The Enrichment Conditions and Resource Potential of Marine-Continental Transitional Coal-Measure Shale Gas: A Case Study of the Permo-Carboniferous Systerm in the Huanghebei Coalfield of North China

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Abstract: Coal-measure shale gas is considered to be an important unconventional oil and gas resource in coal measures. At the present time, coal-measure shale gas has not been well studied. However, in recent years, such potential resources have received increasing attention. In this research investigation, the coal measures of the Permo-Carboniferous Period in North China's Huanghebei Coalfield were taken as the research object in order to evaluate the enrichment conditions and resource potential of the coal-measure shale gas. The results were as follows: 1) A variety of sedimentary environments were developed during the Late Paleozoic Era in the Huanghebei Coalfield region. Lagoon sediment had mainly developed in the Taiyuan Formation, which was conducive to the high-intensity development of shale. In addition, interdistributary bay-floodplain sediment had developed in the Shanxi Formation, which was also favorable to the development of shale; 2) The average value of the total organic carbon (TOC) in the shale of the Taiyuan and Shanxi Formations in the study area was found to be more than 2%. The main type of organic matter was Type II kerogen, followed by Type III kerogen. Furthermore, the thermal evolution degree of the organic matter was considered to be in the mature stage, which indicated a good hydrocarbon generation potential; 3) The gas bearing intervals of the shale in the Taiyuan and Shanxi Formations in the study area were mainly variegated shale, mudstone, carbonaceous shale, and silty mudstone (shale), which belong to the categories of ultra-low permeability and low porosity reservoirs; 4) The average gas content of mud shale in the Taiyuan and Shanxi Formations ranges between 0.645 and 3.34 m^3/t. The shale tends to have large burial depths and well-developed caprock, which is conducive to the preservation of shale gas; 5) This study's comprehensive analysis results showed that the mud shale in the Taiyuan and Shanxi Formations have good hydrocarbon generation potential. A favorable area was delineated in the middle of the Huanghebei Coalfield, and a NE-trending belt distribution was evident along the Pandian-Qihe-Biaobaisi. In summary, the three delineated perspective areas were determined to be the Dulangkou-Zhaoguan prospect area; Yuchengnan prospect area; and Sangzidian prospect area, respectively.

Keywords: Coal-measure shale gas; Sedimentary environment; Physical characteristics of the reservoirs; Shale gas enrichment; Resource potential; Huanghebei Coalfield.

1. INTRODUCTION

As an unconventional oil and gas resource, shale gas mainly occurs in dark organic-rich shale and tends to be sandwiched between thin layers of siltstone and argillaceous siltstone in both the adsorption state and free state. This is referred to as a self-generation and self-reservoir "in-situ" aggregation mode (Zhang *et al*. [1,2]). In recent years, as an important energy mineral and strategic resource, shale gas has attracted major attention in China. The breakthroughs achieved in shale gas exploration, as well as the recent developments in related technology, have had significant impacts on the international natural gas market and global energy patterns.

Major progress has been made in the field of shale gas exploration in China, and the exploration efforts have been gradually increasing in recent years. China's marine shale gas research resources are mainly distributed in the shale of the North China and Tarim platforms, southern China, and so on, and in-depth research investigations are currently being carried out in those areas (Wang *et al*. [3]; Zou *et al*. [4]; Yang *et al*. [5]). China's continental shale gas resources are mainly distributed in the thick lacustrine organic-rich shale of the Meso-Cenozoic Era depression basins, such as the Songliao Basin, Ordos Basin, Sichuan Basin, and so on, as well as such Cenozoic Era rift basins as the Bohai Bay Basin. Generally speaking, fruitful research results have been obtained (Zhang *et al*. [2]; Zou *et al.* [4]; Wang *et al*. [6]; Tang *et al*. [7]).

China's coal-measure shale of marine-continental transitional facies and continental facies are widely distributed in North China, southern China, and the Tarim Basin region (Zhang *et al*. [2]; Li *et al*. [8]; Wang *et al*. [3]; Zou *et al*. [4]; Wang *et al*. [9]). It has been found

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that the organic-rich shale of the Upper Palaeozoic Era marine-continental alternating facies have large single-layer thicknesses in the Upper Yangtze and Yunnan-Guizhou-Guangxi regions of China, and display the conditions for shale gas exploration and development. In contrast, the marine-continental alternating facies and continental facies coal-measure organic-rich shale in the majority of the regions have smaller single-layer thicknesses, which are not conducive to the single-layer independent development of shale gas (Li *et al*. [8]). This study found that although coal measures are widely distributed in China, the research in this field is relatively weak due to the limitations of the identified occurrences of coal-measure shale gas resources. Therefore, it can be said that the comprehensive exploration and collaborative development of coal-measure gas is a new trend (Li *et al*. [10]) and coal shale gas is an important part of it. Consequently, further in-depth research is urgently required at the present time. Based on the aforementioned challenges, this study selected the coal-measure shale in the Huanghebei Coalfield as the research object in order to discuss the formation, occurrence, enrichment, resource potential, and favorable areas for the prediction of coal-measure shale gas. The goals of this study are to provide certain theoretical guidance for the comprehensive exploration and collaborative development of coal-measure gas resources.

2. REGIONAL GEOLOGY

2.1. Geological Structure of the Study Area

The Huanghebei Coalfield is located in the northwest margin of the Luzhong anteklise in the Yellow River Basin of northwestern Shandong Province, and also in the southwestern section of the Jiyang Depression. Therefore, it is considered to be located in a transition zone of the anteklise. The coal-bearing stratum is a gentle monocline structure with a formation strike of N50°E, dip direction of N40°W, and a dip angle of 5 to 8° (Wang [11] and Zhang [12]). However, even though the dip angle of the stratum is gentle, secondary folds have developed in the coalfield region, and a group of short axis-like anticlines and skews with the NE-trending axis can be found along the formation strike, all of which being small-scaled undulations. In addition, faults are well developed in the coalfield and are characterized by moderate structural complexity. These faults are generally located in the northern section of the Dong'e-Jinan-Linqu Monoclinic Depression, with Paleozoic Era strata uplifts and the Taishan Fault convex to the south. The northern boundary is composed of the Liaokao-Qiguang Fractures, and the north fault wall is comprised of the blocky Jiyang Depression in the North China Fault Block. The Yanggu-Chiping Coalfield is located in the west section of the Huanghebei Coalfield. Meanwhile, the Jidong Coalfield is located in the eastern section, as detailed in Fig. (**1**).

2.2. Stratigraphic Distribution Patterns

The Huanghebei formation is a part of the Luxi formation, the Permo-Carboniferous System coal-measures are located above the Middle Ordovician Series limestone layers in the study area which was reported by Zhang [12]. The Permo-Carboniferous System coal-measures are covered by overlying strata, which has resulted in a good coalfield formation. It has been confirmed that the Silurian System, Devonian System, and Lower Carboniferous Series are absent in the area. The coal measures generally display a monoclinic pattern of gentle dips to the north, with developed faults, folds, and magmatic rock deposits, and moderate structural complexity was reported by Zhao [13].

The Permo-Carboniferous System is mainly developed in the Benxi Formation, Taiyuan Formation, Shanxi Formation, and Shihezi Formation.

It has been observed that purple and gray mudstone, siltstone, sandstone, and limestone bearing strata are developed in the Upper Carboniferous Series Benxi Formation (C_{2b}), and Shanxi type iron ore horizons and G-bed bauxite were found to be developed at the bottom, having a disconformity contact with the underlying formation. The Upper Carboniferous Series-Lower Permian Series Taiyuan Formation (P_1C_{2t}) included the development of gray-dark gray mudstone, clay rock, and sandstone interbedding. The majority of the sandstone was observed to be silty and fine-grained, in which the feldspathic sandstone was cemented with clay. The Lower Permian Series Shanxi Formation (P_{1S}) was characterized by gray and gray-white, medium to fine grained arkose and siltstone along with mudstone. The Lower Shihezi Formation (P_{2X}) of the Middle Permian Series was determined to be mainly composed of gray-white feldspathic quartz sandstone and gray mudstone, with purple clay rock appearing in the upper part, which was occasionally mixed with purple quartzite sand and gravel. The upper part of the Upper Shihezi Formation (P_{3SS}) of the Upper Permian Series was observed to be composed of purple-red, gray-green, and other variegated clay rock and mudstone, intercalated with grayish-white medium sandstone. The middle section was determined to be

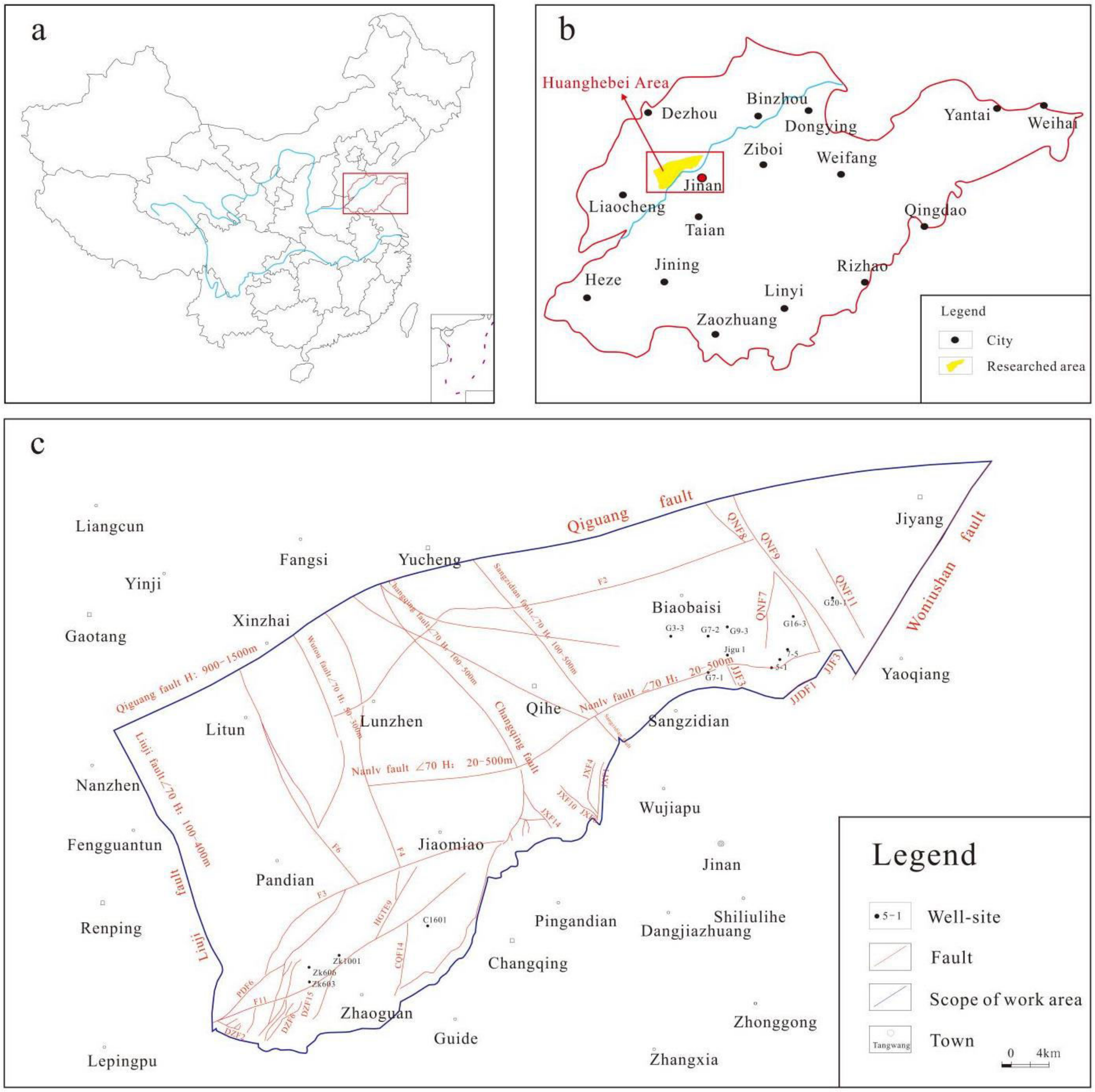

Figure 1: Regional tectonic map of Huanghebei Coalfield.

composed of dense and hard thick layered quartz sandstone with variegated mudstone. The lower portion was made up of grayish, purple, and other variegated clay rock, mudstone, and grayish-green sandstone, with the bottom composed of layered bauxite (Zhao [14]).

3. SEDIMENTARY ENVIRONMENTAL CONDITIONS AND MUD SHALE DEVELOPMENT CHARACTERISTICS

3.1. Sedimentary Environmental Conditions

This study found that Late Paleozoic Era Permo-Carboniferous Period marine, continental, and transitional facies environments were developed in the Huanghebei coal-bearing area. The sedimentary environments of the Late Paleozoic were dominated by a barrier-lagoon system in the lower portion, a delta sedimentary system in the middle section, and a sedimentary system evolution sequence dominated by a river-lake sedimentary system was evident in the upper portion of the study area. It was determined that with the passage of time, the epicontinental sea basin gradually disappeared, and the seawater receded southward. In addition, the southern and northern lifting and falling differences became more obvious. In the plain region, an epicontinental sea environment, transitional environment, and continental environment were distributed from the south to the north, respectively (Chen *et al*. [15]).

During the Benxi Age of the Late Carboniferous Era, the seawater had been gradually intruded into the study area province with the subsidence of the Earth's crust. As a result, a broad epicontinental sea was formed, and a set of platform-lagoon facies dominated sediment had developed. Then, during the Taiyuan Age of the Early Permian Epoch, the Huangheibei Coalfield region was mainly composed of a lagoon-tidal flat sedimentary system, and the barrier island had not yet developed. The coal accumulation time was longer than that in the southern regions, and the marine coal seam was relatively developed. In addition, lagoon-tidal flats were relatively developed in the region, which provided favorable conditions for the development of shale. Prior to another large-scale sea transgression that occurred during the Taiyuan Age in the Luxi area, the tidal flats, lagoons, and swamp deposits were mainly developed, and tidal channel deposits were found in some sections. It is known that lagoon and swamp environmental conditions are favorable for the development of shale. Generally speaking, lagoon sediment had mainly developed in the study area during the aforementioned period, which was considered to be conducive to the development of shale characterized by high strength.

Since the middle of the Early Permian Epoch, the Huanghebei Coalfield has been transformed from an open epicontinental sea environment to a semi-closed lagoon bay environment. During the marine regression process, the bay was gradually filled to form a coastal plain. During the Shanxi Age, delta plain-delta front deposits were developed in the lagoon and tidal flat basement regions in the broad coastal plains. In the Huanghebei Coalfield, there were determined to be interdistributary bay-distributary channel deposits with well-developed coal seams. The coal seams of the Shanxi Formation became the primary mineable coal bed regions. Also, the river mouth sandbars were locally developed. During that period, the study area was mainly composed of developed interdistributary bay-flood plain deposits, which were conducive to the development of mud shale.

3.2. Shale Development

The mud shale is continuously deposited in the Huanghebei Coalfield. The thin shale of the Taiyuan and Shanxi Formations were found to be developed and interbedded with coal seams, sandstone, and limestone, forming a set of continuous sedimentary gas reservoirs. Among those formations, the organic-bearing mudstone not only formed the gas-generating mother rock, but also the reservoirs. The intercalation of the carbonaceous mudstone also played the role of reservoirs. Therefore, those sites were regarded as the target layers of shale gas.

This study found that, based on the seismic and drilling data, the gas-bearing shale intervals in the Taiyuan and Shanxi Formations of the Permo-Carboniferous System had thicknesses ranging approximately between 52.83 m and 97.1 m, with a maximum thickness of 97.1 m, minimum thickness of 52.83 m, and average thickness of 84.8 m. There was observed to be a certain regularity of shale thickness in the area, displaying a gradual decreasing trend from north to south. The thicknesses of the gas-bearing intervals in the Jixi and Changqing mining areas in the southern section were generally more than 80 m. The thicknesses in the Huaji and Mafang mining areas in the southwestern section were found to be smaller, with the majority less than 60 m. Meanwhile, the thicknesses of the gas-bearing intervals in the Lunzhen and Litun mining areas in the northwestern section were observed to be larger, the majority of which averaged more than 90 m (Fig. **2**).

4. ENRICHMENT CONDITIONS OF SHALE GAS

4.1. Abundance of Organic Matter in the Shale of the Study Area

In the study area, it was determined that the organic matter of the effective source rock within the basin provided the material basis of the hydrocarbon formation. Those types of materials are known to generally provide the basis of oil and gas accumulation in sedimentary basins, and also are the main factors determining the hydrocarbon generation ability of source rock (Qian *et al*. [16]).

The total organic carbon content of the mud shale in the Taiyuan and Shanxi Formations of the Permo-Carboniferous System within the Huanghebei Coalfield ranged between 0.43% and 17.65%, respectively, with an average content of 2.56%, as detailed in Table **1**. It was determined that according to the evaluation standards for the abundance of organic matter in the coal-measure source rock of marine-continental alternating facies (Chen, *et al*. [17]), the TOC of the source rock was greater than 2%, which was considered to be conducive to mud shale gas generation. This indicated that the organic matter abundance of the source rock was relatively high and had good gas potential.

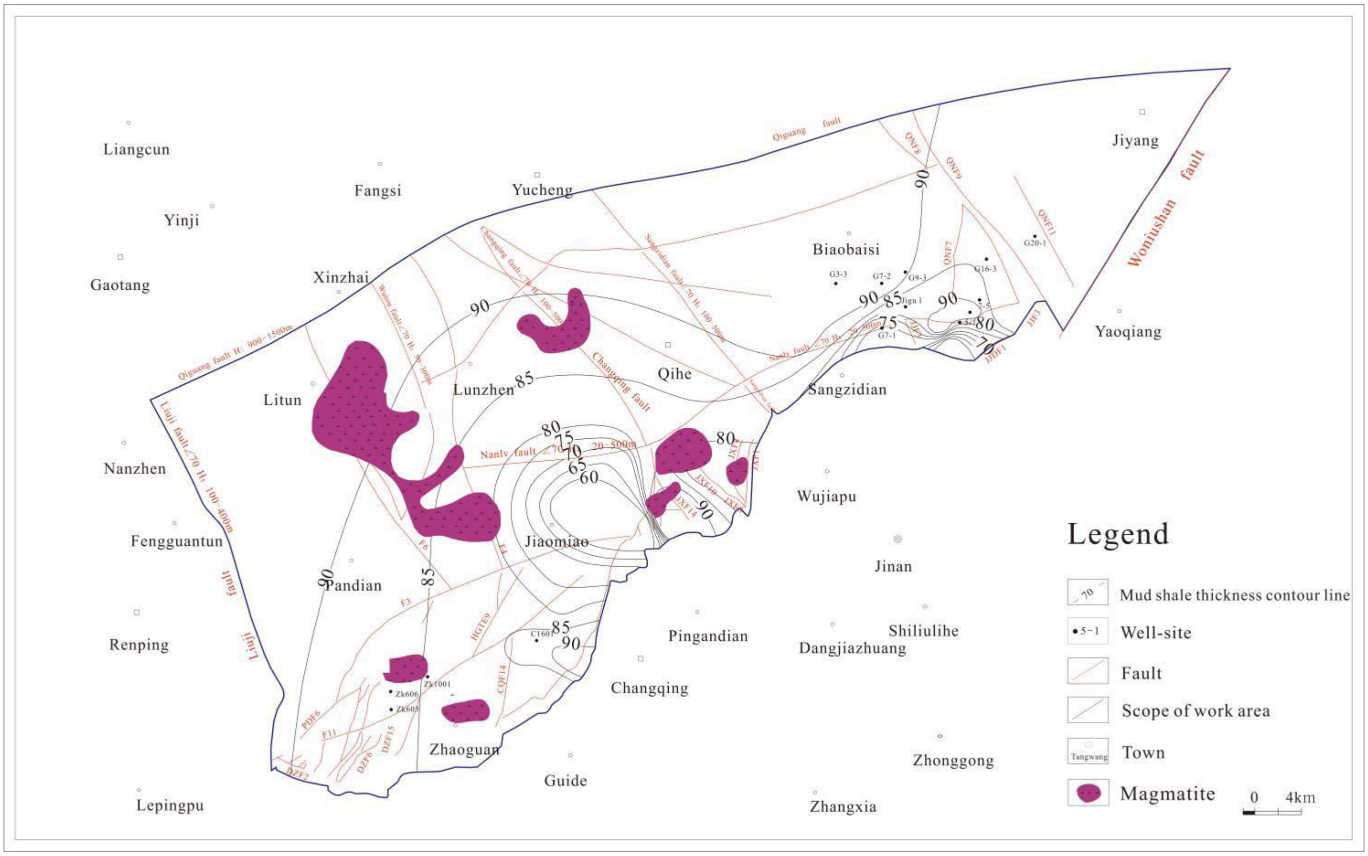

Figure 2: Contour map of the thickness of gas-bearing shale section in Huanghebei Coalfield.

On the plain region, the total organic carbon content was observed to gradually decrease toward the east and west, regarding the north-eastern direction of the Biaobaisi Town and Jiaomiao Town line as the axis. The total organic carbon content levels of the Zhaoguan and Pandian mining areas in the south were basically maintained above 2.0%. The Maozhuang exploration area is generally believed to be a high-value area. The area has an organic carbon content greater than 2.6%, which is considered to be conducive to the generation of shale gas, as shown in Fig. (**3**).

Therefore, based on the evaluation standard for the abundance of organic matter in the coal-measure source rock of the marine-continental alternating facies [17], the advantages and disadvantages of the source rock were classified according to S1+S2. Therefore, S1+S2< 0.5 mg/g will indicate that the rock is not a source rock; 0.5 mg/g < S1+S2 < 2 mg/g will indicate that the rock is an inferior type of source rock; 2 mg/g < S1+S2 < 6 mg/g will indicate that the rock is a medium type source rock; 6 mg/g < S1+S2 < 20 mg/g will indicat that the rock is a good source rock variety; and 20 mg/g < S1+S2 < 200 mg/g will indicate that the rock can be considered to be a very good type of source rock.

In addition, according to the pyrolysis test results of shale in the Taiyuan and Shanxi Formations of the Permo-Carboniferous System in the C1601 well of the Huanghebei Coalfield, it was found that the S1+S2 values had varied greatly, with some strata identified as having high hydrocarbon generation potential. The S1+S2 values were basically maintained within the range of 0.0912 mg/g to 17.4513 mg/g, as shown in Table **2**. The hydrocarbon generation potential of the mud shale at different depths also was observed to display major variations. It was found that the highest S1+S2 values may reach more than 17 mg/g. Therefore, the examined site was considered to contain good source rock, which indicated that parts of Permo-Carboniferous System strata in the Huanghebei Coalfield could potentially be identified as gas-generating source rock-forming shale gas reservoirs. The S_1+S_2 values of the other strata were found to be lower than 2 mg/g. Therefore, they were not considered to fit the category of potential gas source rock for the formation of shale gas reservoirs.

Table 1: Test Data Table of Mud Shale TOC Content in the Study Area

Horizon	Well Number	Depth (m)	TOC, %	Horizon	Well Number	Depth (m)	TOC, %
$P_{1-2}S$	C1601	526.84	3.25	C_2P_1t	C1601	790.94	1.75
$P_{1-2}S$	C1601	545.03	2.47	C_2P_1t	C1601	793.14	1.40
$P_{1-2}S$	C1601	555.32	0.43	C_2P_1t	C1601	798.50	0.81
C_2P_1t	C1601	657.20	1.32	C_2P_1t	C1601	807.88	1.46
C_2P_1t	C1601	660.51	2.24	C_2P_1t	C1601	812.06	0.97
C_2P_1t	C1601	668.00	2.30	C_2P_1t	C1601	821.55	2.79
C_2P_1t	C1601	682.39	2.18	C_2P_1t	C1601	823.55	1.31
C_2P_1t	C1601	692.25	2.42	C_2P_1t	C1601	824	1.85
C_2P_1t	C1601	699.83	2.16	C_2P_1t	C1601	830.55	2.15
C_2P_1t	C1601	702.07	1.37	C_2P_1t	C1601	842.44	1.07
C_2P_1t	C1601	707.37	17.65	C_2P_1t	C1601	851.72	0.84
C_2P_1t	C1601	709.60	2.71	C_2P_1t	C1601	769.96	3.25
C_2P_1t	C1601	711.25	14.75	C_2P_1t	C1601	817.60	2.64
C_2P_1t	C1601	721.71	1.12	C_2P_1t	ZK7-5	480.99	1.78
C_2P_1t	C1601	725.53	1.02	C_2P_1t	ZK1503	633.9	2.74
C_2P_1t	C1601	740.33	1.78	C_2P_1t	ZK2505	706.84	2.09
C_2P_1t	C1601	742.79	1.38	C_2P_1t	G12-1	883.9	1.96
C_2P_1t	C1601	752.22	1.72	C_2P_1t	G13-2	975.43	2.14
C_2P_1t	C1601	755.80	1.71	C_2P_1t	G15-2	969.75	1.97
C_2P_1t	C1601	757.50	0.55	C_2P_1t	G15-3	553.79	1.83
C_2P_1t	C1601	766.00	1.58	C_2P_1t	C1601	660.51	2.24
C_2P_1t	C1601	770.40	4.83				

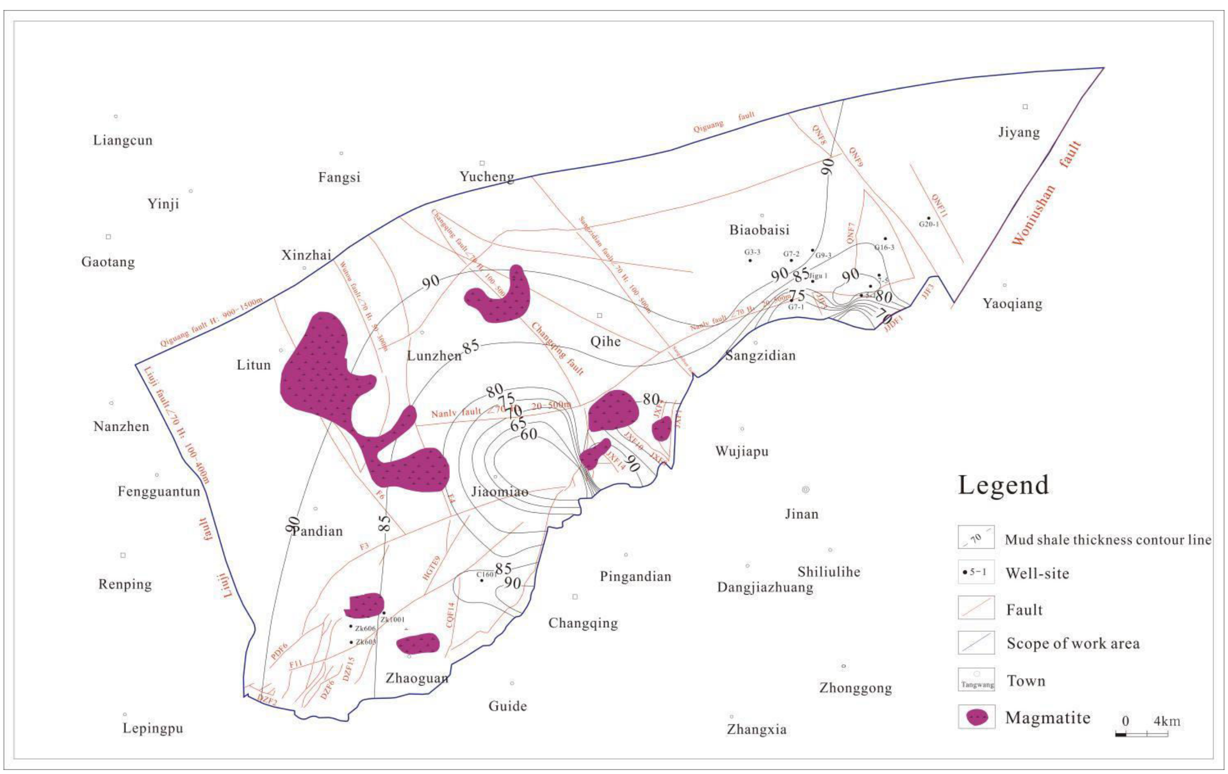

Figure 3: TOC contour map of gas-bearing mud shale bed series in Huanghebei Coalfield.

Table 2: Table of Rock Pyrolysis Data of Permian Series Mud Shale in the Study Area (Borehole C1601)

Horizon	Depth (m)	S1+S2 (mg/g)	Source Rock Level	Horizon	Depth (m)	S1+S2 (mg/g)	Source Rock Level
$P_{1-2}s$	526.84	0.7793	poor	C_2P_1t	752.22	1.5120	poor
$P_{1-2}s$	545.03	0.1935	non	C_2P_1t	755.80	1.7078	poor
$P_{1-2}s$	555.32	0.0912	non	C_2P_1t	757.50	0.3227	non
C_2P_1t	657.20	0.1160	non	C_2P_1t	766.00	0.3015	non
C_2P_1t	660.51	0.1346	non	C_2P_1t	790.94	1.7185	poor
C_2P_1t	668.00	0.1049	non	C_2P_1t	793.14	0.9902	poor
C_2P_1t	682.39	0.4520	non	C_2P_1t	798.50	0.6996	poor
C_2P_1t	692.25	1.1987	poor	C_2P_1t	807.88	1.4963	poor
C_2P_1t	699.83	1.0925	poor	C_2P_1t	812.06	1.0057	poor
C_2P_1t	702.07	0.6985	poor	C_2P_1t	821.55	4.2259	average
C_2P_1t	707.37	17.4513	good	C_2P_1t	823.55	1.0345	poor
C_2P_1t	709.60	2.1042	average	C_2P_1t	824.00	1.3639	poor
C_2P_1t	711.25	13.2923	good	C_2P_1t	830.55	2.7018	average
C_2P_1t	721.71	0.7489	poor	C_2P_1t	842.44	0.9332	poor
C_2P_1t	725.53	0.9290	poor	C_2P_1t	851.72	0.7687	poor
C_2P_1t	740.33	1.5176	poor	C_2P_1t	769.96	4.3600	average
C_2P_1t	742.79	1.2011	poor	C_2P_1t	817.60	0.4344	non

4.2. Types of Organic Matter in the Shale of the Study Area

Under various sedimentary environmental conditions, different types of organic matter will be formed in sedimentary rock due to the variety in the biological input of the sediments. Different types of organic material have varying oil and gas generation potentials. Therefore, it was considered in this study to be of major significance to analyze the types of organic matter of shale in the study area to evaluate the hydrocarbon generation potential of the shale gas [16]. According to the proportion of different kerogen macerals (for example, sapropelinite, exinite, vitrinite, and inertinite), the kerogen types were divided into Type I, Type II_1, Type II_2, and Type III, respectively (Song *et al*. [18]), via petroleum geochemistry methods used in the exploration and application of domestic oil and gas fields.

This study's test results of the shale samples in the Huanghebei Coalfield are shown in Table **3**. The content distribution of vitrinite in the Permo-Carboniferous System dark mud shale of the Huanghebei Oilfield was relatively dispersed, ranging from 3% to 65%. The content distribution of the inertinite ranged from 1% to 18% and was generally less than 10%, showing a scattered distribution. The distribution of sapropelinite was found to vary greatly, ranging from 0% to 93%, with the majority more than 60%. The content of exinite ranged between 3% to 80%. Therefore, it can be seen from the above-mentioned results that the mud shale macerals in the study area have not displayed high regularity. It can be confirmed that Type I, Type II_1, Type II_2, and Type III kerogen are all present. In addition, it can be observed that the Type II kerogen was the main source rock type and had accounted for 50% of the total samples. This was followed by the Type I kerogen, which accounted for 30%. The Type III kerogen accounted for 20% of the total. Meanwhile, the Type III kerogen was found to have humic properties, which indicates that this interval had the potential for gas generation. Generally speaking, the data acquired in this study indicates that the kerogen evolution of the dark mud shale in the study area has reached the mature stage. However, the results also reveal the influences of multi-source organic matter and homologous heterogeneous organic matter.

4.3. Maturity of the Organic Matter in the Shale of the Study Area

The abundance and types of organic matter in sedimentary rock are the material basis for oil and gas generation. However, only when the organic matter reaches a certain degree of thermal evolution can a large amount of hydrocarbon generation begin (Liu *et* *al*. [19]; Qian *et al*. [16]). The maturity levels of organic matter can indicate the degrees of the sedimentary organic matter's thermal evolution into oil and gas. Due to the fact that the physical and chemical properties of organic matter correspondingly change in source rock, and that the above-mentioned processes are irreversible, the maturity levels of organic matter can be judged by certain physical properties and chemical composition characteristics of the organic matter [16]. At the present time, vitrinite reflectance and the peak temperature of the rock pyrolysis are widely used to evaluate the maturity of organic matter (Weng *et al*. [20]).

Vitrinite reflectance (Ro) is used as the main index in the evaluations of the maturity levels of the thermal evolution of organic matter (Qin [21]). It has been found that according to the size of vitrinite reflectance (Ro), the thermal evolution degrees of shale gas reservoirs can be divided into five categories, as detailed in Table **4**.

At the present time, it is generally believed that a vitrinite reflectance (Ro) of 1.0% to 3.3% is the most favorable for shale gas generation. In the current research investigation, the vitrinite reflectance (Ro) of the dark mud shale in the Huanghebei Coalfield was found to range between 0.72% and 1.25%. Its thermal evolution was considered to be in the mature stage, which was favorable for mud shale gas generation. The organic matter maturity of the Pandian and Zhaoguan mining areas in the southern section of the study area was found to be relatively low, and the vitrinite reflectance (Ro) was generally between 0.7% and 0.9%. However, in the northern Zhangbaotun and Ershilipu mining areas, the organic matter maturity was high and the vitrinite reflectance (Ro) ranged from 1.0% to 1.2%. Meanwhile, that of the Jixi and Qidong mining areas had been more than 1.2% (Fig. **4**).

The maximum pyrolysis peak temperature increased with the deepening of shale metamorphism and the increases in the shale burial depth (Lv *et al*. [22]). It is generally considered that a T_{max}°C < 435°C of the rock pyrolysis indicates an immature stage; T_{max}°C within the range of 435 to 445°C of the rock pyrolysis indicates a low maturity stage; T_{max}°C of the rock pyrolysis within the range of 445 to 480°C indicates a medium maturity stage; T_{max}°C of the rock pyrolysis within the range of 480 to 510°C indicates a high maturity stage; and a T_{max}°C > 510°C of the rock pyrolysis indicates an overly mature stage (Gao *et al*. [23]). In the present study, through the demonstrated pyrolysis

Table 3: Data Table on Macerals and Organic Matter Types of Permo-Carboniferous Series Shale in the Study Area

Horizon	Sapropelinite, %				Exinite, %								Vitrinite %			Inertinite %	Type	
	Alginite	Humocollinite	Humodetrinite	Subtotal	Cutinite	Suberinite	Resinite	Sporinite	Humocollinite	Mycetome	Liptodetrinite	Subtotal	Telinite	Euvitrinite	Subtotal	Fusinite	Type index	Type
$P_{1-2}s$	/	/	/	0	/	/	/	/	20	/	9	29	/	65	65	6	-40	Ⅲ
C_2P_1t	/	/	/	0	/	/	/	/	45	/	15	60	/	22	22	18	-5	Ⅲ
C_2P_1t	/	/	/	0	/	/	/	/	45	/	17	62	/	32	32	6	1	Ⅱ$_2$
C_2P_1t	/	5	3	8	/	/	/	/	49	/	23	72	/	15	15	5	28	Ⅱ$_2$
C_2P_1t	/	6	5	11	/	/	/	/	55	/	25	80	/	7	7	2	43	Ⅱ$_1$
C_2P_1t	/	50	14	64	/	/	/	/	18	/	7	25	/	8	8	3	68	Ⅱ$_1$
C_2P_1t	/	55	27	82	/	/	/	/	8	/	4	12	/	5	5	1	83	Ⅰ
C_2P_1t	/	60	30	90	/	/	/	/	3	/	2	5	/	4	4	1	89	Ⅰ
C_2P_1t	/	56	19	75	/	/	/	/	10	/	5	15	/	7	7	3	74	Ⅱ$_1$
C_2P_1t	/	60	33	93	/	/	/	/	2	/	1	3	/	3	3	1	91	Ⅰ

Table 4: Classification of Thermal Evolution Degree of Mud Shale (Cui Xuncai, 2004)

Ro (%)	≥2.0	1.3~2.0	0.7~1.3	0.5~0.7	＜0.5
Thermal evolution degree	over mature	high mature	mature	low mature	immature

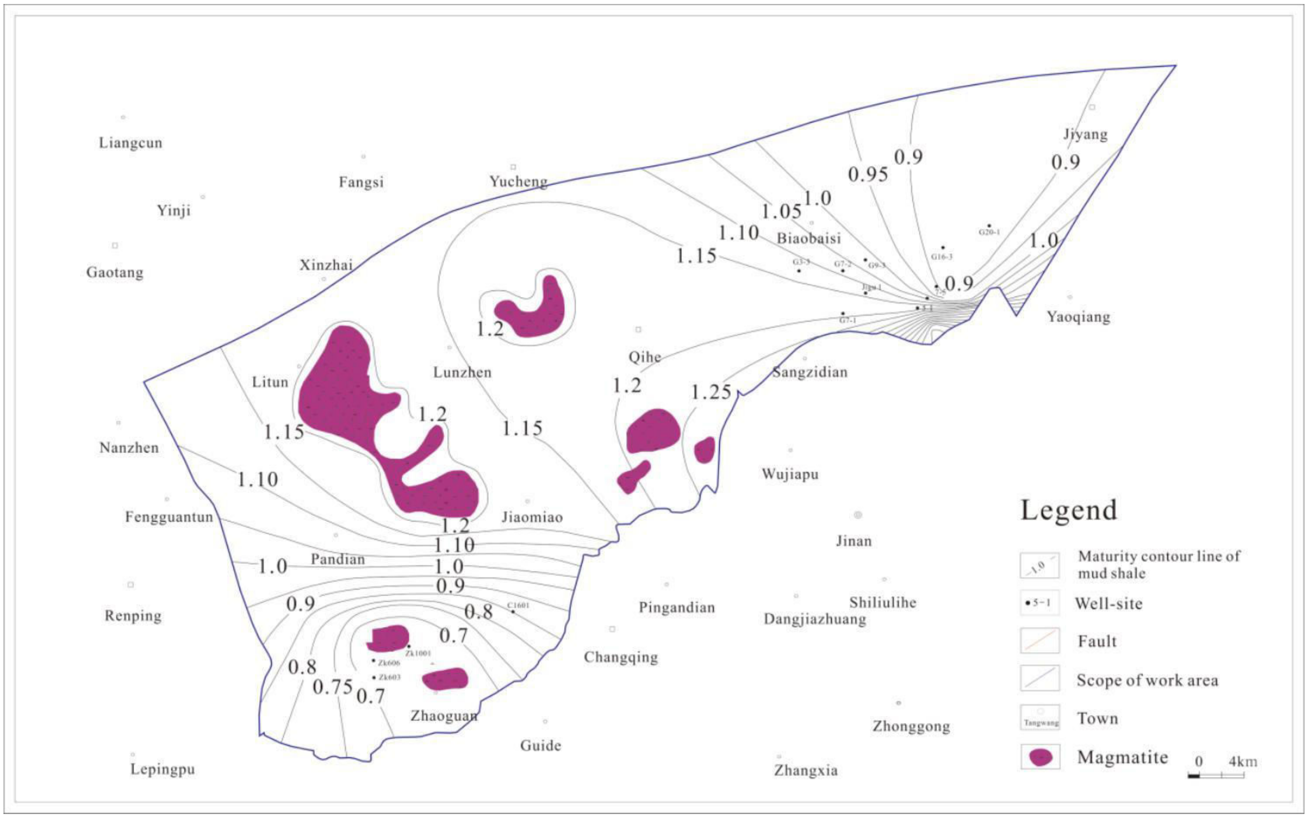

Figure 4: The vitrinite reflectance (Ro) contour map of the gas-bearing mud shale section in the Huanghebei Coalfield.

analysis of the mud shale samples from well C1601, the pyrolysis peak temperature was confirmed to be maintained between 471.9 and 476.4°C, which indicated that the majority of the shale in the study area was in a medium maturity stage, as detailed in Table **5**.

5. PHYSICAL PROPERTIES OF THE MUD SHALE RESERVOIRS

5.1. Types of Mud Shale

In the study area, the gas bearing intervals of the shale in the Taiyuan and Shanxi Formations were found to be mainly variegated shale, mudstone, carbonaceous shale, silty mudstone (shale), kaolinite clay rock, montmorillonite clay rock dominated by mono-minerals, and thin-bedded sandstone and limestone, which were developed in each group of strata. In addition, dark mud shale was well developed in the intervals. The thicknesses of single layers were found to be different, and the accumulated thickness was more than 80 m.

The main lithology of the target intervals of this exploration was the grayish-black siltstone and mudstone. These contained 10 to 20 layers of dark shale of tidal flat facies, which were thin to medium thick strata interbedded with argillaceous sandstone, limestone, and coal seam. Also, gray-dark gray claystone, sandstone, and siltstone were observed, as well as black-gray marine mudstone rich in brachiopod fossils.

5.2. Porosity and Permeability of the Mud Shale

Permeability is an important parameter that is used to determine whether or not shale gas reservoirs have economic value for development. The basic permeability of shale is generally very low, but will greatly increase with the development of fractures (Gan *et al*. [24]; Lu *et al*. [25]). In the present study, according to the *Technical Specifications for the Calculation and Evaluation of Shale Gas Resource Reserves* (DZ/T 0254-2014), the physical properties of the shale gas reservoirs were divided into the following four categories: Ultra-low, low, medium, and high, according to porosity and permeability of the shale gas intervals.

It was revealed from the data analysis of the C1601 well in the Huanghebei Coalfield that the shale reservoirs located in the Taiyuan and Shanxi Formations of the Permo-Carboniferous System had permeability values ranging between 0.141 md and 0.361 md, which is less than 1 md and belonged to the category of ultra-low permeability reservoirs. Generally speaking, the reservoir porosity was between 1.734% and 6.315%.

Table 5: The Peak Temperature Data Table of Permo-Carboniferous Series Shale Rock Pyrolysis in the Study Area

Horizon	Depth (m)	Tmax (°C)	Maturity	Horizon	Depth (m)	Tmax (°C)	Maturity
$P_{1-2}S$	526.84	471.9	mid-mature	C_2P_1t	755.80	476.4	mid-mature
$P_{1-2}S$	545.03	471.9	mid-mature	C_2P_1t	757.50	476.4	mid-mature
$P_{1-2}S$	555.32	471.9	mid-mature	C_2P_1t	766.00	476.4	mid-mature
C_2P_1t	657.20	471.9	mid-mature	C_2P_1t	770.40	476.4	mid-mature
C_2P_1t	660.51	476.4	mid-mature	C_2P_1t	790.94	476.4	mid-mature
C_2P_1t	668.00	476.4	mid-mature	C_2P_1t	793.14	476.4	mid-mature
C_2P_1t	682.39	476.4	mid-mature	C_2P_1t	798.50	476.4	mid-mature
C_2P_1t	692.25	476.4	mid-mature	C_2P_1t	807.88	476.4	mid-mature
C_2P_1t	699.83	476.4	mid-mature	C_2P_1t	812.06	476.4	mid-mature
C_2P_1t	702.07	476.4	mid-mature	C_2P_1t	821.55	476.4	mid-mature
C_2P_1t	707.37	476.4	mid-mature	C_2P_1t	823.55	476.4	mid-mature
C_2P_1t	709.60	476.4	mid-mature	C_2P_1t	824	476.4	mid-mature
C_2P_1t	711.25	476.4	mid-mature	C_2P_1t	830.55	476.4	mid-mature
C_2P_1t	721.71	476.4	mid-mature	C_2P_1t	842.44	476.4	mid-mature
C_2P_1t	725.53	476.4	mid-mature	C_2P_1t	851.72	476.4	mid-mature
C_2P_1t	740.33	476.4	mid-mature	C_2P_1t	769.96	476.4	mid-mature
C_2P_1t	742.79	476.4	mid-mature	C_2P_1t	817.60	476.4	mid-mature
C_2P_1t	752.22	476.4	mid-mature				

Table 6: Porosity and Permeability Data of Permo-Carboniferous Series Shale in the Study Area

Horizon	Depth (m)	Porosity (%)	Permeability (md)	Horizon	Depth (m)	Porosity (%)	Permeability (md)
$P_{1-2}S$	555.32	3.908	0.211	C_2P_1t	692.25	3.455	0.161
C_2P_1t	660.51	3.952	0.141	C_2P_1t	798.50	6.315	0.361
C_2P_1t	682.39	1.734	0.343	C_2P_1t	842.44	3.571	0.426

Therefore, the reservoirs had the characteristics of low porosity reservoirs (Table **6**).

6. GAS BEARING PROPERTIES AND PRESERVATION CONDITIONS OF THE SHALE

6.1. Gas Bearing Properties of the Mud Shale

In accordance with the occurrence modes of shale gas, recoverable shale gas may be mainly free gas and adsorbed gas (Wang [26]). Therefore, this study's discussion regarding the gas generation ability of the shale in the study area mainly focused on the content of free gas and adsorbed gas in the recoverable strata. The sum of the free gas and adsorption gas represented the total gas content of the target layers. According to the collected borehole analysis data (Table **7**), it was determined that the target intervals of the Taiyuan and Shanxi Formations had different analytic gas content, and the content ranged between 0.089 and 3.345 m^3/t, with an average content of 0.645 m^3/t. This was far beyond the standard that the total gas content in resource favorable areas should not be less than 0.5 m^3/t, as stated in the *Technical Specifications for Investigation and Evaluation of Shale Gas Resources (Draft for Comments)*. Moreover, it was found that some of the strata had even exceeded the gas content standard of 1.0 m^3/t in the core areas, which indicates that shale gas resources exist in those areas and the content levels are considerable.

6.2. Conditions for Shale Gas Preservation

6.2.1. Burial Depths of the Mud Shale Strata

According to the preliminary statistics combined with the seismic and drilling data, the burial depths of

Table 7: Vertical Distribution of Gas Content in Huanghebei Region (Borehole C1601)

Horizon	Lithology	Depth (m)	CH_4 (m^3/t)	Total gas (m^3/t)	Horizon	Lithology	Depth (m)	CH_4 (m^3/t)	Total gas (m^3/t)
C_2P_1t	mudstone	679.2	0.118	2.780	C_2P_1t	mudstone	756.28	0.540	3.767
C_2P_1t	mudstone	679.97	0.437	2.478	C_2P_1t	mudstone	756.79	0.116	2.986
C_2P_1t	carbon mudstone	711	3.345	4.328	C_2P_1t	mudstone	768.21	0.089	1.622
C_2P_1t	siltstone	739.22	0.190	0.986	C_2P_1t	mudstone	769.41	0.589	2.239
C_2P_1t	mudstone	739.9	0.382	2.250					

the organic-rich shale in the Huanghebei Coalfield were confirmed to range between 414.05 m and 1,290.55 m, as detailed in Fig. (**5**). The maximum burial depth occurred in well G5-6 and the minimum burial depth occurred in well 8-1. Overall, the burial depths of mud shale in the Huanghebei Coalfield were found to gradually decrease from north to south. Generally speaking, the burial depths in the Zhangbaotun and Ershilipu mining areas in the northern section of the coalfield were observed to be deeper than 1,500 m. The burial depths in the Pandian and Zhaoguan mining areas in the southern section were shallower, with the majority less than 1,000 m and the deepest burial depth only approximately 300 m. The overall development trend was that the burial depths in the southwestern section were shallow, and then gradually increased in the northern direction.

6.2.2. Development Characteristics of the Caprock

Shale gas is a type of self-generation and self-accumulation unconventional energy formed in gas reservoirs. Its occurrence is different from, and also consistent with, conventional oil and gas. Due to the particularity of shale gas occurrence modes, shale gas accumulations are not only controlled by faults, and can also be free from the influences of faults to a certain extent. The faults tend to develop into channels that allow free gas to escape from the gas shale. This may cause damages to the gas reservoirs. However, faults have little effect on the adsorbed gas, and the sealing of faults may even act as an effective caprock. Therefore, the influences of fault development on shale gas occurrence should be further analyzed in specific regions.

The Huanghebei Coalfield is a gentle monocline structure, which is controlled by four groups of high-angle normal faults. In addition, there are obvious differences in fault development between the eastern section and the western section of the coalfield. There are few faults located in the western section of the mining area, and a group of NE-trending faults with simple structures are often observed. These faults have little influence on the shale gas occurrences. However, the faults located in the eastern section of the mining area are more developed, with multiple groups of faults coexisting with displayed complicated structures. These types of structures are not considered to be conducive to the accumulation of shale gas.

From a longitudinal perspective, magmatic rock with different degrees of development, located up and down the target layers, can also play a capping role. It was determined from the vertical gas-bearing tests of well C1601, that the well-developed source rock were deeply buried, and could potentially form good capping rock for the gas reservoirs. The lithology of the Paleogene System overlying the Permo-Carboniferous System gas-bearing strata in the Huanghebei Coalfield was dominated by sandstone, with cap thicknesses ranging between 400 and 2,100 m. It was considered in this study that these areas had the characteristics of good gas cap rock.

7. EVALUATION OF THE SHALE GAS POTENTIAL AND THE OPTIMUM SELECTION OF THE MOST FAVORABLE AREAS

7.1. Evaluation of the Gas Potential

The evaluations of the hydrocarbon generation potential of source rock are important tasks in the exploration and development of unconventional gas resources. Many experiments and research studies in the field have been previously completed (Huang *et al*. [27]; Chen, [17]), and an evaluation system based on such organic geochemical parameters as organic carbon content, hydrocarbon generation potential, kerogen type, vitrinite reflectance, and the pyrolysis parameters of source rock has been established. In addition, with the progress which has been made in the

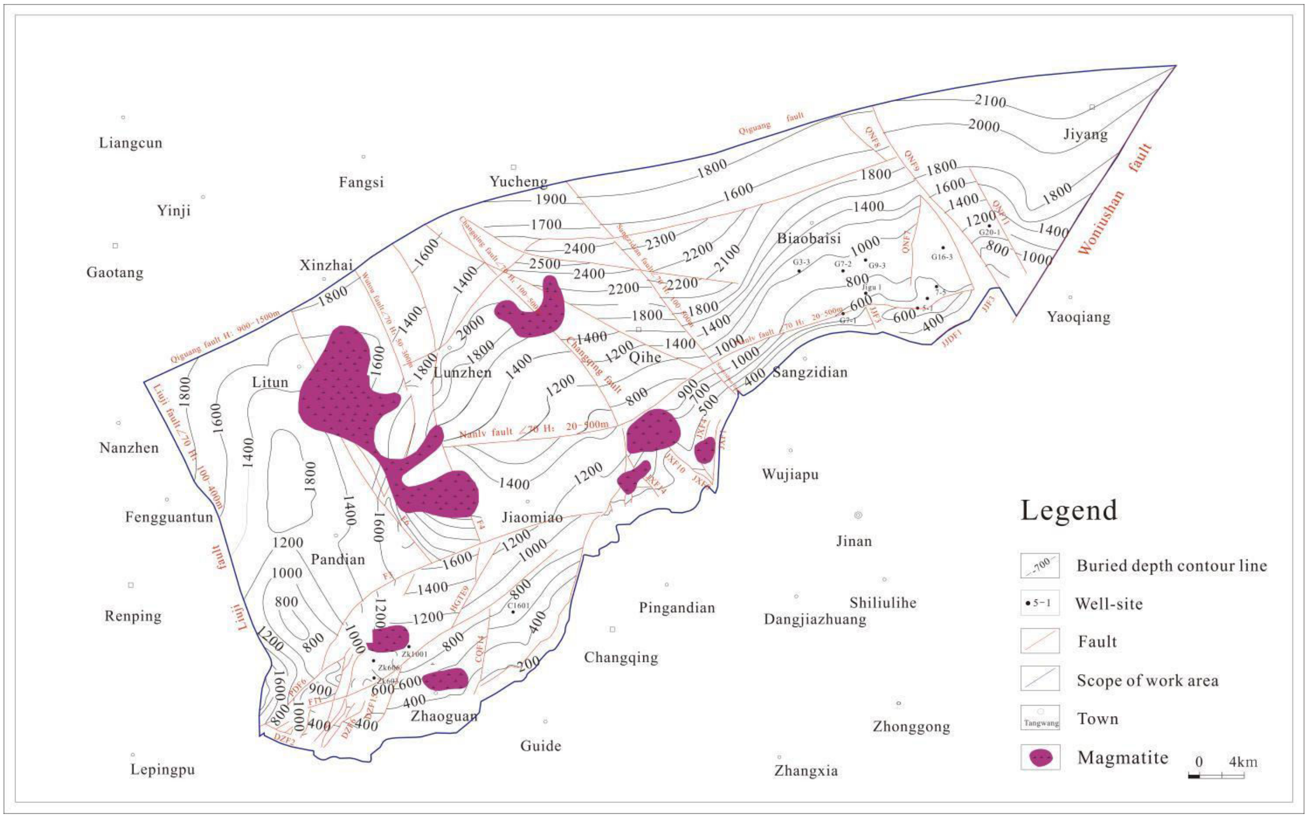

Figure 5: Buried depth contour map of gas-bearing shale section in Huanghebei Coalfield.

research investigations, different evaluation criteria (Dong *et al*. [28]; Wang *et al*. [29]) have been established for the various metamorphic degrees of organic matter in source rock. Therefore, according to the evaluation criteria proposed by Chen *et al.* [17] and Dong *et al*. [28], this study evaluated the hydrocarbon generation potential of the coal-measure shale in the Huanghebei Coalfield.

The results of the sample analyses and examinations of the shale intervals in the Huanghebei Coalfield (Table **8**) revealed that the average value of the total organic carbon content (TOC) in the reservoirs was greater than 2%, and was even greater than 2% in some areas. These results indicated that the shale gas generation conditions had been met. In terms of organic matter types, it was observed that Type II kerogen was the main source rock type, accounting for 50% of the total samples. This was followed by Type III kerogen, which had displayed humic properties. The acquired data indicated that the kerogen evolution of the dark mudstone in the study area had reached a mature stage. Also, according to the pyrolysis test results of the mud shale of the Permo-Carboniferous System in the Huanghebei Coalfield, it was found that the S1+S2 values had varied greatly, with the highest S1+S2 values reaching 17 mg/g. Therefore, the mud shale was considered to be a type of good source rock, indicating that individual strata in the region had very strong hydrocarbon generation potential. The vitrinite reflectance (Ro) ranged from 0.72% to 1.25%, and its thermal evolution was in the mature stage, which was also favorable for shale gas generation. The results of the rock pyrolysis analyses showed that the majority of the shale was in a medium maturity stage and had the characteristics of good hydrocarbon generation potential.

7.3. Optimum Selection of the Most Favorable Areas

In this study, according to the geological characteristics and influencing factors of the shale gas of the Permo-Carboniferous Period transitional facies in the Huanghebei Coalfield, the six most important shale gas selection parameters for shale gas evaluations in the study area were successfully selected. These were organic carbon content, shale burial depth, shale thickness, organic matter maturity, structural complexity, and magmatic rock development. The aforementioned parameters were used in this study as the key parameters in the evaluations of the shale gas in the study area.

Table 8: Hydrocarbon Generation Potential Analysis of Mud Shale in Huanghebei Coalfield

No.	Parameter	Sample Data	Hydrocarbon Potential
1	TOC	1.78%~2.74%	middle-high
2	S1+S2	0.0912mg/g~17.4513mg/g	change greatly, individual layers have good potential
3	organic matter type	Ⅱ (50%), Ⅲ (30%)	gas generation potential is good
4	Ro	0.72%~1.25%	mature stage, good potential
5	Tmax	471.9~476.4℃	medium maturity stage

Furthermore, in accordance with the development of the mudstone in the Permo-Carboniferous System of the study area, the favorable and prospective areas for the development of shale gas resources in the Huanghebei Coalfield were determined using a method which adopted the superposition of geological parameters (Fig. **6**). One particularly favorable area was delineated, which was located in the central part of the Huanghebei Coalfield. The aforementioned area displayed a NE-trending belt distribution along the Pandian-Qihe-Biaobaisi. Three more prospective areas were also delineated, which were located in the Dulangkou-Zhaoguan prospect area, Yuchengnan prospect area, and the Sangzidian prospect area in the east, respectively. These areas also displayed NE-trending belt distributions.

8. CONCLUSIONS

In the present study, based on the investigation results of the development characteristics of the Permo-Carboniferous shale gas resources in the Huanghebei Coalfield, the following conclusions were reached:

(1) There were found to have been many types of sedimentary environments developed in the Huanghebei Coalfield during the Late Paleozoic Era. The

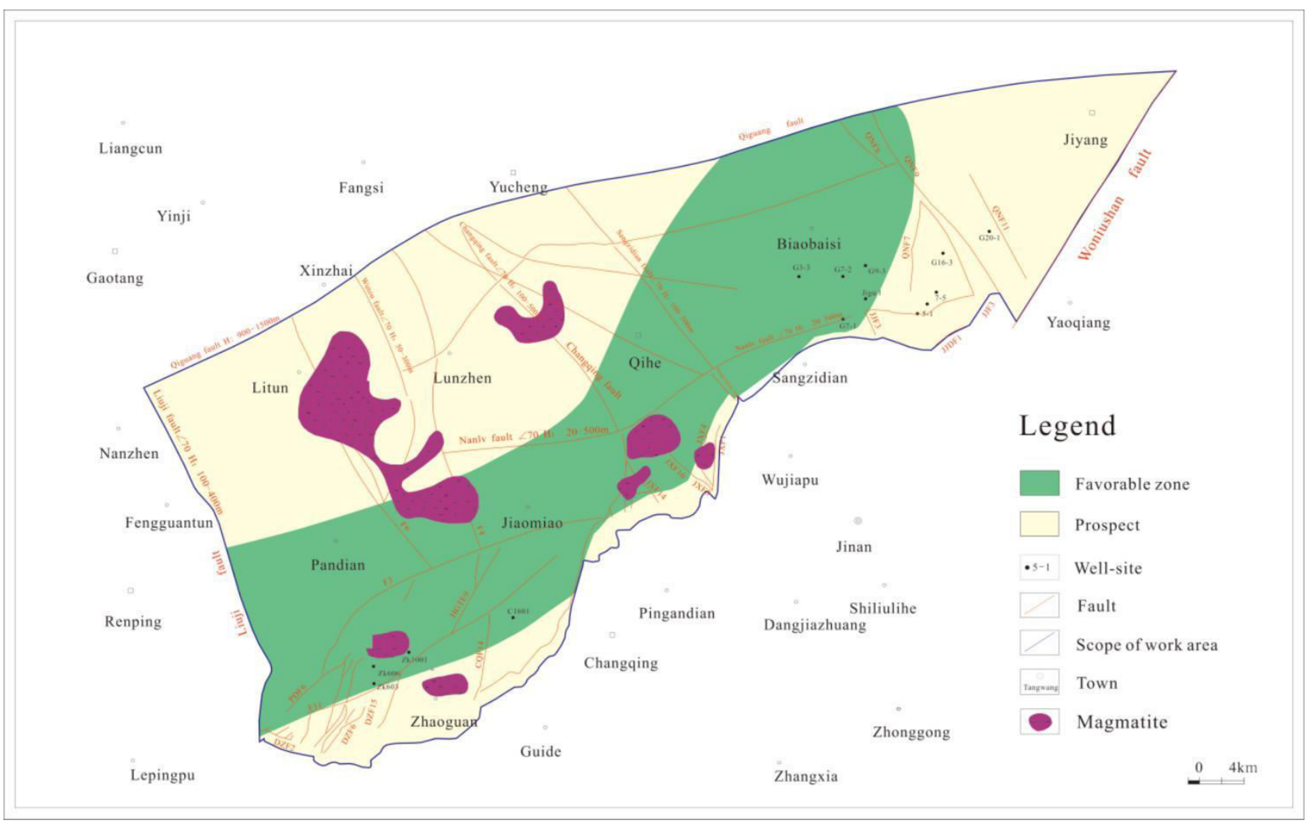

Figure 6: Shale gas resource prospect area division map of Huanghebei Coalfield.

Taiyuan Formation was mainly developed from lagoon sediment, which was considered to be conducive to the development of shale with high strength. In addition, the development of interdistributary bay-floodplain deposits in the Shanxi Formation was also determined to be conducive to the development of mud shale.

(2) The average values of the total organic carbon (TOC) of the shale in the Taiyuan and Shanxi Formations of the study area were determined to be more than 2%. The type of organic matter was observed to mainly be Type II kerogen, which was followed by Type III kerogen. The thermal evolution of the organic matter was in a mature stage and had good hydrocarbon generation potential.

(3) The mud shale gas-bearing intervals of the Taiyuan and Shanxi Formations in the study area were mainly variegated shale, mudstone, carbonaceous shale, and silty mudstone (shale), which belonged to the categories of ultra-low permeability and low porosity reservoirs.

(4) The average gas content levels of the mud shale in the Taiyuan and Shanxi Formations ranged between 0.645 and 3.34 m^3/t. The burial depths of the shale were confirmed to be deep and the caprock was well developed. All these factors were considered to be conducive to the preservation of shale gas.

(5) This study's comprehensive analysis results revealed that the mud shale in the Taiyuan and Shanxi Formations of the study area had good hydrocarbon generation potential. As a result, a favorable area was delineated in the central part of the Huanghebei Coalfield, which displayed a NE-trending belt distribution along the Pandian-Qihe-Biaobaisi. In addition, three other prospect areas were successfully delineated, which include the Dulangkou-Zhaoguan prospect area, Yucheng South prospect area, and Sangzidian prospect area, respectively.

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