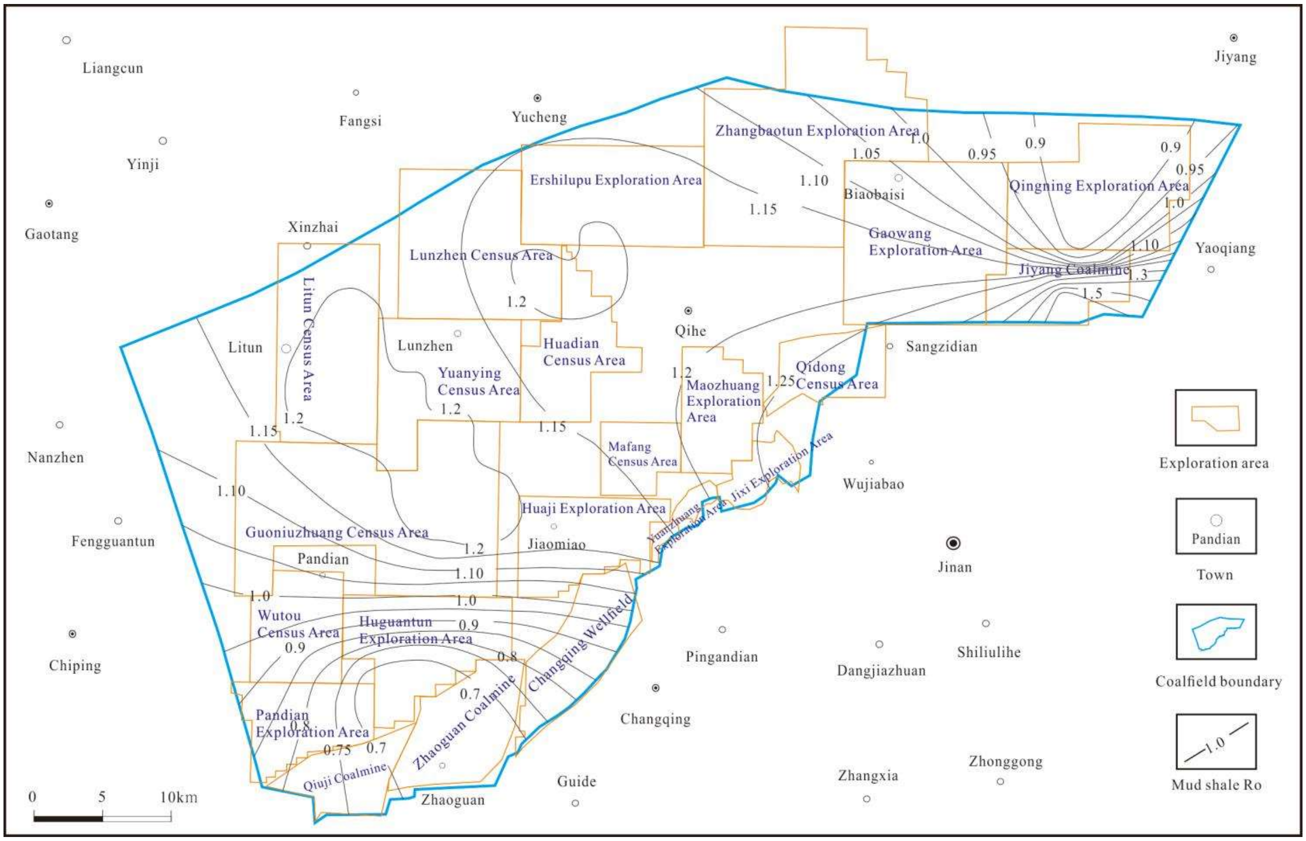

Figure 6: Vitrinite reflectance (%, Ro) of Carboniferous-Permian mud shale in Huanghebei Coalfield.

4.2. Coalbed Methane Enrichment and Resource Distribution

Coalbed methane is an important unconventional energy source. It contains CH_4 as the main component in coal seams, mainly adsorbed on the particle surface of coal matrix and partially free in coal pores or dissolved in coal seam water (Zhang [47]; Peng [48]). The strong magmatic activity in Yanshanian made the coal measure strata in the whole coalfield subject to the influence of magma intrusion, which played a decisive role in the general increase of the temperature in the coalfield and made the coal seam produce strong thermal metamorphism into gas. A large number of coalbed methane resources have been discovered in the Huanghebei Coalfield, and much research has been done in this field (Fan *et al*. [49]; Lv *et al*. [7]). Coal rank is an important parameter that affects thermal gas generation, and high coal rank areas are often regarded as better gas generation targets (Sang *et al*. [50]). When magma intrudes into coal-bearing series or coal seams under the influence of thermal metamorphism and contact metamorphism of magma, the degree of metamorphism of coal increases, and under the action of high temperature, the coal seam produces secondary gas. In the magmatic thermal metamorphic region, due to the rapid cooling of coal measures in the later stage, the coal reservoir layer secondary cleats developed and the permeability is improved, and the thermal evolution degree of the coal seam increases, which is conducive to the formation of a coalbed methane enrichment and high-yield area. There is considerable resource potential of coalbed methane resources in the Huanghebei Coalfield, and relatively favorable areas of coalbed methane resources are located in the south of the coalfield, such as Zhaoguan, Changqing, Qiuji and Jiyang Coalmine (Figure **7**). The prospective area is located in the north of the coalfield, mainly including Maozhuang Pandian and Gaowang exploration areas. It can be seen that the best coalbed methane mining area are Zhaoguan and Changqing regions.

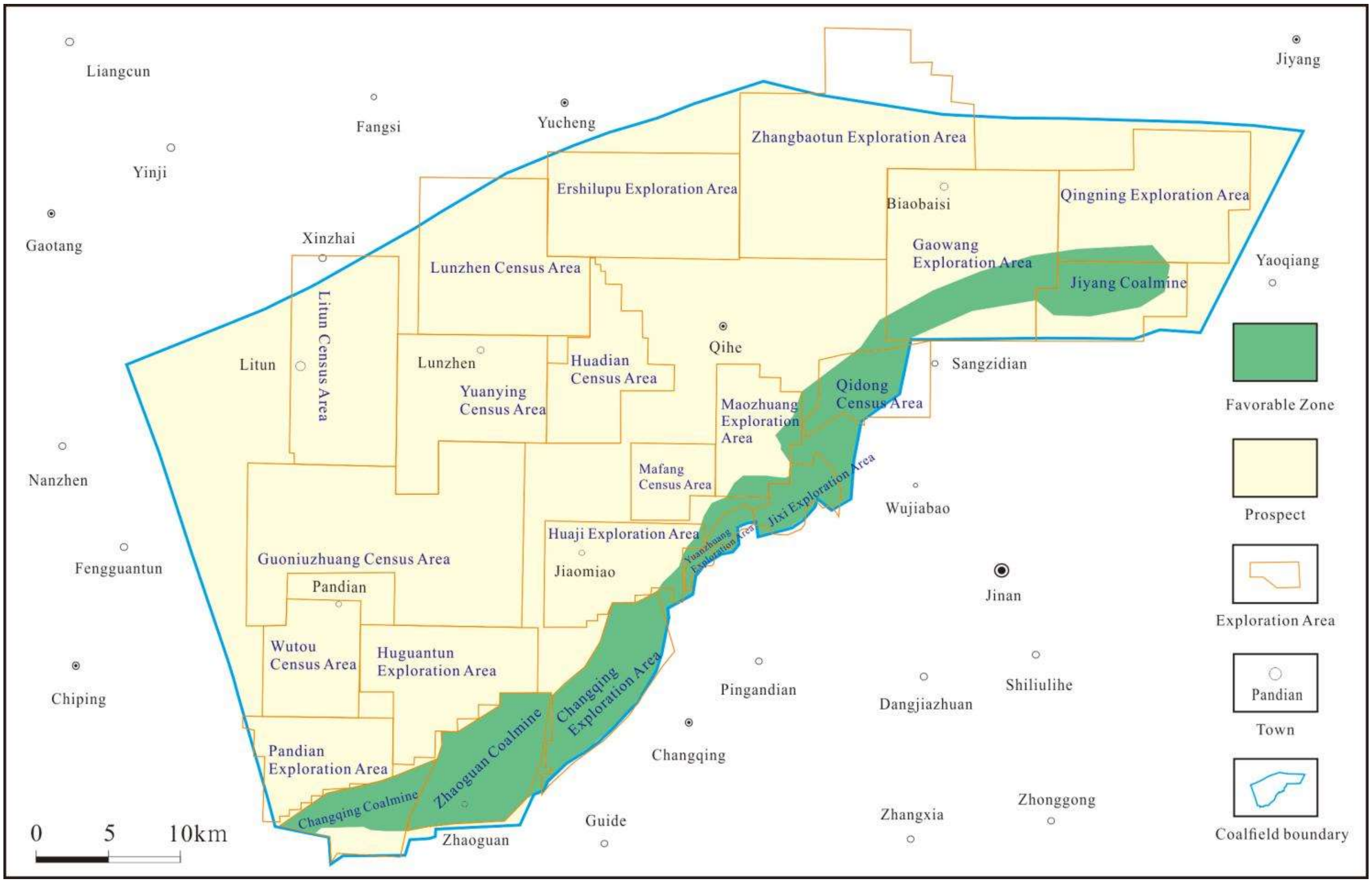

Figure 7: Distribution of coalbed methane resources in the Huanghebei Coalfield (Modified from Meng, 2011).

4.3. Shale Gas Enrichment and Resource Distribution

The intrusion of magmatic rock not only affects the characteristics of coal types but also plays an important role in the formation and development of shale gas in this area. On the one hand, magma intrusion has a destructive effect on the carbonaceous shale formation; on the other hand, magmatic rocks can promote the increase of maturity of organic matter in mud shale (Othman *et al*. [51]; Wan [52]). The vitrinite reflectance of mud shale in the western and southeastern magmatic rocks development zone has an obvious increasing trend which is beneficial to the secondary hydrocarbon generation of source rocks. Magma intrudes into the stratum, and under the influence of magma thermal metamorphism and contact metamorphism, the hydrocarbon generation capacity of the gas-bearing shale stratum increases. The hydrocarbon source rocks accelerate into the gas window, and the gas volume increases, the adsorption capacity of mudstone increases, and the adsorption gas content increases. Huanghebei Coalfield Carboniferous-Permian Shanxi and Taiyuan Formations shale gas reservoir presents "Mud shale thickness accumulates thick rich in organic matter medium in hydrocarbon generation ability mainly type II kerogen medium maturity low porosity and low permeability"(Zhou *et al*. [17]). One shale gas favorable area is delineated by the Huanghebei Coalfield, which is located in the central part of the coalfield. It is distributed along the Pandian-Qihe-Biaobaisi in a north-east trending belt (Figure **8**), mainly concentrated in the Wutou census area and Pandian exploration area, and Maozhuang exploration area, among others. The two prospects are located in the northwest and east of the Huanghebei Coalfield, such as the Jiyang Coalmine Litun census area and Lunzhen census area.

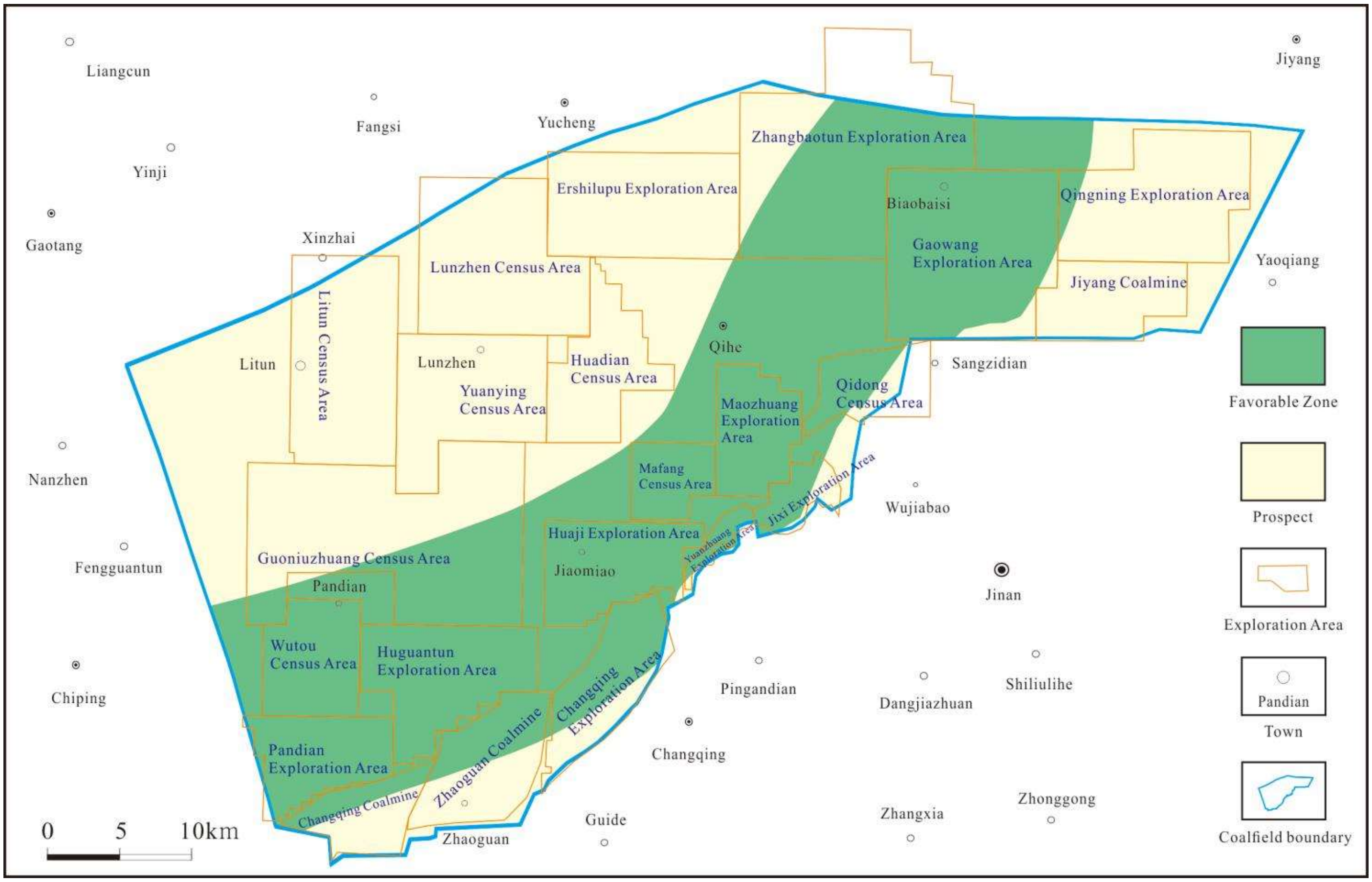

Figure 8: Distribution of Shale gas resources in Huanghebei Coalfield.

5. Genesis Model of Coal Measures Minerals and Rich Iron Ore

The Carboniferous-Permian coal measures in the Huanghebei Coalfield are rich in energy minerals such as coal, coalbed methane, and coal measure shale gas. At the same time, there are also well-developed metasomatic rich iron deposits underling the coal measures. The formation of rich iron ore is mainly controlled by Mesozoic magma intrusion and has no genetic relationship with Carboniferous-Permian coal seams and shale; however, the intrusion of magma greatly increases the degree of the thermal evolution of organic matter in coal and shale. Various coal types have been promoted to promote the generation and accumulation of coalbed methane and shale gas; therefore, there is a certain connection between coal measure minerals and rich iron ore in the enrichment process.

The entire Huanghebei Coalfield constitutes a multi-energy mineral enrichment system in which the minerals are mainly coal, coalbed methane, shale gas, and rich iron ore (Figure **9**). Their enrichment patterns can be summarized as follows: In the Late Paleozoic Carboniferous-Permian Marine continental and transitional facies environment, organic matter accumulation in hydrocarbon source rocks and coal seams to form various reservoirs. The intrusion of Mesozoic magma into the limestone strata of the Majiagou Formation in the Paleozoic Ordovician is also an important period for the metamorphism of the overlying coal seam and the thermal evolution of the hydrocarbon source rocks to some extent. Magmatic intrusion affects iron ore formation to a certain extent, and iron ore distribution areas such as Litun Dazhang and Pandian have high content. This is the result of contact metasomatism between hydrothermal and surrounding rocks, which leads to the formation of skarn and magnetite mineralization occurred in the process of degenerated alteration, finally forming contact metasomatism type iron deposit. The iron ore deposits development sites can be divided into outer skarn zone, iron ore zone, inner skarn zone, altered diorite zone, and diorite zone from top to bottom. A large amount of heat carried by magma constantly bakes the overlying coal seams and mud shale leading to the occurrence of coal type zonation with magma intrusion as the core. The closer to the intrusion, the higher the degree of metamorphism of coal and even the natural coke (Lv *et al*. [7]). The gas content porosity/pore size, thermal evolution degree of organic matter, and hydrocarbon generation capacity of shale are also increased. Magmatic activity accelerates the thermal evolution of coal measure organic matter, increases the gas production capacity of source rock, and makes the content of coalbed gas and shale gas near the rock mass higher than that near the rock mass contact position and far from the rock mass position. Based on the characteristics of mineral development and distribution in the study area, a multi-mineral development and distribution model of "coal-coalbed methane-shale gas-rich iron ore" coexists in the Huanghebei Coalfield, which is referred to as the "Huanghebei model".

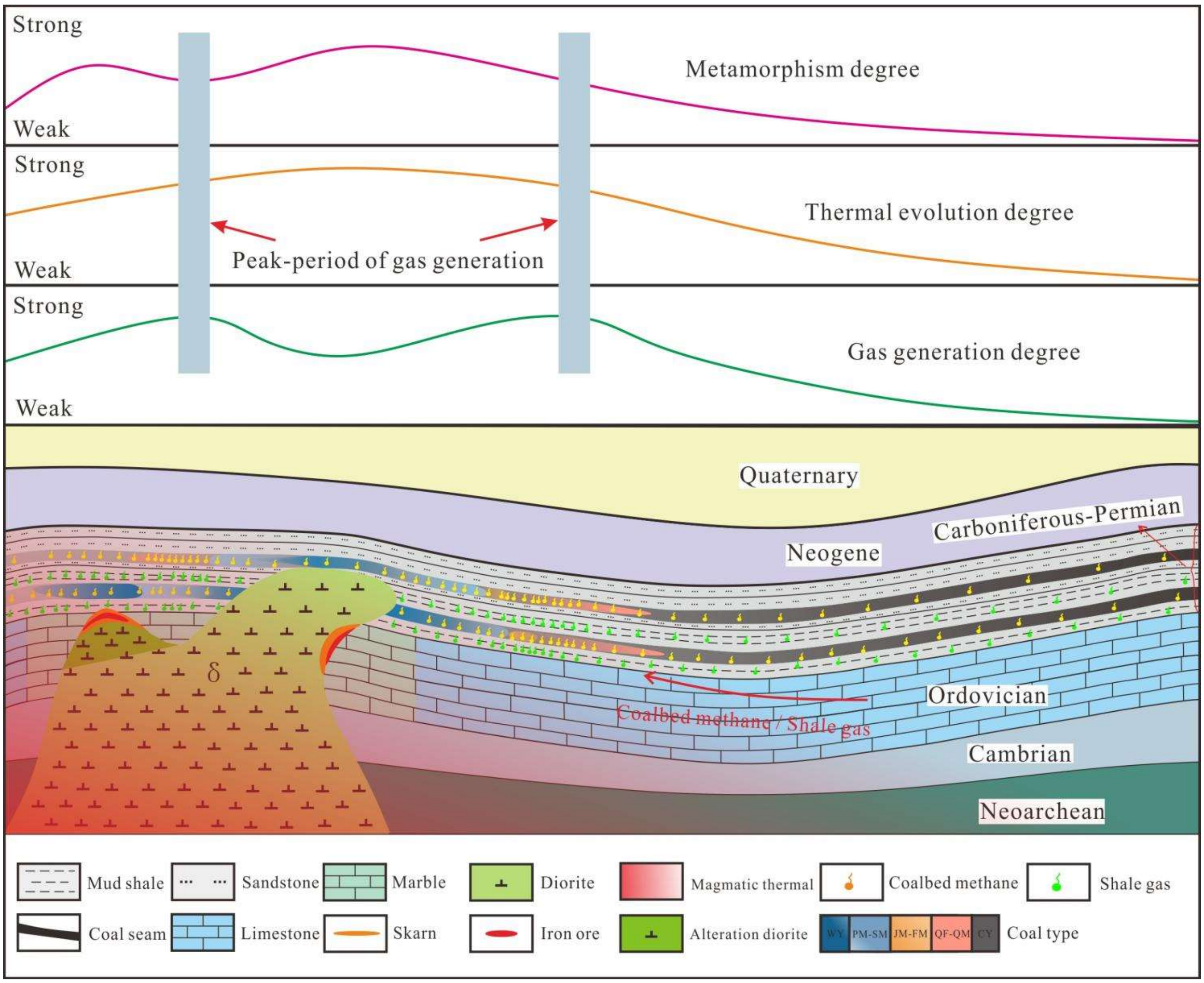

Figure 9: Multi-mineral enrichment model of Huanghebei Coalfield (Huanghebei model).

6. Conclusions

There are many mineral resources in the Carboniferous-Permian coal measures in the Huanghebei Coalfield, such as coal, coalbed methane, and shale gas. At the same time, rich iron ore is well developed in the underlying strata of coal measure. These energy minerals' coexistence in the coalfield is apparent.

1. The Late Paleozoic Carboniferous-Permian Marine facies terrestrial facies and transitional facies all developed in the coal-bearing area in the Huanghebei Coalfield, and the coal seams and mud shales developed well in Shanxi Formation and Taiyuan Formation.

2. Yanshanian magma intruded into Ordovician limestone. Contact metasomatism occurred between ore-bearing hydrothermal fluids and surrounding rocks to form skarn, and magnetite mineralization occurred in the process of degenerated alteration, finally forming contact metasomatism type iron deposit;

3. Yanshanian magma intrusion significantly impacts the generation of coal coalbed methane and shale gas in the coal measures of the Late Paleozoic. The magma carries much heat, baking the coal seam and shale overlying, which is reflected explicitly in the increasing metamorphism degree of coal. Under the action of high temperature, the secondary gas of coal seam and coalbed methane increase sharply. The maturity and thermal evolution of organic matter in shale beds increased, and the shale gas entered a favorable range.

4. The intrusion of magma greatly enhances the thermal evolution of organic matter in coal and shale, forming a variety of coals and promoting the generation and accumulation of coalbed methane and shale gas. At the same time, Mesozoic magmatic intrusion also controlled the formation of rich iron ores. According to the characteristics of mineral development and distribution in the study area, a multi-mineral development and distribution model of "coal - coalbed methane - shale gas - rich iron ore" coexists in the Huanghebei Coalfield, which is referred to as the "Huanghebei model".

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