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Research Article

Evaluation of the Accumulation Conditions and Favorable Areas of Shale Gas in the Upper Palaeozoic Marine-Continental Transitional Facies in the Daning-Jixian Area, Ordos Basin

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This study focuses on the organic-rich mud shale in the Upper Palaeozoic transitional facies in the southeastern margin of the Ordos Basin. It systematically analyzes the shale gas accumulation conditions of the organic-rich mud shale in the Lower Permian Shanxi-Taiyuan Formation, including the thickness, distribution, organic matter type and content, thermal maturity, reservoir space, gas-bearing property, and rock brittleness. The results show that the thick dark mud shale contains a high organic matter content, is a suitable kerogen type for gas generation, and exhibits moderate thermal evolution, providing excellent conditions for hydrocarbon accumulation. Residual primary pores formed by shale compaction, secondary pores formed by organic matter hydrocarbon generation, clay mineral transformation and dissolution, and fractures provide suitable reservoir spaces for shale gas. The shale in the study area has a higher gas content than the shale strata in the marine basins of the United States. In addition, the content of brittle minerals such as quartz is higher, and Poisson's ratio is lower, facilitating the subsequent transformation. The accumulation conditions indicate the high potential of the study area for shale gas exploration and development. The geological analogy method is used to compare the study area with five major shale gas basins in the United States. The results indicate that the shale gas resources of the Shanxi-Taiyuan Formation in the study area are in the range of $2800–3200 \times 10^8$ m^3. The primary controlling factors affecting shale gas reservoirs in this area are the abundance of organic matter, thermal maturity, shale thickness, and quartz content. Favorable areas are predicted based on these factors.

1. Introduction

Shale gas is an unconventional natural gas [1–3]. Due to the increasing difficulty of the exploration of China's conventional oil and gas resources and the success of the shale gas revolution in the United States, China's shale gas production has reached 20 billion cubic meters, accounting for 28% of the growth of total natural gas production [4]. Shale gas production has become an essential part of China's natural gas production. Shale gas in the United States is dominated by marine facies [5]. In contrast, China's shale gas resources are predominantly marine-continental transitional facies, with a volume of about 19.8×10^{12} m^3, accounting for 25% of China's total shale gas resources [6], representing an important aspect of shale gas exploration. China's marine-continental transitional organic-rich shale is widely distributed in the Ordos and Sichuan Basins. These areas have good shale gas resources and the potential for exploration and development [7–9]. The Ordos Basin in China is a large onshore petroliferous basin with natural gas resources of 29.2×10^{12} m^3. A preliminary breakthrough in shale gas exploration in the marine-continental transitional facies has been achieved at the eastern margin of the basin [10]. However, few studies have been conducted on shale gas in marine-continental transitional facies in China. Some scholars have investigated the sedimentary environment, shale gas-bearing characteristics, and storage space of the shale gas resources in the marine-continental transitional facies in the Upper Palaeozoic of the Ordos Basin. However, these studies were based on regional data of the entire basin. It is also necessary to select representative blocks in the basin to conduct in-depth research on the exploration potential of the entire basin. Some scholars focused on the evaluation and optimization of favorable shale gas exploration areas in this region. Yan et al. [11] and Zhai et al. [12] carried out an evaluation of favorable areas for shale gas exploration in the Upper Palaeozoic transitional facies of the Ordos Basin and investigated the shale gas deposition environment, source rock characteristics, and gas-bearing properties. Dazhong et al. [13] analyzed the shale development environment and single well production conditions to evaluate the prospects of marine-continental transitional shale gas exploration in the Ordos Basin. An evaluation of favorable areas for gas exploration requires a comprehensive analysis with a focus on the generation, storage, and sealing characteristics of shale gas. An analysis of the accumulation conditions based on a single factor is insufficient to support the subsequent oil and gas exploration [14]. This study focuses on the Daning-Jixian area at the southeastern margin of the Ordos Basin. Many exploratory wells have been drilled in the study area, and some have shown significant oil and gas potential in the shale section of the Shanxi-Taiyuan Formation of the Permian strata in the Upper Palaeozoic facies. Therefore, this study systematically investigates the characteristics of the organic matter, petrology, storage space, and mechanical properties of the shale section in the block. Other accumulation features, such as formation brittleness and roof and floor conditions, which are closely related to shale gas exploration and development, are evaluated. The study area is scientifically and comprehensively evaluated by comparing its shale gas zones with those of the United States, and favorable regions are predicted based on geological conditions. This study provides a foundation for evaluating the exploration potential of the Upper Palaeozoic shale gas region in the entire Ordos Basin.

2. Geological Background

2.1. Structure. The study area is located at the southeastern margin of the Ordos Basin on the western flank of the Lvliang Mountain anticline and the west side of the Zijingshan fault zone. As shown in Figure 1, the study area is characterized by a northwest-inclined monoclinic structure. The strata strike northeast or north-northeast and dip gently to the west or northwest, with dip angles of 5°–10°. The entire structure is nearly rectangular and has a north-south orientation (Figure 1). Few geological structures are found in the study area, such as small folds and faults. For example, the Guyi-Yaoqu anticline and Xueguan-Yukou flexure spreading in the northeast-southwest direction are parallel, juxtaposed, and run through the entire area. The Guyi-Yaoqu anticline is the main structure in the study area. Its overall trend is 30°, the length is 40 km, and it has a steep eastern flank and gentle western flank. In conjunction with the Guyi-Yaoqu anticline, the Xueguan-Yukou flexure developed at a distance of 3 km-3.5 km from the southeastern side of the anticline and parallel to it, with a total length of nearly 40 km. Its flexural strength is strong at both ends and weak in the middle [15]. In addition, small-scale anticlines have developed locally, such as the Hougetai anticline, Shanggoukou syncline, Fengjialing anticline, and Huangjiazhuang syncline. The primary fault structure in the study area is the Zijingshan fault zone on the eastern side, whose attitude is moderately steep near the flexure zone. There are relatively few faults in the study area; most are small faults, with no large faults in the central and deep areas.

2.2. Stratigraphy. The basement of the basin in the study area is composed of Cambrian, Ordovician, Carboniferous, Permian, Triassic, Neogene, and Quaternary strata. The Upper Palaeozoic includes the Carboniferous and Permian strata. The lower Permian consists of marine-continental transitional to continental delta deposits, forming thick layers of dark mud shale. The upper Shihezi Formation and Shiqianfeng Formation have developed sand-shale interbedded deposits. The regional geological conditions indicate that the Permian Taiyuan and Shanxi Formations are potential areas to develop marine-continental transitional facies shale gas reservoirs. Therefore, these two formations are the target horizons of this study (Figure 2).

2.2.1. Carboniferous Strata (C). Only the Benxi Formation of the Upper Carboniferous strata has been developed, with layers of coal-bearing rock deposited in a marine and alternative continental environment. This formation has parallel unconformity contact with the underlying Fengfeng Formation of the Middle Ordovician. It is mainly characterized by yellow-green bauxitic mudstone with thin coal seams and limestone strata.

2.2.2. Permian Strata (P). The Permian strata are widely distributed in the study area, mainly including marine-continental transitional coal-bearing strata, continental clastic coal-bearing strata, and clastic non-coal-bearing strata. The Taiyuan Formation, Shanxi Formation, Shihezi Formation, and Shiqianfeng Formation are found from bottom to top. Relatively complete Permian strata have been exposed in Taitou Town, Shanxi Province, and the section has been measured and investigated. As shown in Figure 2, the Taiyuan Formation is mainly composed of dark mud shale, limestone, and sandstone. The limestone is abundant and rich in biological fossils. The Shanxi Formation is primarily composed of continental clastic rocks with many coal seams in the lower part. Based on the regional data, it has been concluded that the Shihezi Formation is in direct contact with the underlying Shanxi Formation and the overlying Shiqianfeng Formation. There are multiple sand and mudstone assemblages with interbeds of unequal thickness. A massive thick layer of grayish-yellow, grayish-green, medium-thick, medium coarse-grained sandstone has developed at the bottom of the Lower Shihezi Formation, marking the bottom of the Shihezi Formation.

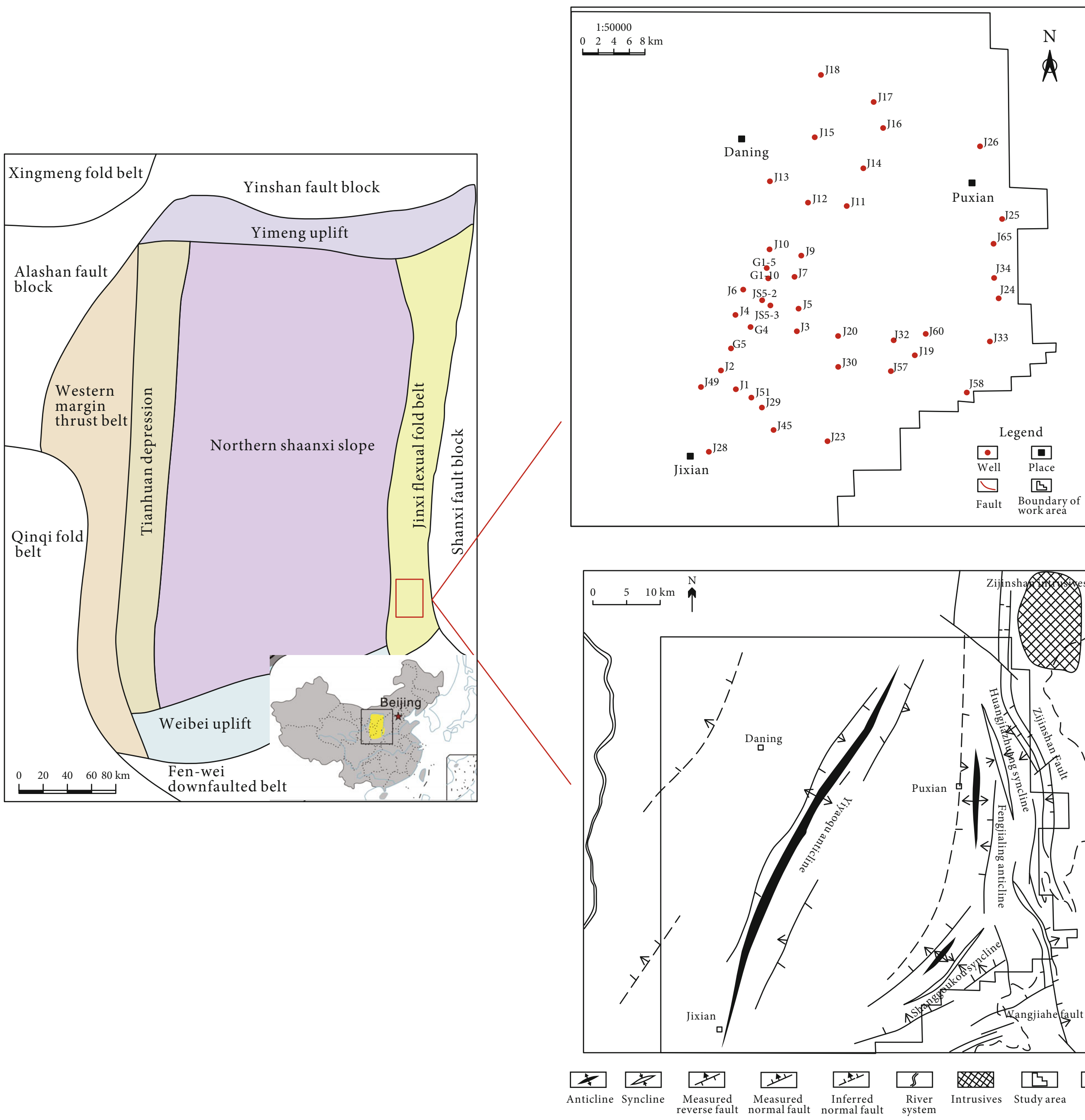


Figure 1: The location of the study area.

3. Samples and Methods

Total organic carbon (TOC) is an essential indicator for evaluating the abundance of organic matter. A total of 383 core samples were analyzed for organic carbon, including 280 samples from the Shanxi Formation and 103 samples from the Taiyuan Formation.

The petrological characteristics of the shale gas reservoir were quantitatively characterized by X-ray diffraction (XRD) analysis, a method to determine the internal spatial distribution of materials consisting of crystals [16]. Random-powder XRD (Bruker D2 PHASER X-ray diffractometer) was used to analyze the mineral components. The shale powder (<300 mesh) was placed in a sample plate and scanned from 4.5°to 50°with a step length 0.02°. Core samples from more than 20 exploration wells in the area were analyzed using whole-rock XRD.

Imaging techniques and quantitative measurement were used to analyze the micropore structure of the shale. A field emission scanning electron microscope (FE-SEM) was used to analyze 15 samples from 6 exploration wells (J6, J51, J5, J57, and J45). The dried samples were pressed into cubes (1 cm × 1 cm × 1 cm), which were polished by argon ions. The samples were analyzed by the SEM to obtain the backscattered electron (BSE) image of the sample. A pore permeability

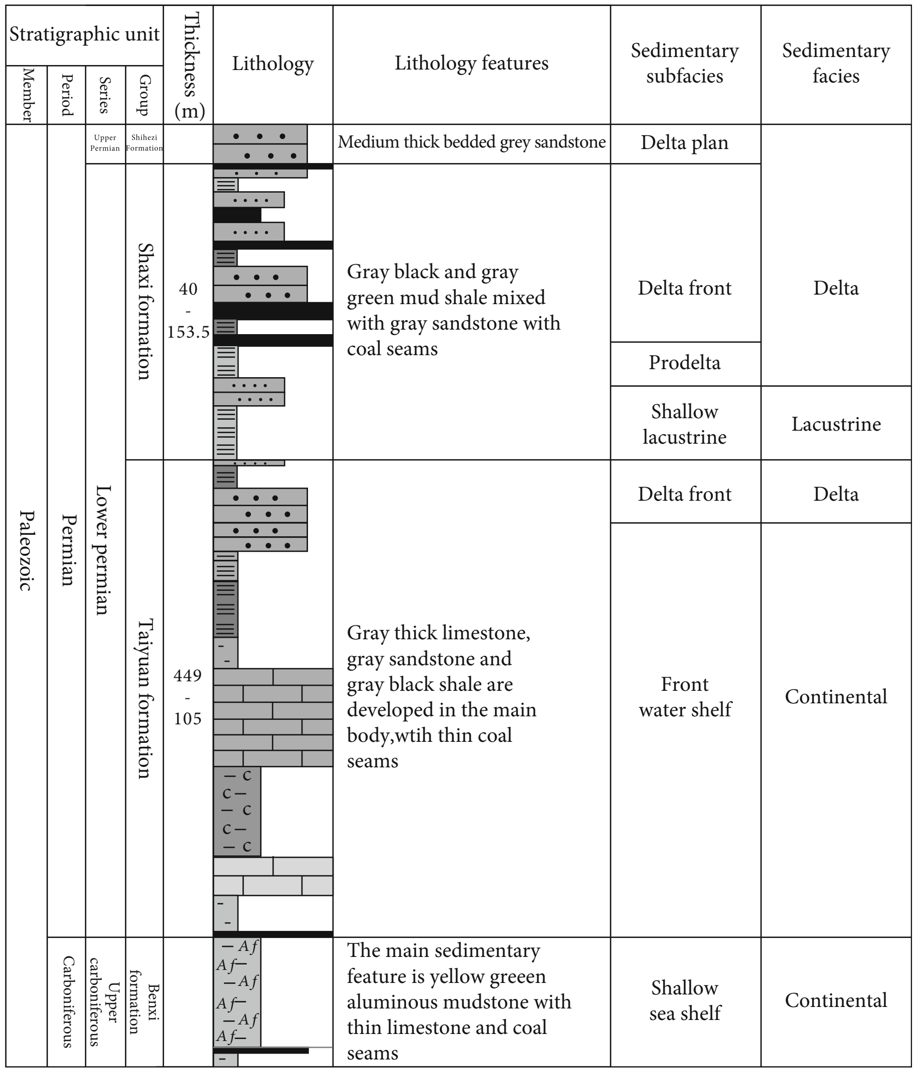


Figure 2: The C-P measured section column of the Taitou profile in Shanxi Province.

test was conducted on samples obtained from 20 exploration wells in the Shanxi Formation and Taiyuan Formation to determine the overburden pressure.

3.1. Source Rock Characteristics

3.1.1. Organic Matter Characteristics. A large dark mud shale area exists in the study area, representing favorable conditions for the development of source rocks. The abundance of organic matter determines the hydrocarbon generation capacity of shale and its adsorption capacity for shale gas.

As shown in Figure 3, the highest value of TOC in the samples of the Shanxi Formation is 29.25%, and the lowest value is 0.07%; 67.86% of the samples have a TOC of 0%–2%, and 32.14% have a TOC higher than 2%. The highest value of the samples from the Taiyuan Formation is 22.52%, and the lowest value is 0.011%; 43.69% of the samples have a TOC of 0%–2%, 40.78% of the samples have a TOC of 2%–4%, and 56.31% of the sample have a TOC higher than 2%. The TOC content of the five major shale gas basins in North America is 0%–25% [17], and the lower limit is generally 2.0% [18]. Based on previous studies, 2.0% was used as the lower limit of TOC to evaluate the organic matter abundance in the study area. As shown in Figure 4, areas in the Shanxi Formation with a TOC higher than 2% are mainly located in the central and eastern areas of the study area (wells G1-10, J7, J1, G5, G4, J3, J20, J45, J19, J24, J34, and J25), with the highest value of 19.57%. Areas with a TOC higher than 2% in the Taiyuan Formation are located in a region with northeast to southwest orientation. The northeast to southwest direction represented by Wells J16-J9-G5 is a high-value area with a TOC of more than 6%. Wells J25-J19-J23 in the east represent a high-value area of organic carbon content, with values exceeding 5%. The area between the wells with the two high values has a relatively low organic carbon content, but the organic carbon content in wells J20 and J29 is relatively high (more than 4%). In summary, the organic carbon content of more than 32.14% (56.31%) of the samples in the Shanxi group (Taiyuan group) is higher than 2%. The study area is rich in organic matter. The primary type of organic matter in the Shanxi Formation and Taiyuan Formation in the study area is type II2, which is rich in humic kerogen and can

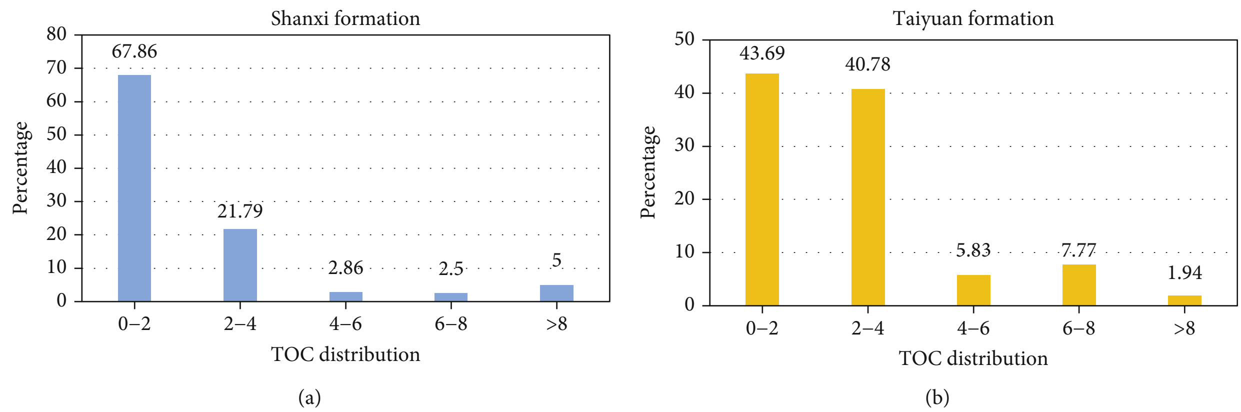


FIGURE 3: The total organic carbon content of the mud (shale) stone reservoirs in the study area.

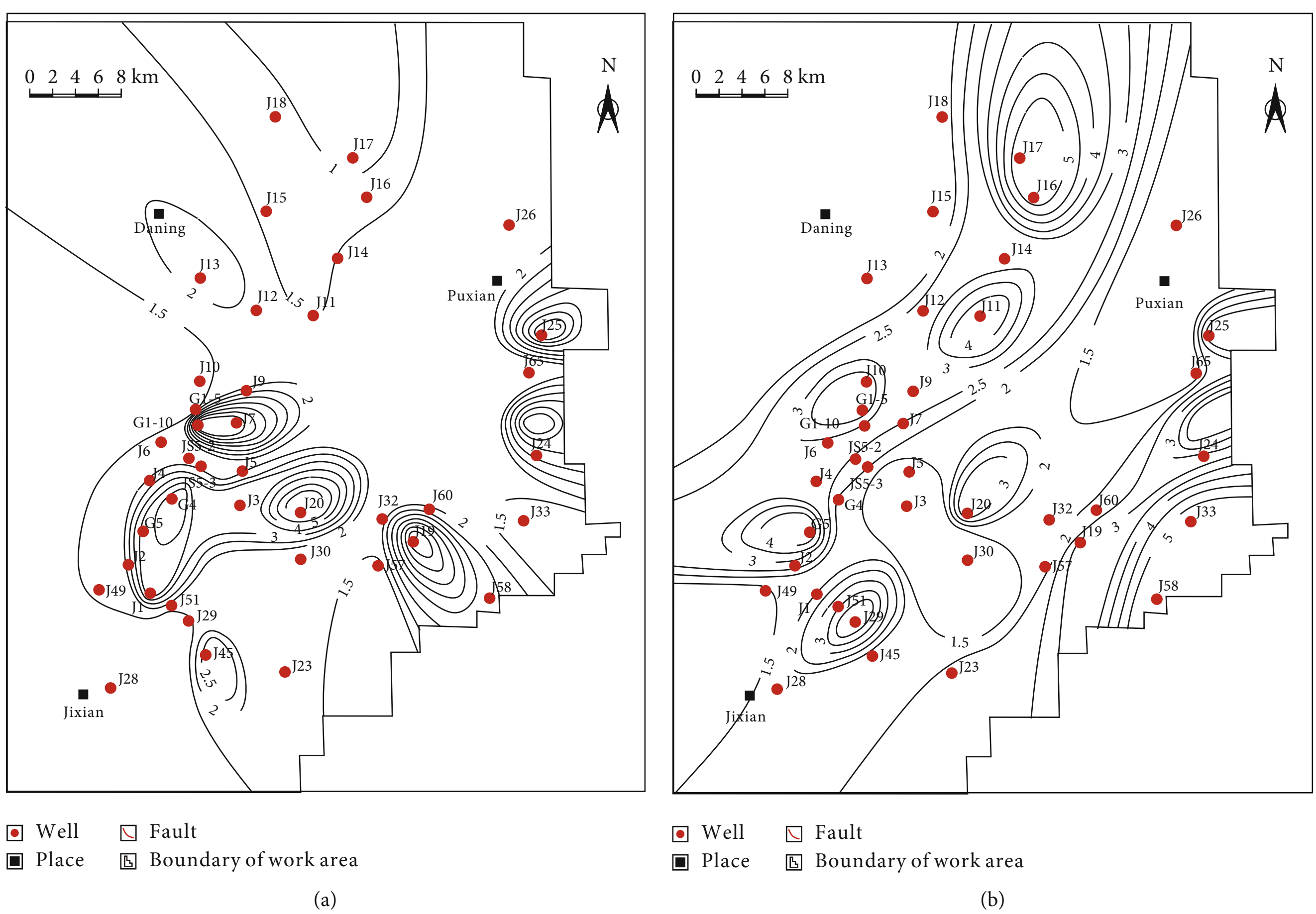


FIGURE 4: The contour map of the TOC of mud (shale) reservoirs in the study area. (a) Shanxi Formation; (b) Taiyuan Formation.

generate large amounts of natural gas [19]. Therefore, these two areas show excellent potential for shale gas formation.

3.1.2. Shale Thickness. The burial depth of the Shanxi Formation in the study area is 571 m–1447.5 m, and the shale thickness is 23.18 m–99.84 m, with an average of 54.18 m. The shale is thicker in the northeast, with a maximum thickness of more than 90 m. Only a few well areas in the central, western, and eastern parts of the study area show high shale thickness values. The burial depth of the Taiyuan Formation is 620.5 m–1503 m, and the thickness of the shale ranges from 17.22 m to 66.94 m, with an average of 30.72 m, thinner than the shale of the Shanxi Formation. Wells J11 and J13 in the northwest, east, and south of the study area have larger shale thicknesses (Figure 5). In summary, the shale in the study area is relatively thick and has adequate conditions for shale gas

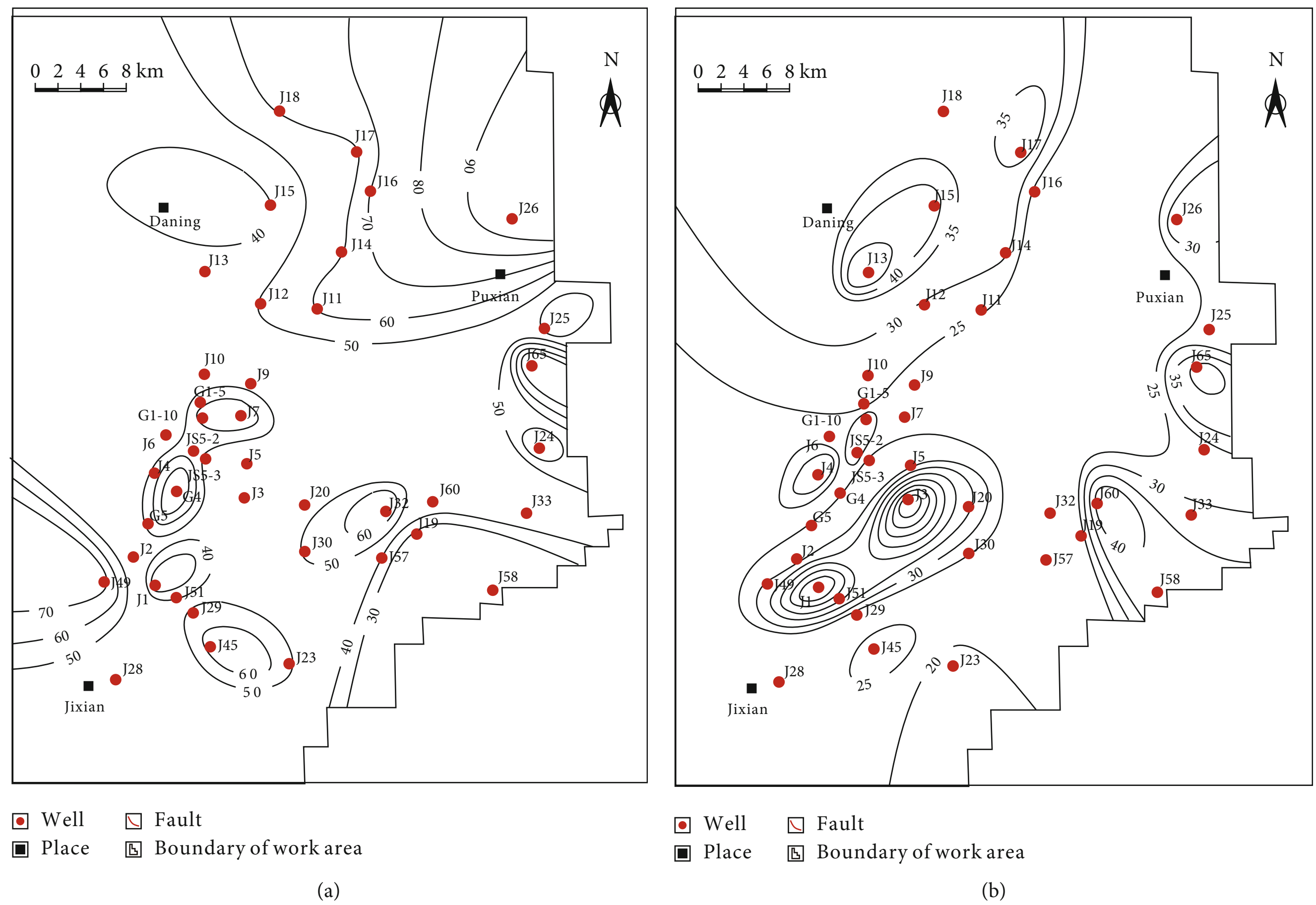


Figure 5: The contour map of the thickness of the mud (shale) reservoirs in the study area. (a) Shanxi Formation; (b) Taiyuan Formation.

hydrocarbon accumulation. The area experienced deep burial historically and subsequent uplift, resulting in a relatively shallow burial depth [20].

3.1.3. Types of Organic Matter. Under normal circumstances, the four components in kerogen can be observed under the microscope (vitrine, inertinite, exinite, and sapropelite). Different types of kerogen are formed by different combinations of these four microscopic components. The hydrogen-rich saprolite and chitinous formations have better hydrocarbon generation potential [20]. Vitrinite generally has only gas generation potential. Fluoro vitrinite has the potential to generate oil, while inertite cannot generate oil or gas.

The analysis results show that the main type of organic matter in the Shanxi Formation in the study area is typeII2, with some occurrences of type III. The Taiyuan Formation is dominated by type II2, with some occurrences of type II1. Therefore, the main type of organic matter in the Shanxi Formation and Taiyuan Formation in the study area is type II2.

3.1.4. Thermal Maturity. The statistics of the samples show that the vitrinite reflectance values of the shale in the study area are in the range of 1.0%–3.0%, and more than 80% are in the range of 1.0%–2.0%, which is favorable for shale gas formation.

As shown in Figure 6, the vitrinite reflectance of the Shanxi Formation is relatively low in the north and high in the south, with the highest value of over 2.2% in Well J45 in the south. The vitrinite reflectance characteristics are similar in the Taiyuan Formation. The highest values are found in Wells J45 and J23 (>2.1%), and most of the values in the north are lower than 1.4%. In summary, the vitrinite reflectance values are high in the south and low in the north; thus, the south of the study area is more favorable for shale gas generation than the north (Figure 6).

3.2. Reservoir Characteristics

3.2.1. Mineral Composition. The results show that clay minerals are the dominant minerals in the shale member of the study area, followed by quartz and plagioclase. The plagioclase content is low, but the areas of plagioclase are well developed. The average mineral composition of the shale members of the Shanxi Formation is as follows: clay (51.04%), quartz (40.74%), potassium feldspar (1.00%), plagioclase (2.56%), calcite (1.00%), dolomite (4.00%), pyrite (3.00%), and siderite (7.10%). The average mineral composition of the shale member of Taiyuan Formation is as follows: clay (48.35%), quartz (40.91%), potassium feldspar (1.56%), plagioclase (1.68%), calcite (24.00%), dolomite (2.67%), pyrite (4.23%), and siderite

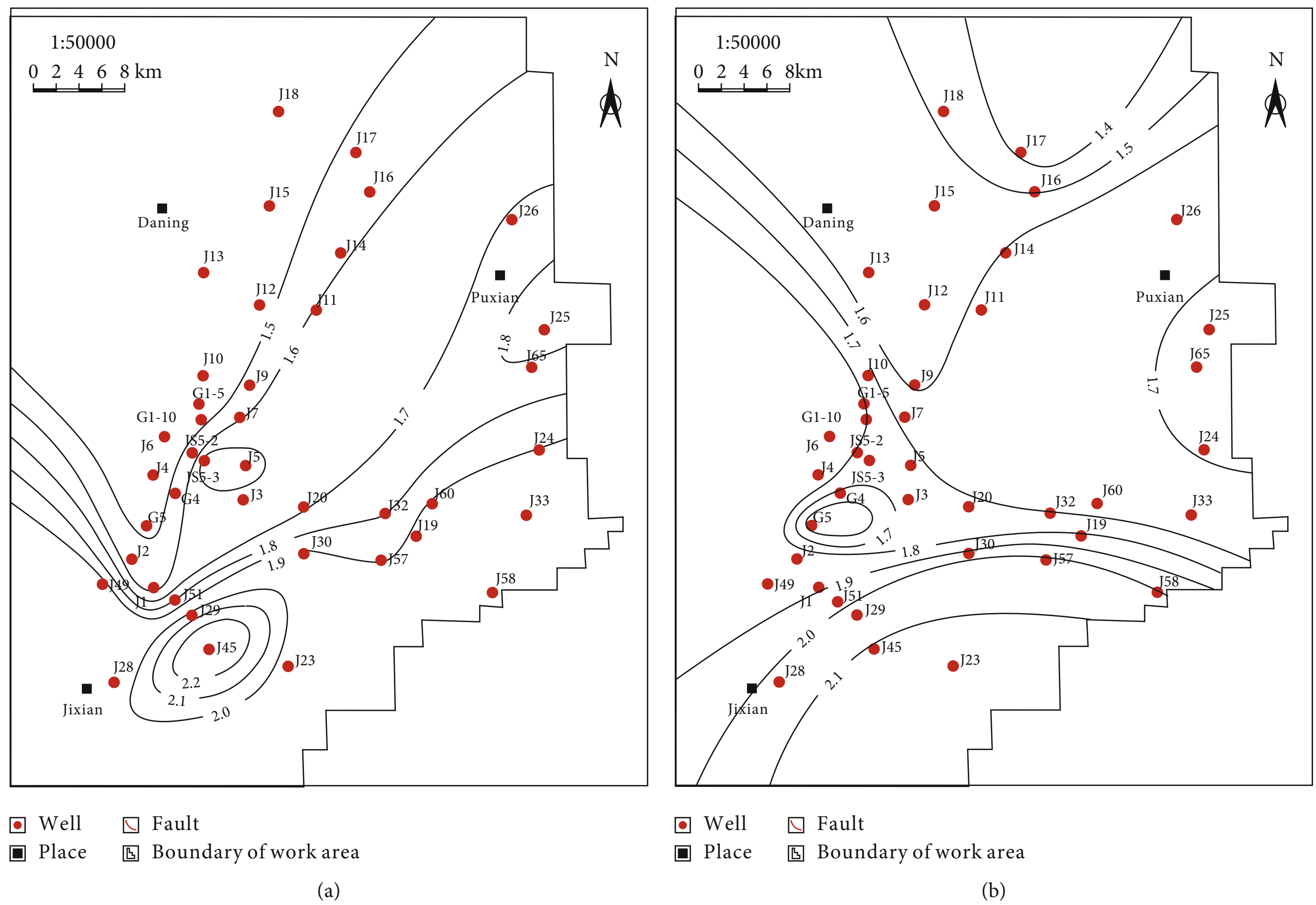


Figure 6: The contour map of vitrinite reflectance (Ro) of the mud (shale) stone reservoirs in the study area. (a) Shanxi Formation; (b) Taiyuan Formation.

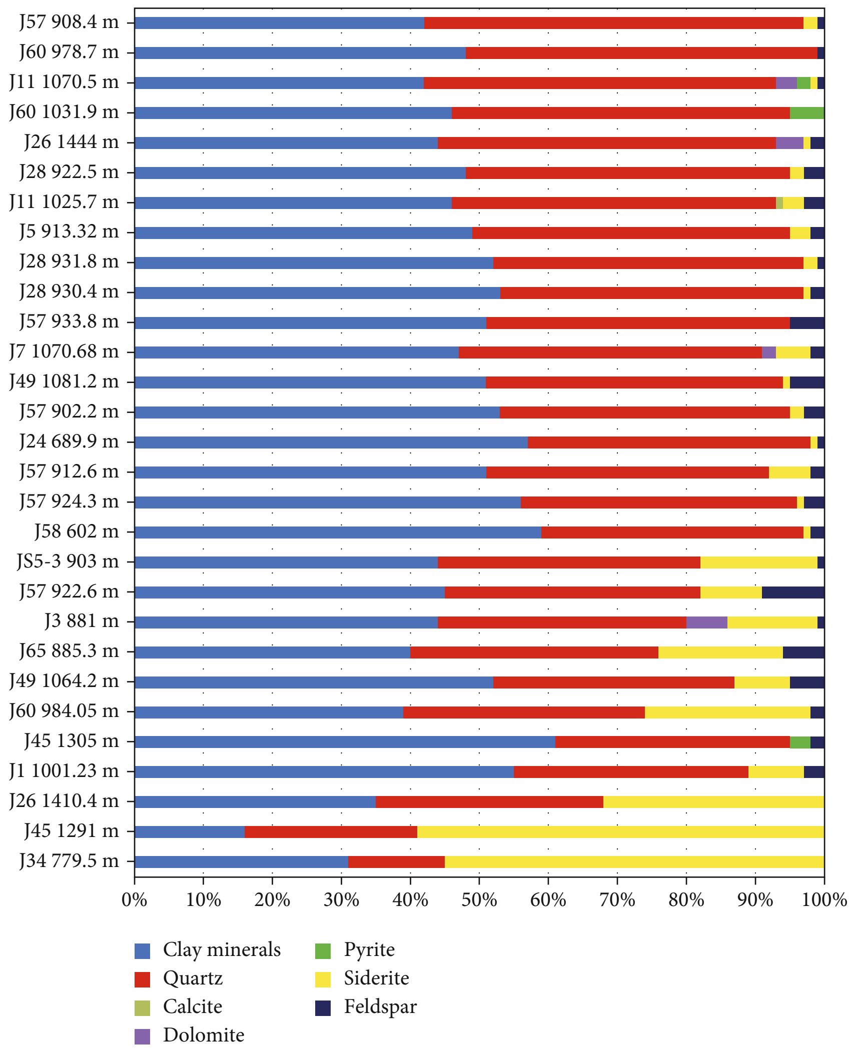
(4.04%) (Figure 7). The quartz content of the Shanxi Formation is higher than 35%, and the quartz areas are located in the northwest, central-east, and southwest of the study area. Wells J13, J15, and J32 have the highest quartz content (>50%).

The quartz content in the Taiyuan Formation is relatively high (>30%) in many areas, and the highest value exceeds 60%. Quartz is found in wells J17, J25, J65, and J58; only G1-5, G1-10, J29, and J49 have a quartz content of less than 20%. Regarding clay minerals, the average illite content of the Shanxi Formation is 25.97%, and the high-value area is located near Well J7, with a quartz content of more than 45%. The areas near Well J15 in the north, J3, J6, and J7 in the middle, and J28, J30, and J24 in the south have relatively higher illite contents (>25%). In the Taiyuan Formation, the average illite content is 21.29%, and that of Well J15 is higher than 35%. The relatively high-value areas in the region are found in the northwest and southeast of the study area, with contents exceeding 20%. The average content of clay minerals in the ironite-montmorillonite mixed layers in the Shanxi Formation is 36.50%. The contents are generally low in the center and high around the periphery. The high-value areas of ironite- montmorillonite mixed layers are in the vicinity of Wells J12 in the northwest, J26 in the northeast, G4 in the west, and J60 and J65 in the southeast of the study area, with contents exceeding 35%. The average content of the ironite-montmorillonite mixed layer in the Taiyuan Formation is 26.60%. Wells J16, J9, J4, and J28 in the northwest and southwest of the study area and Wells J20, J19, and J34 in the southeast are relatively high-value development areas with a content of more than 25%.

3.2.2. Storage Space. The porosity of the shale formation in the study area is generally less than 3%, and the permeability is less than 0.1 md. The porosity of the Shanxi formation ranges from 0.72% to 1.33%. Relatively high-value areas are located in the north, central, and western regions of the study area. The porosity of the Taiyuan formation ranges from 0.76% to 2.61%. Relatively high-value areas are found in a few well areas in the north, west, and southeast of the study area.

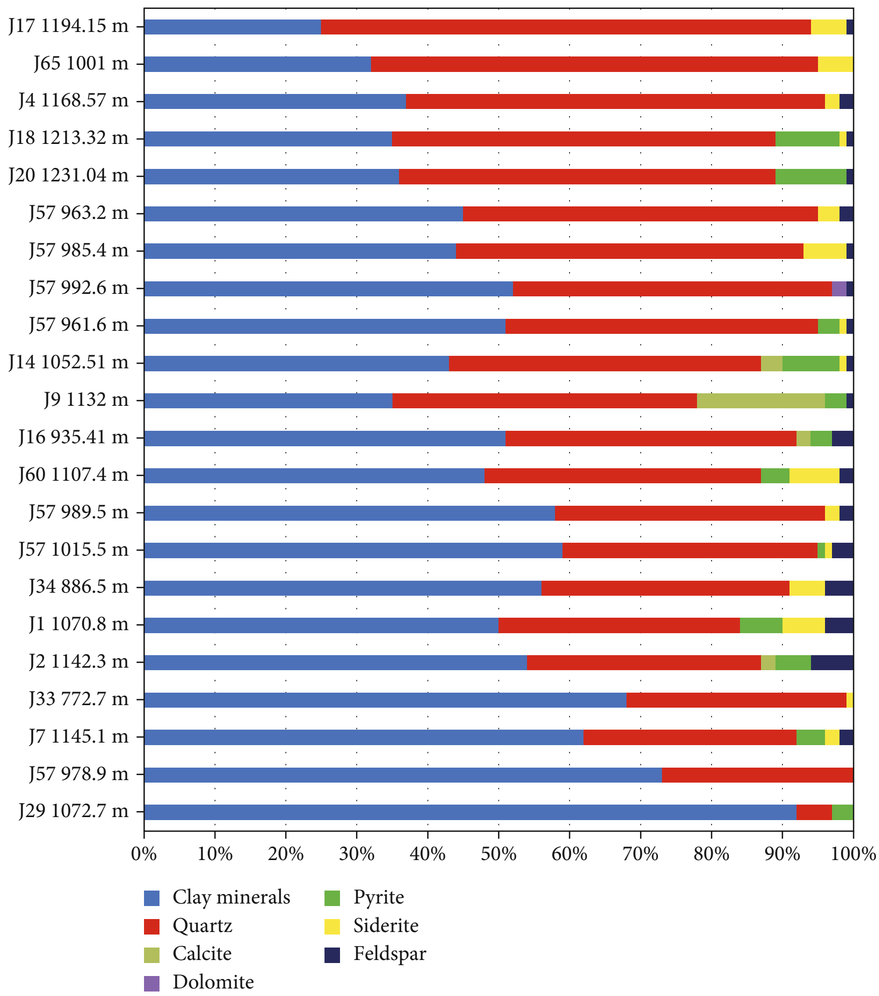
The reservoir space of mud shale in the study area includes matrix pores and fractures, especially pores related to organic matter, clay minerals, and dissolution. The pores include primary pores, secondary pores, intergranular pores, and dissolution pores. Fractures include structural fractures and diagenetic fractures (Figure 8).

(1) Residual primary pores: these are scattered among the silty intergranular pores of the clay flakes. The



(a)

Figure 7: Continued.



(b)

Figure 7: The detrital components of the mud (shale) stone reservoirs in the study area. (a) Shanxi Formation; (b) Taiyuan Formation.

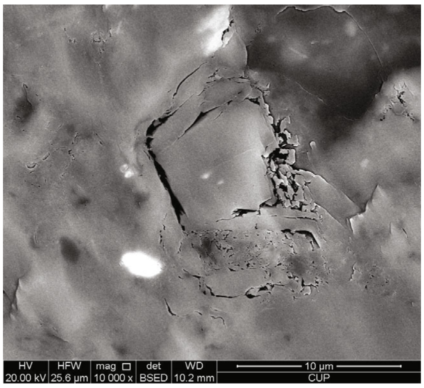
samples from the Shanxi Formation mostly exhibit point-line contacts between particles, whereas those from the Taiyuan Formation primarily show line-concave-convex contacts and some point-line contacts. The compaction increases, and the number of residual primary pores decreases substantially with the burial depth.

(2) Organic matter pores: these are pores formed in the organic matter in the shale by large amounts of hydrocarbon generation, including micropores inside organic matter, pores between organic matter and other detritus, and pores formed by dissolution of organic matter clumps. Most pores have a honeycomb or irregular shape, and the pore size is about 5–30 μm.

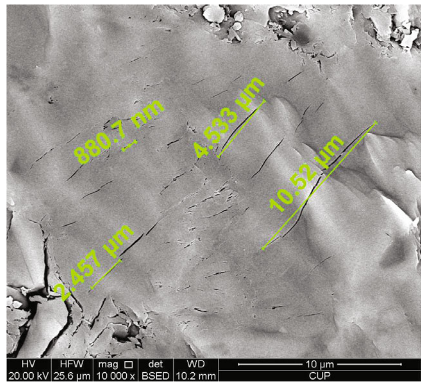
(3) Micropores formed by clay mineral transformation: the montmorillonite in the ironite/montmorillonite mixed-layer clay minerals is transformed into illite, and micropores are generated due to volume reduction. Secondary dissolution pores are produced by the strong dissolution of feldspar and rock debris along the joints. Most of the pores are arranged in long strips, and the pore size ranges from 5 μm to 20 μm.

(4) Fractures: the study area is located at the margin of the basin. Fractures have developed in the shale segment. Most have high angles, and a few have low angles, and most are filled with calcite.

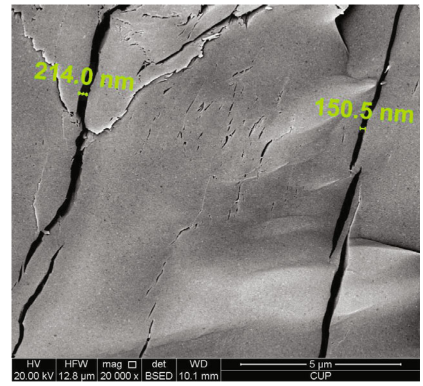
3.2.3. Brittleness and Mechanical Properties of the Reservoir. The brittleness of rock depends primarily on its petrological characteristics [21]. The higher the content of brittle components (such as silica), the stronger the brittleness of the rock is [22, 23]. The average quartz content and clay content in the target strata in the study area are 40% and 49%, respectively. The silica content is relatively high, which is favorable for the fracturing of shale gas reservoirs [24, 25]. Poisson's ratio (μ) of the rock is an indispensable rock mechanics parameter for fracturing, drilling, and engineering. It is the ratio of the relative transverse compression to the relative



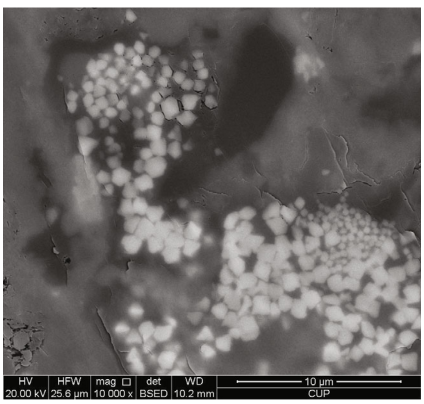
Mineral intergranular pores
J6Well, 1067.1 m, P1s



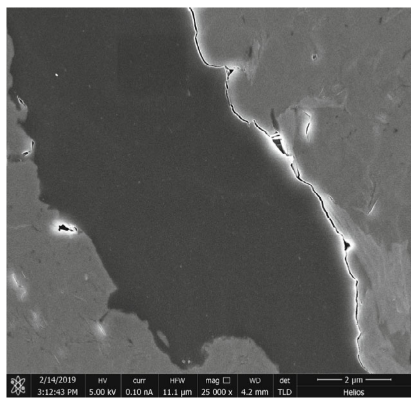
Micropores formed by mineral transformation
J6Well, 1048.6 m, P1s



Residual primary pores
J51Well, 2208.5 m, P1s



Intergranular pores of pyrite
J6 Well, 1044.9 m, P1s



Marginal pores and fissures of organic matter
J51Well, 2273.4 m, P1s

High angle cracks
J5Well, 910 m, P1s

FIGURE 8: Scanning electron microscopy images of the shale.

longitudinal elongation of an elastomer; it is typically calculated using the density and the time difference between the P-wave and S-wave.

The shear wave velocity was calculated using the empirical formula and acoustic time difference and density data, and Poisson's ratio and Young's modulus were calculated. Figure 9 shows the results for Well Ji 5. Poisson's ratio is below 0.35, with an average of 0.32, and Young's modulus is generally above 20.00 MPa, which is similar to the shale brittleness of the Monterey formation in the San Joaquin Basin of the United States. According to well logging data, Poisson's ratio of the Shanxi Formation is 0.29–0.45, with an average of 0.31. Poisson's ratio of the Taiyuan Formation is 0.28–0.42, with an average of 0.31. At present, it is generally believed that Poisson's ratio of shale is relatively high (>0.4) and the plasticity is high, whereas sandstone has a relatively low Poisson's ratio (<0.3) and high brittleness. Therefore, the lower the Poisson's ratio of rock, the higher its brittleness is. Poisson's ratios of the shale reservoirs in the study area are generally less than 0.35. Therefore, they contain components with high brittleness, which results in good mechanical properties of shale gas reservoirs after fracturing. Only Well J18 in the north has a high Poisson's ratio, and the mudstone has high plasticity, which is not conducive to fracturing and shale gas reservoir development.

3.3. Gas Content Analysis. The total gas content of the Barnett shale in the Fort Worth Basin is 8.49–9.91 m^3/t, with an adsorbed gas content of 40%–60%, ranking first among all shale gas scales. The gas content of the Antrim shale in the Michigan Basin is 1.415–2.83 m^3/t, indicating a positive correlation with the organic carbon content. This shale gas formation has a high proportion of adsorbed gas (more than 70%). The total gas content of the Ohio shale source rocks in the Appalachian Basin ranges from 1.70 to 2.83 m^3/t, and the adsorbed gas content is about 50%. The total gas content of the New Albany Shale in the Illinois Basin is relatively low, ranging from 1.13 to 2.26 m^3/t, and that of the Lewis shale in the San Juan Basin ranges from 0.42 to 1.27 m^3/t, with 60% to 88% adsorbed gas content. The gas contents of the Gordondale shale (0.7–3.0 m^3/t) in northeastern British Columbia, Canada, and the Qiongzusi shale (0.27~1.03 m^3/t) are significantly lower than that of the Barnett shale (8–9 m^3/t). The measured gas content of the shale core of Well Daji 51 in the study area is 0.5–3.7 m^3/t, indicating an upper-medium level.

3.4. Calculation of Resource Quantity. The resource quantity of the Shanxi Formation and Taiyuan Formation in the study area was calculated. Although the shale gas reservoirs are discontinuous, they have strong heterogeneity. Therefore, the resource quantity of shale gas reservoirs should be calculated

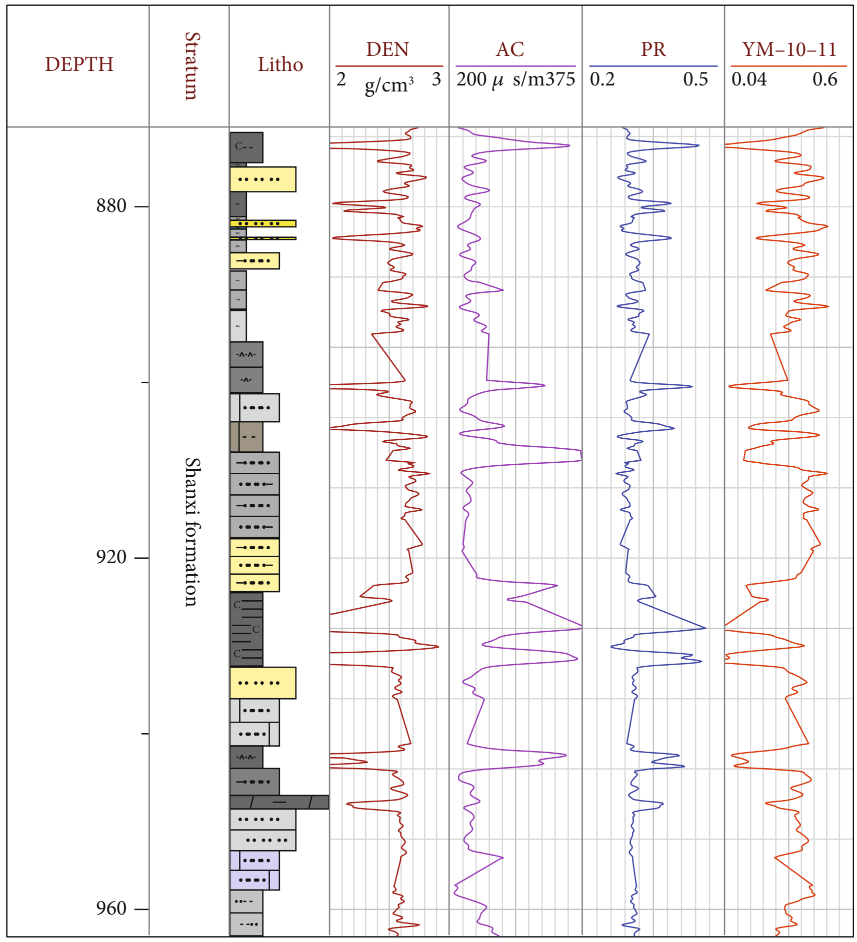


Figure 9: Calculation results of rock mechanics parameters of Well J5.

by integrating geological factors, technical factors, and economic factors. At present, evaluation methods of shale gas resources in foreign countries include the analogy method, material balance method, trend curves, and numerical simulations. Since the study area is currently in the early stage of shale gas exploration, there are insufficient geological data. Thus, we used existing data, regional geological survey data, the geological characteristics of mature shale gas reservoirs in the province, and resource evaluation to determine the resource quantity in the Shanxi Formation and Taiyuan Formation by analogy. One of the key parameters in the analogy method is the selection of the calibration area. The study area was compared with five major shale gas basins in North America using six evaluation parameters: organic carbon content, maturity, brittle mineral content, porosity, thickness, and burial depth. We created a comprehensive score for all shale gas basins and used the basin with the closest score as the calibration area.

As shown in Table 1, Barnett shale has the highest score, followed by the New Albany Shale and the Ohio Shale. The Shanxi Formation in the study area has a score of 72.98, which is lower than the score of the five largest shale gas basins in North America. It is most similar to the Antrim Basin shale. Therefore, the Antrim Basin shale is selected as the calibration area. Equation (1) is used for an analogy calculation of the shale gas resources in the study area and the calibration area to obtain the shale gas resources in the study area. The calculation results are listed in Table 2.

$$R_i = \left(\frac{S}{A_i}\right) \bullet () \bullet Q_i, \tag{1}$$

where R_i is the number of analogous resources in the study area ($\times 10^{12}$ m^3); S is the area of the study site ($\times 10^4$ km^2); A_i is the calibration area ($\times 10^4$ km^2); λ/λ_i is the study area and calibration area score ratio; and Q_i is the resource amount in the calibration area ($\times 10^{12}$ m^3).

As shown in Table 2, the Shanxi Formation and Taiyuan Formation have similar geological conditions, areas, and shale gas resources. Compared with the shale in the Antrim Basin, the resources of the Shanxi Formation and Taiyuan Formation are 1500×10^8 m^3 and 1300×10^8 m^3, respectively. The average analogous resources of the Shanxi Formation and Taiyuan Formation are 1680×10^8 m^3 and 1560×10^8 m^3, respectively, and the total amount of resources in this area is $2{,}800–3{,}200 \times 10^8$ m^3.

Table 1: Comparison of five shale gas basins in the United States and two in the southeastern Ordos Basin.

Parameters	Weight coefficient	Barnett		Antrim		Ohio		New Albany		Lewis		Shanxi formation		Taiyuan formation	
		Features	Score	Features	Score	Features	Score	Features	Score	Features	Score	Features	Score	Features	Score
TOC (%)	0.25	4.5	80	0.3-24	92	0-4.7	66	1-25	86	0.45-2.5	45	0.51-29.15	46.2	0.011-22.52	50.6
Ro (%)	0.15	1.0-1.3	78	0.4-0.6	34	0.4-1.3	56	0.4-1.0	32	1.6-1.88	100	1.45-2.341	94.8	1.25-2.165	94
Brittle minerals (%)	0.15	35-50	96	20-41	74	45-60	100	50	100	50-75	100	28-58	84	27-69	81
Porosity (%)	0.10	4-5	80	9	100	4.7	80	10-14	100	3-5.5	72	0.5-3.1	32.5	0.9-4.9	34.5
Thickness (m)	0.20	61-91	100	49	80	91-305	100	30-122	92	152-579	100	23.18-99.84	81.8	17.22-66.94	56
Buried depth (m)	0.15	1981-2591	79	183-732	90	610-1524	98	183-1494	96	914-1829	92	571-1447.5	100	620.5-1503	99.5
Score			86		78.7		82.6		84.1		82.3		72.98		68.475

Table 2: Comparison of the shale gas resources in the United States and the Lower Permian formation in the southeastern Ordos Basin after calibration.

Shale name	Area × 10^4 km^2	Resources × 10^{12} m^3	Resources of the Shanxi Formation × 10^{12} m^3	Resources of the Taiyuan Formation × 10^{12} m^3
Barnett	3.81	5.66	0.37	0.35
Antrim	3.16	0.99-2.15	0.15	0.13
Ohio	25.01	6.37-7.02	0.07	0.07
New Albany	9.08	2.44-4.53	0.10	0.09
Lewis	3.0909	1.74	0.15	0.14

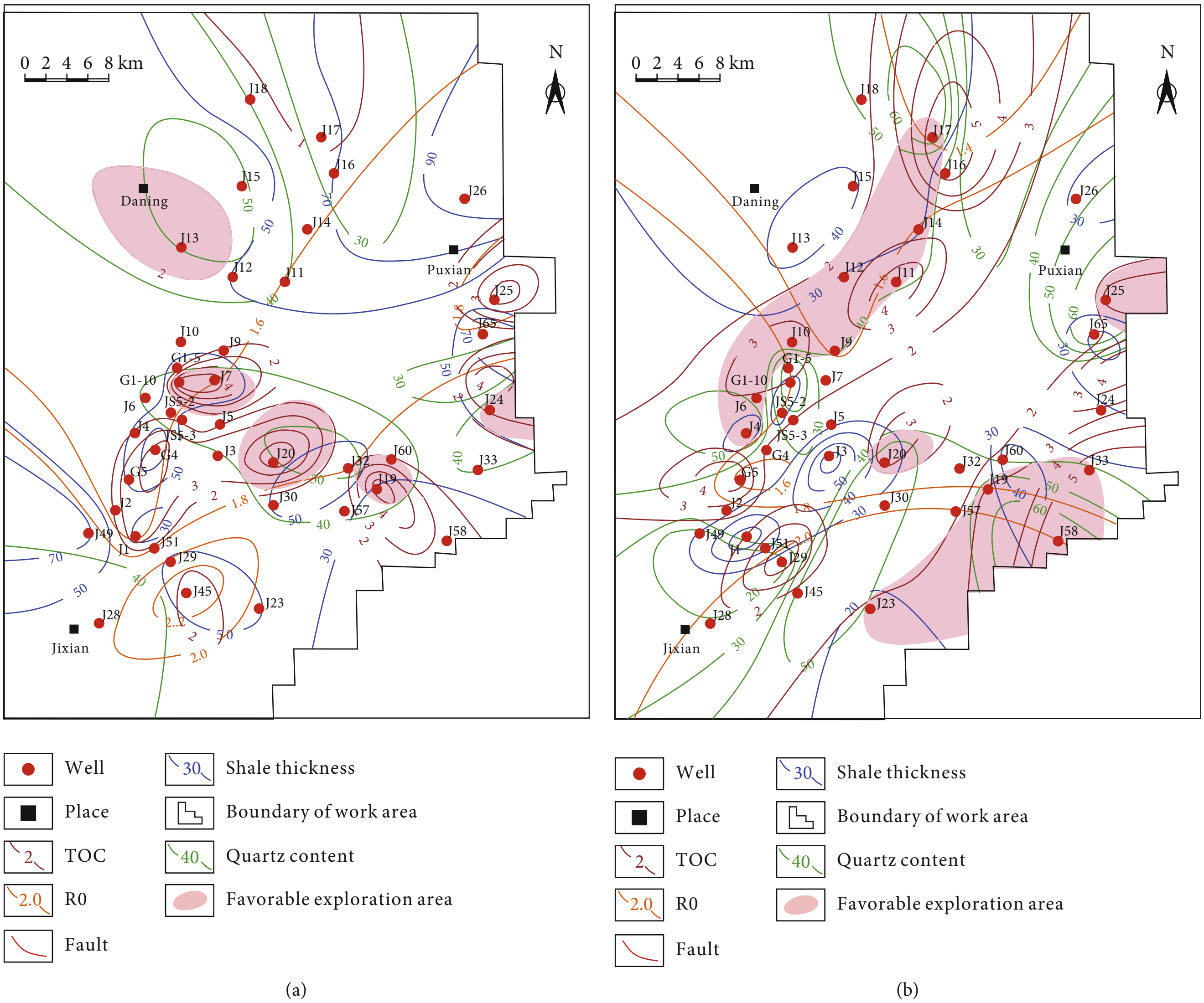


Figure 10: Prediction results of favorable areas for shale gas exploration in the lower Permian strata in the southeastern Ordos Basin. (a) Shanxi Formation; (b) Taiyuan Formation.

4. Discussion

4.1. Comparison of Shale Gas Characteristics in the Daning-Jixian Block and in the United States. The commercially developed shale gas in the United States has a higher organic matter content (above 5% on average) than the domestic shale gas. However, its maturity is generally lower than 2% before the main gas generation stage, resulting in insufficient hydrocarbon generation (shale gas) and limited resource potential. China's main shale gas areas include the Qiongzhusi shale and Longmaxi shale in the Sichuan Basin, the Shanxi-Taiyuan formation in the Ordos Basin, and the Cambrian-Ordovician shales in the Tarim Basin. Their high maturity of organic matter means that they are in the high maturity and overmaturity stages beyond the main gas generation stage [8]. The degree of transformation from organic matter to hydrocarbon is relatively high, and the resource amount is massive. Shale gas reservoirs in the United States are mainly carbonate rocks in shale layers and generally have a thickness of less than 50 m [26], limiting the abundance of shale gas. Meanwhile, shale gas reservoirs in the United States are brittle, form structural fractures easily, and have poor roof and floor conditions [27]. However, domestic shale is generally thicker. For example, the thickness of the shale in the study area of the Edong gas field exceeds 100 m in some areas. The roof and floor conditions are superior, providing good source rock and preservation conditions for the generation and preservation of shale gas. These conditions are favorable to the development and preservation of shale gas reservoirs. Furthermore, the three major shale gas areas in China are located in several large basins, such as the Ordos Basin. The widely distributed shales are superimposed in the same basin with a relatively high concentration and strong comparability, which is conducive to large-scale exploration and development.

4.2. Prediction of Favorable Shale Gas Zones. Based on previous studies [27–31] and the geological characteristics of the study area, the following factors should be considered to predict favorable shale gas zones. (1) When the abundance of organic matter is high and has reached a certain level of thermal maturity, the hydrocarbon gas can be stored in the form of adsorbed gas on the surface of the clay and organic matter [32, 33]. Therefore, the abundance and thermal maturity of organic matter are crucial geological factors for determining shale gas accumulation. (2) The porosity and permeability of the mud-shale formation are low, and there is no significant difference between the regions in the study area. (3) The shale formation depends on the brittleness degree of the formation, which is related to the mineral type. Usually, a high silica content results in better mechanical properties of the shale gas reservoir. Therefore, the main factors affecting the economic value of shale gas reservoirs are the abundance of organic matter, thermal maturity, thickness, and quartz content. Thus, the favorable areas for shale gas exploration were predicted using these factors.

Figure 10 shows the prediction results of the favorable areas for shale gas exploration. The favorable areas in the Shanxi Formation are located in the central and eastern parts of the study area and in the north near Daning area. The organic carbon content of the favorable area in the middle is 2%–8%, the vitrinite reflectance ranges from 1.5% to 2.0%, the thickness ranges from 20 m to 70 m, and the quartz content is 40%–52%. In the favorable eastern area, the organic carbon content is 2%–4%, the vitrinite reflectance exceeds 1.8%, the thickness is larger than 60 m, and the quartz content is greater than 40%. In the favorable northern area near Daning, the organic carbon content is greater than 2, the vitrinite reflectance is higher than 1.3%, the thickness is larger than 40 m, and the quartz content exceeds 50%.

The favorable areas in the Taiyuan Formation are located in the northwest, southeast, east, and middle of the study area. The favorable area in the northwest contains 2%–7% organic carbon, the vitrinite reflectance is 1.3%–1.9%, the thickness is 20 m–40 m, and the quartz content is 40%–70% quartz. In the southeast, the organic carbon content is 2%–9%, the vitrinite reflectance is 1.6%–2.2%, the thickness is 17 m–40 m, and the quartz content is 40%–70%. In the eastern part, the organic carbon content is 2%–4%, the vitrinite reflectance is greater than 1.7%, the thickness is larger than 25 m, and the quartz content exceeds 60%. The central area has a TOC of 2%–3.5%, vitrinite reflectance of more than 1.6%, and a thickness greater than 35 m, and the quartz content exceeds 55%.

5. Conclusions

The Shanxi-Benxi Formation in the study area is a transitional marine-continental shale system with good reservoir-forming conditions. The organic matter in the study area is abundant, the kerogen type is predominantly of type II 2, and the area has high maturity. These conditions are favorable for gas generation.

The Shanxi-Benxi Formation has diverse reservoir spaces and contains mainly residual primary pores formed by compaction, secondary pores formed by organic matter hydrocarbon generation and clay mineral transformation, secondary dissolution pores, and fractures. The average content of clay minerals is about 50%, the quartz content near the provenance is relatively high, and Poisson's ratio is 0.31. The rock is brittle and fractures easily.

The shale gas reservoir characteristics in the study area and five major shale gas basins in the United States were compared using the analogy method based on geological conditions. The Antrim Basin was selected as the calibration area. The cumulative resources of the Shanxi and Taiyuan Formations in the study area were calculated as $2{,}800–3{,}200 \times 10^8\,m^3$.

The organic matter abundance, thermal maturity, thickness, and quartz content are the main controlling factors affecting the development of shale gas in the study area. The favorable areas of shale gas are predicted using these factors. The most favorable areas of the Shanxi Formation are located in the middle, east, and north of the study area, and those of the Taiyuan Formation are located in the northwest, southeast, and east, with a small area in the middle.

Data Availability

Data is not available for confidential reasons.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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