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Characterization and Development Potential Evaluation of the No. 5 Coal Reservoir in the Shanxi Formation of a Block in Southeastern Ordos Basin

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Abstract: The southeastern margin of the Ordos Basin holds immense potential for coalbed methane (CBM) resources, yet its development faces severe challenges due to the extremely low permeability of the reservoirs. To thoroughly investigate the reservoir characteristics and development potential of the No. 5 primary coal seam in the Lower Permian Shanxi Formation within a specific block, this study systematically analyzed the spatial distribution, coal lithology and quality, gas-bearing properties, pore-permeability characteristics, and mechanical properties of the coal seam. The methodology integrated well logging interpretation, core observation, maceral identification, isothermal adsorption experiments, and rock mechanics testing. The results indicate that the No. 5 coal seam is controlled by a gently dipping monocline structure that is high in the east and low in the west, with a thickness ranging from 4.42 to 8.61 m (averaging 6.39 m). Three phases of tectonic fractures have developed: the Indosinian near north-south trending fractures are weakly developed, whereas the Yanshanian northwest-southeast trending and Himalayan northeast-southwest trending fractures are strongly developed. This leads to significant spatial variations in the in-situ stress field and fracture intensity, constituting the macroscopic geological background for reservoir heterogeneity. The coal seam is characterized by high rank, high vitrinite content, and low ash and moisture. The coal texture is predominantly primary and cataclastic. Gas content increases with burial depth, generally exceeding 15 m^3/t in deep zones; however, the permeability is overall lower than 0.4 mD, exhibiting an ultra-low permeability feature. The maximum and minimum horizontal principal stresses and the breakdown pressure all increase with depth. The difference coefficient of in-situ stress is generally greater than 0.37, indicating that the reservoir is in a state of strong stress disequilibrium. A comprehensive evaluation suggests that the No. 5 coal seam in the study area has undergone multi-stage tectonic modifications. Despite its high resource abundance, it possesses extremely low permeability and exists in a state of strong stress disequilibrium. It is a typical reservoir type that requires large-scale hydraulic fracturing stimulation to achieve industrial productivity.

Keywords: The southeastern part of the Ordos Basin, Shanxi Formation, sedimentary characteristics, reservoir features.

1. Introduction

Coalbed methane (CBM) is an important type of unconventional natural gas, and its efficient development is vital for optimizing the energy structure. Preliminary exploration indicates that the No. 5 coal reservoir in the Shanxi Formation, southeastern Ordos Basin, is characterized by high resource abundance and overall ultra-low permeability. Consequently, the natural productivity of single wells generally fails to meet the standards for commercial industrial gas production. In recent years, despite certain breakthroughs in fracturing stimulation technology, fracturing stimulation effects show strong regional differentiation, which is closely related to reservoir heterogeneity. However, the tectonic stress control mechanism of reservoir heterogeneity has not been fully revealed. The coupling effect between the differential development of paleostructural fractures formed by the superposition of multi-stage tectonic movements and the distribution of the present-day in-situ stress directly determines the reservoir's fracability and the propagation direction of hydraulic fractures. Yet, previous studies have mostly focused on single-factor analysis, lacking comprehensive systematic research on tectonic deformation, fracture staging, in-situ stress state, and reservoir physical properties.

The overall tectonic setting of the No. 5 coal seam in the study area is a gently dipping monocline with an east-highand west-low structural pattern, where faults are poorly developed. Nevertheless, it has undergone tectonic stress field transformations during the Indosinian, Yanshanian, and Himalayan orogenies, forming multiple sets of tectonic fractures with different orientations. The differential development of multi-stage fractures not only alters the matrix permeability of the coal reservoir but also further aggravates reservoir heterogeneity by locally adjusting the in-situ stress state. Therefore, on the basis of clarifying the fundamental characteristics of coal lithology and physical properties, establishing the intrinsic correlation among tectonics, fractures, stress, and physical properties is the key to scientifically evaluating the reservoir's development potential.

Taking the No. 5 coal seam of the Shanxi Formation in a block of the southeastern Ordos Basin as the research object, and based on drilling cores, well logging, and testing data, this paper systematically carries out coal petrographic and coal quality analysis, gas content testing, pore structure and permeability parameter analysis, as well as rock mechanics and in-situ stress evaluation. The research objectives include: (1) clarifying the thickness distribution and tectonic framework of the coal seam, and characterizing the development features of multi-stage tectonic fractures; (2) defining key reservoir parameters such as coal lithology and quality, gas-bearing properties, pore-permeability, and mechanical properties; (3) revealing the control laws of in-situ stress and fracture development on reservoir heterogeneity, and comprehensively evaluating the fracturing stimulation potential of the reservoir. The technical route follows the logic of "geological background constraint—multi-attribute reservoir characterization—stress field analysis—engineering potential evaluation," aiming to achieve a transformation from static reservoir description to dynamic stimulation potential evaluation. This study intends to provide a theoretical basis and technical reference for the scientific development of CBM reservoirs in the study area and those with similar geological conditions.

2. Regional Geological Setting

2.1. Structural Characteristics of the Study Area

Currently, the Ordos Basin exhibits a north-south trending rectangular outline, with a steep and narrow eastern limb, and is classified as a craton-margin superimposed basin. According to basement properties, tectonic morphology and geological evolutionary history, previous studies have divided the basin into six first-order tectonic units: the Yimeng Uplift, Western Shanxi Flexural Fold Belt, Weibei Uplift, Tianhuan Depression, Western Margin Thrust Fault Belt, and Northern Shaanxi Slope [1-3].

The study area is located in the southern segment of the Western Shanxi Flexural Fold Belt in the Ordos Basin. Structurally, it is an east-west dipping monocline, displaying a tectonic pattern of “one uplift, one depression and two slopes” [4-6]. Specifically, it includes the central reverse fault-controlled Taoyuan anticline (Xueguan-Yaoqu uplift), the Puxian Depression (Xueguan-Yukou depression-uplift), as well as the flanking Xiangning Slope and Daning Slope[7,8]. The study area belongs to the Daning Slope zone, which is characterized by a gentle gradient and small dip angle, and is mainly affected by Yanshanian and Himalayan tectonic movements.

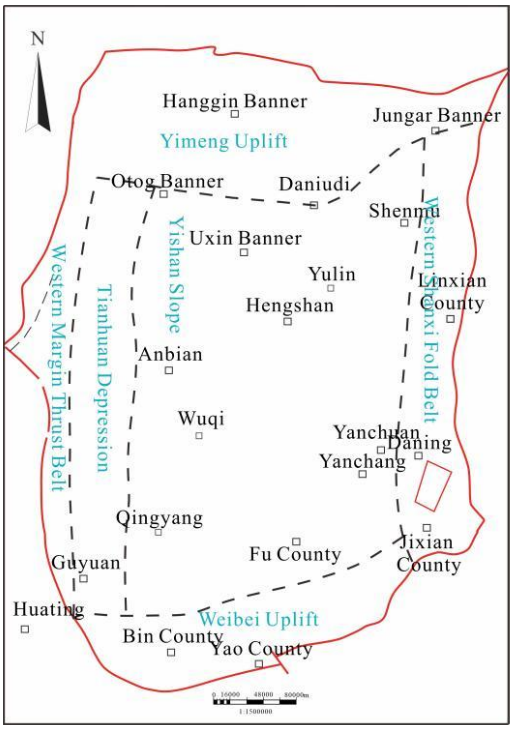

Figure 1. Geological overview of the study area

Seven coal seams are developed in the Shanxi Formation, among which the No. 5 coal seam is the primary target for CBM development. This coal seam shows an east-high and west-low monocline occurrence, dipping northwestward. Six NE-SW trending reverse faults are developed within the area, with small fault throws and short extended lengths. In planar distribution, the northwestern part is a broad and gentle fold zone, while the southeastern part is a tight and continuous fold zone.

Following the deposition of the Shanxi Formation, the study area primarily underwent four major phases of tectonic movements: the Hercynian, Indosinian, Yanshanian, and Himalayan orogenies. In particular, the Late Yanshanian and Himalayan tectonic events exerted a significant influence on the formation of the tectonic framework and the coupled enrichment of coal-measure gas in the Shanxi Formation.

(1) Coupled Enrichment of Monocline Structures and Coal-Measure Gas

After hydrocarbon generation in the coal reservoir, the study area experienced differential tectonic uplift, characterized by stronger uplift in the east and weaker uplift in the west. During this uplift process, free gas escaped and migrated to other strata; consequently, coalbed methane (CBM) exists primarily in the form of adsorbed gas, with little to no free gas remaining. The monocline structure has a minor impact on the coal reservoir rock structure, which is dominated by primary coal structures. With thick mudstone acting as the roof and floor, CBM preservation conditions are favorable. However, effective reservoir stimulation is required during development to achieve ideal industrial productivity.

(2) Coupled Enrichment of Micro-Folds and Coal-Measure Gas

In the micro-fold developed zones of the study area, the presence of micro-folds has facilitated the development of open fractures and cleats within the reservoir. The coal reservoir rock structure ranges from primary to cataclastic. These open fractures provide storage space for free gas. Together with micro-fractures in the coal reservoir and its roof and floor strata, a portion of the free gas in the coal reservoir migrates into adjacent shale and tight reservoirs. Therefore, a certain amount of free gas is retained in these adjacent shales and tight rocks, laying a material foundation for short-term high-yield CBM production in the micro-fold developed zones.

(3) Coupled Enrichment of Fault Structures and Coal-Measure Gas

Six small faults in the study area cut through the entire Shanxi and Taiyuan Formations. The fault fracture zones are primarily filled with shale, exhibiting good water-blocking and gas-sealing properties. As a result, in addition to adsorbed gas, a significant amount of free gas is present in the coal seams. However, in areas where the fracture zones intersect with the limestone of the Taiyuan Formation, CBM exists primarily as adsorbed gas with little to no free gas, due to the influence of groundwater hydrodynamic processes.

2.2. Characteristics of Coal-Bearing Strata in the Study Area

2.2.1. Sedimentary Facies Characteristics

Sedimentary facies comprehensively reflect sedimentary environments and their sedimentary products, and collectively summarize the features and distribution regularities of sediments under specific depositional conditions. A sedimentary environment refers to the paleogeographic background during sediment formation, including climatic conditions, tectonic settings, and physical-chemical properties of depositional media. Sedimentary products can be identified via paleontological and lithological assemblages, as well as paleoclimatic and paleotectonic evidence.

Therefore, the sedimentary environment is the dominant controlling factor of sedimentary rock attributes, whereas sedimentary products act as the material record of the sedimentary environment. Systematic analysis of both sedimentary environment and sedimentary products enables accurate identification of sedimentary facies types and characteristics.

Based on sedimentology and sequence stratigraphy theories, combined with core observations, outcrop surveys, well logging interpretation, cutting logging data and laboratory test results, this study identifies sedimentary microfacies types indirectly according to reflected sedimentary features.

The results show that the Permian Taiyuan Formation in the Daning-Jixian Block was formed in a sedimentary evolutionary sequence of carbonate platform - barrier island - lagoon - tidal flat. Four major sedimentary systems are recognized: carbonate platform, barrier island-lagoon, braided river delta, and fluvial-lacustrine system. The main coal seams of the Taiyuan Formation mainly developed in peat flat microfacies of the lagoon subfacies. The Shanxi Formation developed within an evolutionary sequence of barrier island - lagoon - tidal flat - delta, with its coal seams mostly accumulated in peat swamp microfacies of the delta plain subfacies [7-14].

(1) Epicontinental Marine Facies

The Lower Permian Taiyuan and Shanxi Formations in the study area were deposited in an epicontinental marine environment. Five subfacies are identified, including open platform, restricted platform, barrier island, lagoon and tidal flat.

Open Platform Subfacies

This subfacies mainly occurs in the Taiyuan Formation. Limestone strata in the southern study area are mostly deposited in this facies. The lithology is dominated by micritic bioclastic limestone, with massive and wavy bedding well developed. Fossil assemblages are abundant and dominated by stenohaline organisms, such as calcareous foraminifera, corals, articulate brachiopods and echinoderms. A small number of euryhaline organisms are also locally developed, including inarticulate brachiopods, bryozoans and pelecypods.

Restricted Platform Subfacies

This subfacies is also mainly developed in the Taiyuan Formation, with a smaller distribution extent than the open platform subfacies. It is mostly concentrated in the eastern and northern parts of the study area, and laterally intergrades with open platform, lagoon and tidal flat subfacies.

Barrier Island Subfacies

This subfacies is widely developed in both the Taiyuan and Shanxi Formations. The sediments are dominated by medium-fine grained quartz sandstone, with local interbeds of conglomeratic coarse quartz sandstone. Detrital constituents are mainly quartz, accounting for over 90 % of the total content. The rocks are cemented by siliceous and argillaceous materials, with relatively high compositional and textural maturity, indicating that terrigenous clastics experienced repeated tidal reworking. Low-angle tabular, wedge-shaped and bidirectional cross-bedding are well developed. Vertically, it commonly intergrades with tidal flat and lagoon subfacies.

Lagoon Subfacies

This subfacies is mainly developed in the Taiyuan and Shanxi Formations, consisting of gray and dark gray mudstone and sandy mudstone. Clay minerals are dominated by illite, followed by kaolinite and montmorillonite. Abundant plant fossil fragments and a small amount of animal fossils are developed, including brachiopods, gastropods and ostracods. Fossil taxa are monotonous and small-sized, with common bioturbation structures. The depositional setting is a brackish to saline reducing water environment. Horizontal bedding and seasonal laminations are widespread. Ellipsoidal, nodular and irregular siderite nodules are commonly distributed along bedding planes, and pyrite crystals can be observed locally, indicative of a reducing sedimentary condition. Vertically, this subfacies frequently intergrades with barrier island and tidal flat subfacies.

Tidal Flat Subfacies

The tidal flat subfacies consists of multiple microfacies, including tidal channel, sand flat, mixed flat and mud flat. Its lithology comprises gray fine sandstone, conglomeratic uneven-grained sandstone, silty mudstone and mudstone. Vertically, it is characterized by the superposition of inclined bedding, swash cross-bedding, wavy bedding and horizontal bedding. Bioturbation and sand pipe structures are clearly visible.

(2) Delta facies

The North China epicontinental sea was characterized by shallow, open water, with river channel depths comparable to those of the epicontinental sea itself. This paleogeographic setting determined the uniqueness of its delta system: the delta plain is relatively well-developed, whereas the delta front and prodelta subfacies are relatively underdeveloped.

A delta is a nearshore clastic sedimentary system formed when rivers transport detrital materials into a lake (or marine) basin. The sudden decrease in flow velocity results in rapid sediment accumulation at the estuary, leading to irregular seaward progradation of the shoreline. The geometric shape of framework sandbodies and the vertical sedimentary sequence are the most significant identification markers of delta facies. Based on previous research results and analysis of the sedimentary background in the study area, it is concluded that the Shanxi Formation is dominated by delta facies deposition.

Prodelta Subfacies

Located at the distal end of the delta front toward the sea (or lake), this subfacies is mainly distributed in the lower part of the Shanxi Formation and the middle to upper parts of the Taiyuan Formation. The lithology is dominated by black mudstone and sandy mudstone, which are rich in organic matter and pyrite nodules, contain pelecypod fossils, and exhibit horizontal bedding. The GR (Gamma Ray) logging curve shows a smooth or weakly serrated mudstone baseline.

Delta Front Subfacies

Mainly developed at the top of the Taiyuan Formation and the bottom of the Shanxi Formation, this subfacies comprises several microfacies, including underwater distributary channels, mouth bars, distal bars, and interdistributary bays. It constitutes the main body of delta sandbodies and represents the underwater portion of the delta sedimentary system. In the study area, the four aforementioned microfacies are dominant, each with distinct sedimentary characteristics.

① Underwater Distributary Channel Microfacies

The sediments are dominated by sand and silt. The lithology consists of light gray fine sandstone and siltstone, occasionally capped with silty mudstone and gray mudstone. The fine sandstone exhibits fining-upward normal grading, with parallel bedding, tabular cross-bedding, and trough cross-bedding developed, and scour surfaces present at the base. The siltstone shows wavy bedding and argillaceous laminae, while the mudstone at the top displays horizontal bedding and contains plant carbon debris. Wavy bedding, cross-bedding, and scour-and-fill structures are common. The GR logging curve mostly presents a bell shape or a box-shaped to broad-bell composite shape.

② Mouth Bar Microfacies

Vertically, it is often located beneath underwater distributary channels, with its base frequently truncated by scouring, and is mainly observed in the Shanxi Formation. The lithology is gray fine- to medium-grained quartz sandstone and lithic quartz sandstone, with medium to high compositional maturity. Locally, the impurity content is relatively high, and glauconite is visible. Medium- to small-scale tabular and wedge-shaped cross-bedding, as well as parallel bedding, are developed. Slump deformation structures are locally observed, containing very few plant debris and carbon debris. The vertical sequence exhibits coarsening-upward reverse grading. The GR logging curve presents a bell shape, funnel shape, or a bell-funnel composite morphology.

③ Distal Bar Microfacies

Located at the distal end of the mouth bar toward the sea (or lake), it is a bar-shaped body formed by the accumulation of fine-grained sediments. The main components are silt and clay. The lithology is dominated by interbedded thin-layered siltstone, mudstone, and sandy mudstone, appearing gray and grayish-green. Its thickness is generally less than that of the mouth bar. Parallel bedding, small-scale cross-bedding, wavy bedding, and lenticular bedding are developed. Bioturbation structures are well-developed, containing a small amount of plant fossil fragments, plant debris, and carbon debris. The GR logging curve presents a finger shape, a small serrated box shape, or a bell shape.

④ Interdistributary Bay Microfacies

This is a relatively depressed quiet-water area between underwater distributary channels, dominated by clay deposition. The lithology is gray or dark gray mudstone or silty mudstone. Horizontal bedding and syndepositional deformation structures are locally developed. The GR logging curve presents a relatively smooth or weakly serrated short-segment mudstone baseline.

Delta Plain Subfacies

Mainly developed in the Shanxi Formation, this subfacies includes several microfacies, such as distributary channels, floodplains, natural levees, crevasse splays, and peat swamps.

2.2.2. Characteristics of Coal-Bearing Strata Development

The main coal-bearing strata in the study area are the Carboniferous Benxi Formation, and the Permian Taiyuan and Shanxi Formations. The stratigraphic contact relationships are as follows: the Benxi Formation is bounded at the bottom by ferroaluminum rock and is in angular unconformity with the underlying Ordovician Fengfeng Formation; the Taiyuan Formation is bounded at the bottom by the roof of the No. 8 coal seam and is in conformable contact with the Benxi Formation; the Shanxi Formation is bounded at the bottom by the base of the Beichagou Sandstone and is in conformable contact with the underlying Taiyuan Formation, and is bounded at the top by the base of the Luotuobozi Sandstone, in conformable contact with the overlying Lower Shihezi Formation. A total of 10 coal seams have developed in the study area. The Shanxi Formation contains coal seams No. 1 to No. 5 from top to bottom, the Taiyuan Formation contains coal seams No. 6 to No. 7, and the Benxi Formation contains coal seams No. 8 to No. 10. The No. 5 coal seam (Shanxi Formation) and the No. 8 coal seam (Taiyuan Formation) are the main mining seams, with the No. 5 coal seam serving as the target layer of this paper.

The main coal-bearing strata in the study area are the Lower Permian Taiyuan and Shanxi Formations, which contain a total of 10 coal seam sets. Among them, the No. 5 coal seam of the Shanxi Formation and the No. 8 coal seam of the Taiyuan Formation are the main mining seams.

(1) Taiyuan Formation

The Taiyuan Formation can be divided into three lithological cycles:

Lower part: The lithology is dominated by claystone, sandy mudstone, and siltstone, containing the regionally stable and minable No. 8 and No. 9 coal seams. The rocks generally contain ferruginous oolites and pyrite nodules, with argillaceous materials mostly appearing in clots and poorly developed bedding. The sedimentary sequence of this cycle starts from the riverbed facies, successively transitions to the floodplain facies, lake facies, and peat swamp facies, and finally ends in the lagoon-bay facies. The lithological assemblage from bottom to top consists of quartz sandstone, siltstone, mudstone, coal seam, marl or calcareous mudstone, siltstone, etc. The bottom is composed of gray to grayish-white thick-bedded quartz sandstone, interbedded with lenses of sandy mudstone or siltstone, yielding abundant plant fossils. It can be correlated with the Jinci Sandstone of Xishan, Taiyuan, Shanxi, serving as the basal marker bed of this formation.

Middle part: The lithology is dominated by marine limestone and calcareous mudstone, developing unstable thin coal seams. This cycle starts from the lagoon-bay wave zone facies and transitions upward to the shallow sea facies. The lithological sequence from bottom to top is quartz sandstone, black mudstone (interbedded with coal seams and siltstone), topped by limestone, which is black, pure in quality, rich in marine fossils, with calcite veins filling the fissures, and containing pyrite nodules.

Upper part: The lithology is dominated by dark gray siltstone, sandy mudstone, and mudstone. This cycle transitions from lake facies, swamp facies, and peat swamp facies to lake facies from bottom to top.

(2) Shanxi Formation

Based on lithological and lithofacies characteristics, the Shanxi Formation can be divided into three cycles from bottom to top:

First cycle: Mainly composed of lithic quartz greywacke, siltstone, sandy mudstone, mudstone, and coal seams. The lower lithic quartz greywacke represents alluvial plain river deposition; the overlying fine-grained lithic quartz greywacke and siltstone represent natural levee deposition; the upper part of the cycle develops a floodplain swamp, forming the relatively well-developed No. 5 coal seam across the region.

Second and third cycles: Relatively small in thickness, the lithology is dominated by sandstones of various grain sizes, siltstone, and sandy mudstone, belonging to continental river-floodplain deposition, developing the No. 2 and No. 1 coal seams respectively.

(3) Boundary between the Shanxi and Taiyuan Formations

The Shanxi Formation is in conformable contact with the underlying Taiyuan Formation. The boundary is usually defined by the base of the Beichagou Sandstone. The main lithology of this sandstone is medium-thick bedded grayish-white fine-grained or medium-to-fine-grained quartz sandstone or lithic quartz sandstone. It is thick, stable in distribution, and the bottom often develops scour surfaces caused by channel downcutting. On well logs, the natural gamma ray (GR) curve often presents a bell or box shape with a sudden change at the bottom. The lithology and sedimentary environment of the strata above the Beichagou Sandstone are distinctly different from the underlying strata: its lower part mostly develops the Dongdayao Limestone, which represents a marine sedimentary environment. Above the limestone, there are mudstones and coal seams about 1~2 m thick, overlying the No. 4 and No. 5 coal seams.

2.2.3. Development Characteristics of the Shanxi Formation

The Shanxi Formation is the primary coal-bearing stratum in the study area. The rocks are generally dark in color and dominated by sandstone and siltstone, with sandstone, siltstone, and sandy mudstone appearing in a regular, repetitive pattern. The Shanxi Formation is bounded at the top by the base of the Luotuobozi Sandstone and is in conformable contact with the Lower Shihezi Formation; it is bounded at the bottom by the base of the Beichagou Sandstone and is in conformable contact with the underlying Taiyuan Formation. The formation is divided into the Shan 1 Member and Shan 2 Member, using the base of the Jinjiagou Sandstone as the boundary. The Shan 1 Member is further subdivided into Coal Member 1, Coal Member 2, and Coal Member 3, bounded by the Tiemogou Sandstone and Niumaozhan Sandstone, respectively. The Shan 2 Member is divided into Coal Member 4 and Coal Member 5, bounded by an unnamed thick-bedded sandstone. Coal Member 5 is the main target interval of this study, containing a total of 10 sub-layers [15-17].

In the study area, the burial depth of the top of the Shanxi Formation ranges from 704.06 to 1372.74 m, with an average of 986.79 m; the burial depth of the base ranges from 910.66 to 1479.14 m, with an average of 1144.59 m. The burial depth is relatively greater in the western part and shallower in the eastern part. The elevation of the top of the Shanxi Formation ranges from -161.65 to 325.41 m, averaging 39.92 m. The elevation of the base ranges from -285.43 to 420.04 m, averaging -94.29 m. The elevation trends of the top and base of the formation are similar, gradually decreasing from east to west, overall presenting a monocline structure that is high in the northeast and low in the southwest. The thickness of the Shanxi Formation ranges from 52.69 m to 210.62 m, averaging 134.61 m. The thickness variation is largely controlled by the combined effects of the original depositional thickness and later tectonic movements, resulting in significant fluctuations.

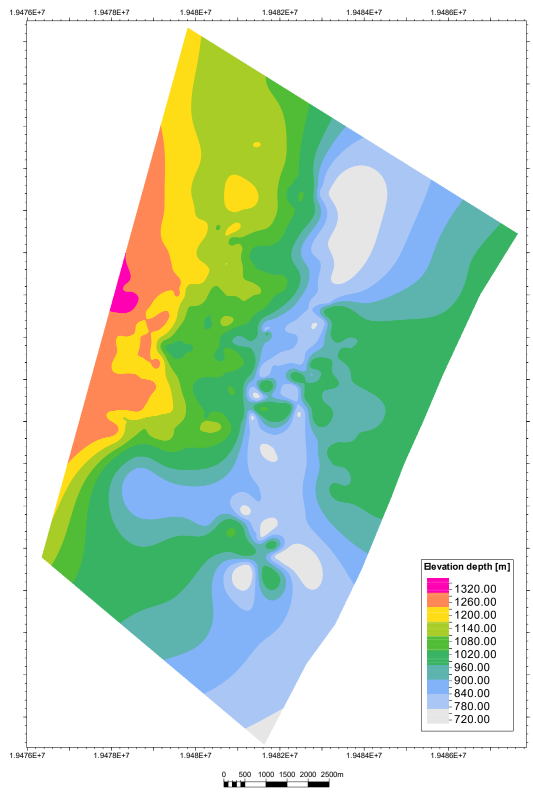

Figure 2. Burial depth of the top of the Shanxi Formation

2.2.4. Development Characteristics of The Coal Seam Section

In the study area, the burial depth of No. 5-1 coal sub-seam ranges from 889.9 to 1458.2 m, with an average of 1146.5 m; No. 5-2 coal sub-seam ranges from 891.0 to 1465.5 m, with an average of 1117.8 m; and No. 5-3 coal sub-seam ranges from 896.5 to 1465.9 m, with an average of 1132.3 m. The results show that the burial depth trends of all sub-seams are similar, increasing progressively from east to west.

The roof elevation of No. 5-1 coal sub-seam ranges from -260.14 to 139.37 m, with an average of -77.87 m; that of No. 5-2 coal sub-seam ranges from -265.31 to 136.99 m, with an average of -80.86 m; and that of No. 5-3 coal sub-seam ranges from -271.04 to 130.63 m, with an average of -87.32 m. The spacing between the three coal sub-seams is generally less than 5 m. The results indicate that the roof elevation trends of all sub-seams are consistent, decreasing progressively from east to west. In the northwestern part of the study area, broad and gentle folds plunging southeastward have developed, while tight and continuous folds are present in the southwestern part (Figure 3).

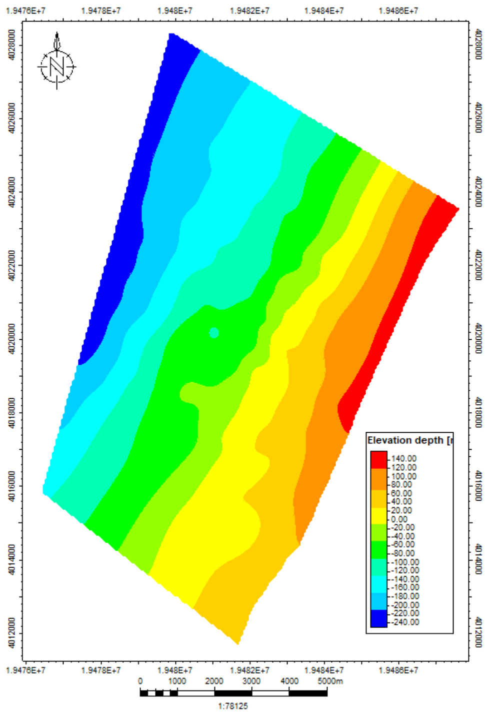

Figure 3. Elevation of the roof of the No. 5 coal seam section

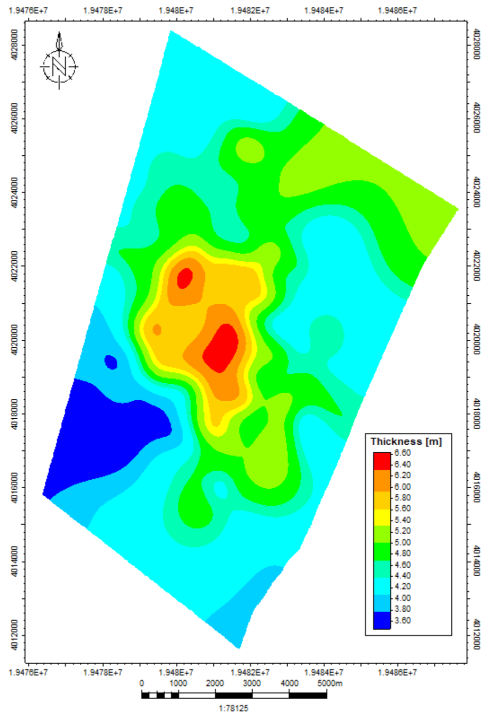

Figure 4. Thickness of the roof of the No. 5 coal seam section

The total thickness of No. 5 coal seam in the study area ranges from 4.42 to 8.61 m, with an average of 6.39 m, and most thicknesses are concentrated between 4.5 and 8.5 m. The thickness is greater in the northern part of the area and relatively smaller in the southern part. Among the individual coal plies, No. 5-2 coal has the greatest thickness and the most stable distribution, while No. 5-1 and No. 5-3 coals are relatively thinner. Specifically, the thickness of No. 5-1 coal ranges from 0 to 1.52 m, with an average of 0.67 m, mostly concentrated between 0.5 and 1 m, and this coal sub-seam locally pinches out. The thickness of No. 5-2 coal ranges from 3.45 to 6.62 m, with an average of 4.6 m, and its distribution is relatively uniform, mostly concentrated between 3.3 and 5.5 m; this coal sub-seam often contains carbonaceous mudstone and mudstone partings. The thickness of No. 5-3 coal ranges from 0.28 to 2.03 m, with an average of 1.12 m, mostly concentrated between 0.5 and 1.8 m, and tends to increase from south to north. The results show that each sub-seam within No. 5 coal member is relatively thin, and their thicknesses are mainly controlled by the sedimentary environment, showing no obvious planar variation trend (Figure 4).

3. Characteristics of the Primary Coal Reservoir

3.1. Coal Lithology and Quality

The No. 5 coal seam of the Shanxi Formation in the study area is characterized by high coal rank, high vitrinite content, low ash yield and low moisture content. The maximum vitrinite reflectance (Ro) ranges from 1.3 % to 2.2 %, corresponding to coking coal, lean coal and meager coal. It experienced obvious hypozonal metamorphism, and the spatial distribution of Ro is consistent with burial depth variation, increasing gradually from the northeast and southeast toward the central-west.

High metamorphism lays a solid foundation for the coal seam's strong gas generation potential and high adsorption capacity. In terms of maceral composition, the average vitrinite content reaches 82.03 %, showing an overall increasing trend from east to west and from south to north. The inertinite content is less than 25 %, and liptinite content is below 8 %. The extremely high vitrinite content indicates that the coal seam was formed in a closed reducing sedimentary environment, which favors the development of fractures and matrix pores and provides favorable conditions for CBM enrichment.

In terms of coal quality, the No. 5 coal seam is classified as low–medium ash coal. Its ash content ranges from 5.31 % to 15.25 %, with an average of 12.4 %; only a few local sampling points exceed 20 %. The volatile matter content is relatively low, ranging from 12.49 % to 19.3 % and averaging 15.72 %, further confirming its high metamorphic degree.

The average moisture content of the coal seam is 1.69 %, classifying it as low-moisture coal. From the perspective of macroscopic lithotype, the coal seam is dominated by bright coal and semi-bright coal, with dull coal developing thick banded structures. The coal seam exhibits both simple and complex structures locally, containing mudstone partings with a thickness of 0.1–1.0 m. The number of parting layers is less than that of the underlying No. 8 coal seam (Table 1).

Table 1. Coal petrology and coal quality in the study area

Well ID	Volatile matter/%	Reflectance/%	Porosity/%
1	14.90	1.64	2.97
2	18.28	1.34	3.00
3	14.78	1.95	2.20
4	15.25	1.65	2.40
5	12.49	1.97	2.40
6	17.28	1.35	3.20
13	19.30	1.78	3.89
14	15.60	1.89	2.46
15	14.81	1.80	3.74

3.2. Gas-Bearing Characteristics

The No. 5 coal seam of the Shanxi Formation is stably distributed across the study area. Its gas content increases with burial depth, exceeding 15 m^3/t in deep burial zones. The gas content of the No. 5 coal seam ranges from 10.53 to 16.56 m^3/t, with an average of 13.01 m^3/t (Figure 5).

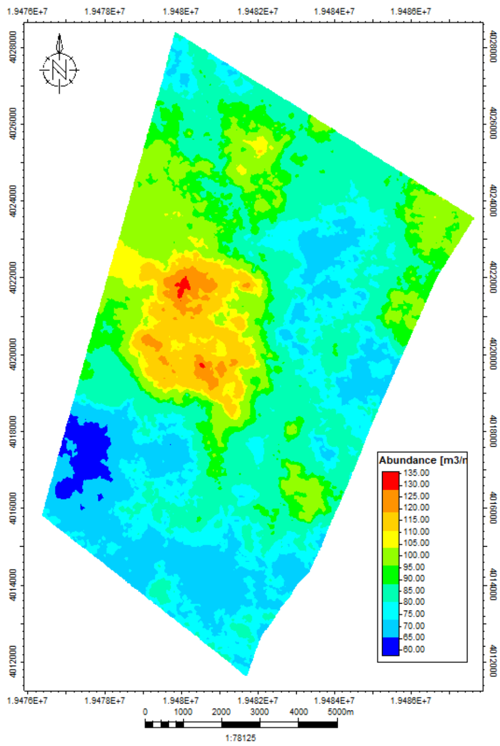

Figure 5. Contour map of resource abundance of No. 5 coal

CBM resource abundance is jointly controlled by coal seam thickness and gas content. The total resource abundance of the No. 5 coal seam ranges from 0.76 to 1.87×10^8 m^3/km^2, with an average of 1.18×10^8 m^3/km^2, and presents relatively low values in the southern study area.

3.3. Pore-Permeability Characteristics

Prediction results for the porosity of the main coal reservoir show that the porosity of the No. 5 coal ranges from 0.20 % to 6.95 %, with an average of 3.21 %, and is mainly concentrated between 1.5 % and 5 %.

Prediction results for the permeability of the main coal reservoir indicate that the permeability of the No. 5 coal ranges from 0.01 to 0.64 mD, averaging 0.16 mD, with values generally below 0.4 mD.

3.4. Mechanical Characteristics of Coal Reservoirs

In the study area, the proportion of soft coal in the No. 5 coal seam of the Shanxi Formation ranges from 0 to 0.63, with an average of 0.1, mostly concentrated between 0 and 0.2. Soft coal is undeveloped in the southern part of the area, and the coal texture of the main mining seam is dominated by hard coal (primary structure and cataclastic structure).

The Young's modulus of the No. 5 coal ranges from 0.76 to 5.91 GPa, with an average of 3.32 GPa, mostly concentrated between 2.5 and 4 GPa. The Poisson's ratio of the No. 5-2# coal ranges from 0.28 to 0.37, averaging 0.34, and is concentrated between 0.33 and 0.35.

The in-situ stress difference coefficient of the No. 5 coal seam in the study area ranges from 0.21 to 0.58, with an average of 0.39.

4. Conclusion

(1) The No. 5 coal reservoir in the study area has a relatively simple structural setting, showing an east-high and west-low gently dipping monocline. The coal seam thickness ranges from 4.42 to 8.61 m, with an average of 6.39 m. Three stages of tectonic fractures are mainly developed. Indosinian near N-S-trending fractures are poorly developed, while Yanshanian NW-SE-trending and Himalayan NE-SW-trending fractures are intensely developed. This results in obvious spatial variations of in-situ stress and fracture density, providing the macroscopic tectonic basis for reservoir heterogeneity.

(2) The No. 5 coal seam is characterized by high coal rank, high vitrinite content, low ash yield and low moisture content. The coal structure of major minable seams in this area is dominated by primary and cataclastic types. Both the breakdown pressure and the maximum/ minimum horizontal principal stresses increase gradually with burial depth, and the in-situ stress difference coefficient is generally greater than 0.37. Gas content rises with increasing burial depth, exceeding 15 m^3/t in deep zones, whereas the reservoir permeability is generally lower than 0.4 mD. Overall, the CBM reservoir is featured by high resource abundance and ultra-low permeability, which is a typical reservoir type requiring large-scale hydraulic fracturing to achieve commercial industrial productivity.

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