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Research on the Main Controlling Factors of Low-Abundance Gas Reservoirs in Mizhi Gas Field, Eastern Ordos Basin

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Abstract

The natural gas resources in the Upper Paleozoic Permian Shanxi Formation Section 2 and Shihezi Formation Section 8 of the Mizhi gas field in the eastern part of the Ordos Basin are abundant. However, the geological conditions for natural gas accumulation are complex, and the favorable exploration direction is not clear, which has led to no significant breakthroughs in the development of the main layer of the Mizhi gas field for the time being. To clarify the main controlling factors of the low-abundance gas reservoirs in the Mizhi Gas Field of the Ordos Basin, through drilling, logging, seismic and experimental data and other materials, the geological conditions for reservoir formation in the Mizhi Gas Field were systematically analyzed to reveal the geological reasons for the poor development effect and establish the reservoir formation model of the main layer of the Mizhi Gas Field. Research shows that the Mizhi gas field has an abundant gas source, and an adequate gas supply is the material basis for the formation of natural gas reservoirs. Poor reservoir quality is the core internal cause of the formation of low abundance. The insufficient supply of material sources restricts the development of sand bodies. Intense compaction and cementation further aggravate the deterioration of physical properties, and the improvement effect of dissolution is limited. The basin tectonic inversion since the Late Cretaceous has led the Mizhi area to be in the gas-water transition zone. The original water saturation in the gas reservoir is high, reducing the effective storage space for natural gas. The developed fracture system has disrupted the sealing property of the original gas reservoir, leading to the escape of natural gas and the formation of a low-pressure gas reservoir. Together, they constitute the key external factors for the formation of low abundance. Based on the above analysis, the accumulation model of the main layer of the Mizhi gas field was established. This research can provide theoretical support for the exploration and development of low-abundance gas reservoirs in the eastern part of the Ordos Basin.

Keywords

Ordos Basin, Mizhi Gasfield, Low-abundance Gas Reservoir, Fracture.

1. Introduction

The Ordos Basin, as one of China's largest petroliferous basins, hosts abundant natural gas resources in its Upper Paleozoic strata [1]. In recent years, with the deepening of exploration and development, the Mizhi Gas Field in the eastern part of the basin, as an important production replacement area, has demonstrated significant resource potential. Exploration of the Mizhi Gas Field began in 1985, and by 2006, the field entered the phase of basic capacity

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construction implementation [2]. The Upper Paleozoic in this region develops multiple gas-bearing layers. It is estimated that the exploitable natural gas reserves of the Mizhi Gas Field are approximately 358.5×10^8 m^3. However, due to the relatively tight reservoirs and low productivity, the Mizhi Gas Field has not undergone large-scale development [3]. The main productive layer in the Mizhi Gas Field is Member Shan 2 of the Permian Shanxi Formation, with the secondary productive layer being Member He 8 of the Shihezi Formation. Compared with high-yield enrichment areas in the northern basin, such as the Yulin Gas Field, Sulige Gas Field, and Shenmu Gas Field, which have undergone large-scale development, the Mizhi Gas Field, despite its confirmed substantial resource potential, generally exhibits characteristics of "low abundance," meaning the geological reserves of natural gas per unit area are relatively low. This directly affects the single-well production and overall development efficiency of the gas field.

Previous studies on the main controlling factors of gas reservoirs in the Ordos Basin have mostly focused on single-factor analyses, with insufficient comprehensive understanding of the enrichment and high-yield patterns of natural gas. It is widely believed that the high gas generation intensity of coal-measure source rocks in the Upper Paleozoic of the basin provides a solid material basis for large-scale gas accumulation. The development and distribution of high-quality reservoirs are key to controlling gas enrichment, with distributary channel sand bodies in the northern delta plain being the primary sites for high-yield gas enrichment [4]. However, for the Mizhi Gas Field located in the eastern part of the basin, its geological conditions differ significantly from those in the north. Existing studies have pointed out that the Mizhi area is relatively distant from the northern Yinshan provenance area [5], with a depositional system dominated by delta front and plain environments, resulting in relatively thin and poorly continuous sand bodies and generally inferior reservoir properties. Additionally, the late-stage tectonic evolution of the basin, particularly tectonic inversion events since the Late Cretaceous, has significantly impacted the adjustment and re-accumulation of natural gas [6]. The relatively developed faults in the Mizhi area may pose challenges to gas reservoir preservation conditions.

Although there have been sporadic reports and studies on the Mizhi Gas Field, systematic and in-depth analyses of the causes of its low-abundance gas reservoirs remain limited. The formation of low-abundance gas reservoirs is often the result of multiple coupled factors. Clarifying their main controlling factors is crucial for evaluating the exploration potential of the area and selecting favorable target zones. Therefore, this study aims to comprehensively and systematically analyze the main controlling factors of low-abundance gas reservoirs in the Mizhi Gas Field. It will involve detailed research on the geological characteristics and physical properties of the Mizhi Gas Field, analysis of the main factors controlling the formation and distribution of low-abundance gas reservoirs-such as tectonic factors, source rock factors, and their interactions-and the establishment of an accumulation model for low-abundance gas reservoirs in the Mizhi Gas Field based on the analysis of main controlling factors to clarify the formation mechanisms and enrichment patterns. Combining the research findings, the development potential of the Mizhi Gas Field will be evaluated to provide scientific and rational recommendations for its exploration and development.

2. Regional Geological Overview

The Ordos Basin is one of the primary targets for unconventional oil and gas exploration and development in China. It contains extremely abundant petroleum and natural gas resources, with the latter mainly occurring in the Paleozoic strata of the basin. Also known as the Shaan-Gan-Ning Basin, it is located in central-western China and spans five provinces and autonomous regions: Shaanxi, Gansu, Ningxia, Inner Mongolia, and Shanxi. As the second-largest sedimentary basin in China, it covers an area of approximately 370,000 km^2 [7]. The basin is

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characterized as a multi-cycle cratonic basin with stable subsidence, notable depression migration, and significant shear deformation. Based on its present structural configuration, the basin can be divided into six first-order tectonic units: the Yimeng Uplift, the Western Thrust Belt, the Tianhuan Depression, the Yishan Slope, the Jinxi Flexural Fold Belt, and the Weibei Uplift. Among these, the Yishan Slope serves as the primary core area for hydrocarbon accumulation in the basin.

The study area, the Mizhi Gas Field, is located in the eastern part of the Northern Shaanxi Slope on the eastern flank of the Central Paleo-uplift of the Ordos Basin (Fig. 1left), adjacent to the Jinxi Flexural Fold Belt on the eastern margin of the basin. Influenced by tectonic activities during the Late Cretaceous and the late Yanshanian Movement, the eastern part of the basin underwent intense uplift and structural inversion. This led to the reversal of the regional structural framework from an earlier east-dipping monocline to the present-day west-dipping monocline, with a structural dip generally less than 1° and a gradient of 5–10 m/km. This tectonic inversion event not only reconfigured the regional fluid-potential field but also caused the reactivation of pre-existing faults and the development of new fractures. While the presence of fault structures has improved reservoir permeability to some extent, facilitating more efficient gas migration and accumulation, it may also compromise the integrity of gas accumulations, leading to gas escape [8]. In the Mizhi Gas Field, the Upper and Lower Paleozoic strata exhibit a parallel unconformity in vertical sequence. The Upper Paleozoic succession in the study area is relatively continuous, showing conformable contacts within the succession [9], and was deposited in a transitional marine-continental to inland lacustrine setting. The vertical stratigraphic sequence in this region is complete, consisting, in ascending order, of the Carboniferous Benxi Formation, and the Permian Taiyuan, Shanxi, Lower Shihezi, and Upper Shihezi Formations (Fig. 1right). The Upper Paleozoic strata are uniformly distributed across the area with relatively consistent thickness. The main gas-bearing intervals are the Permian Shanxi and Shihezi Formations, with the Shan-2 Member currently serving as the primary production layer and the He-8 Member as the secondary production layer. The average thicknesses of the Shan-2 and He-8 Members are 60 m and 70.2 m, respectively [10]. The primary layer, the Shan-2 Member, exhibits a depositional system that transitions from delta plain through delta front to shallow-marine environments from north to south. Distributary-channel sand bodies are well developed, and the lithology is dominated by interbedded grayish-white quartz sandstone, siltstone, and dark gray to gray-black mudstone or transitional sandstone-mudstone facies. The depositional environment of the He-8 Member is interpreted as a braided-river delta-front subfacies, with developed microfacies including underwater distributary channels and inter-distributary bays. The underwater distributary-channel microfacies is primarily composed of gravel-bearing medium- to fine-grained sandstone, intercalated with thin layers of sandy mudstone and gray mudstone in some intervals. Grain sorting ranges from poor to moderate, individual sandstone beds are thick, and the detrital grains are relatively coarse.

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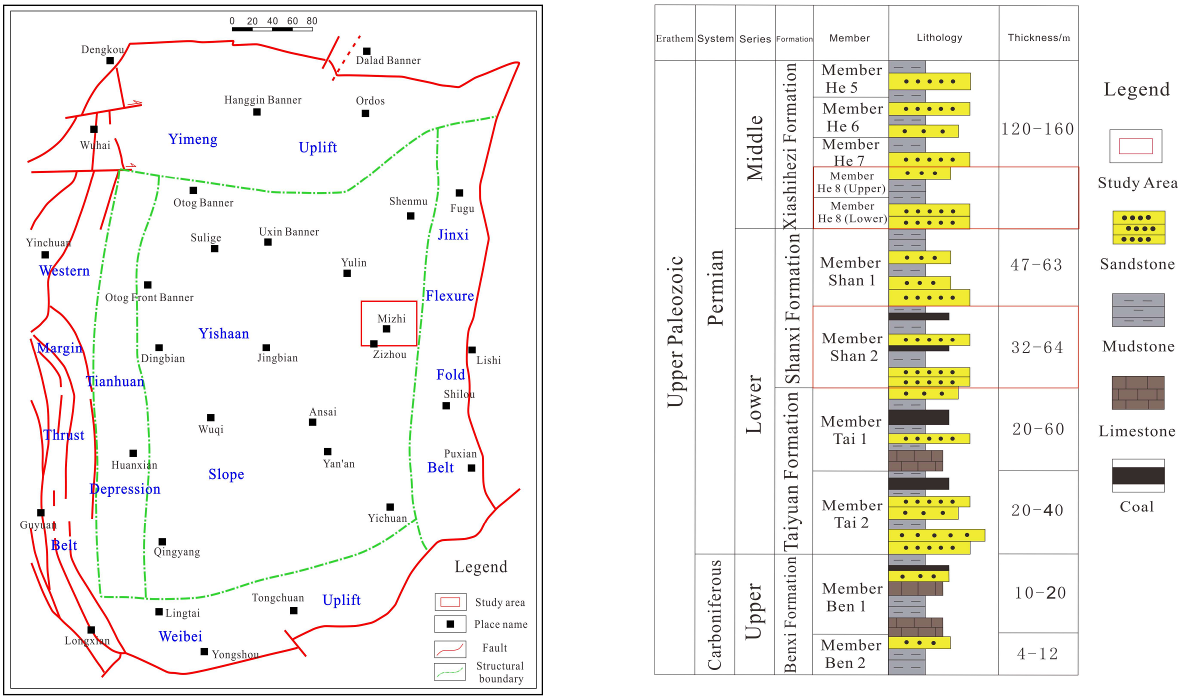

Fig. 1 Location of the study area (left) and division of stratigraphic units (right)

3. Characteristics of Low-Abundance Gas Reservoirs

The reservoir pores in the Mizhi Gas Field are dominated by residual intergranular pores and secondary dissolution pores, with a complex pore structure characterized by small and unevenly distributed pore-throat radii. Variations in pore-throat structure result in weak percolation capacity of the reservoirs, making it difficult for natural gas to migrate and accumulate efficiently within the reservoir. As a consequence, the single-well production is generally low, typically ranging from 0.5–2.0×10^4 m^3/d. Strong reservoir heterogeneity is another key characteristic of the low-abundance gas reservoirs in the Mizhi Gas Field. Diagenetic studies indicate that the reservoirs have undergone intense compaction and pressure solution as well as multi-stage cementation, particularly silica and carbonate cementation, which have significantly reduced reservoir porosity. Although some dissolution has occurred, creating secondary pores, the improvement is limited and unevenly distributed. In the Mizhi area, pore-throat radii are mainly distributed between 0.1 and 1.0 μm, noticeably smaller than those in the northern regions. Additionally, poor pore-throat sorting further intensifies reservoir heterogeneity [11-13].

The gas reservoirs in the Shan-2 and He-8 members of the Mizhi Gas Field are typical low-abundance gas reservoirs, characterized by multiple aspects. First, the sand bodies are thin and exhibit poor lateral continuity. In the Mizhi Gas Field, the average thickness of sand bodies in the Shan-2 member is only 5.2 m, and that in the He-8 member is 7.8 m. These values are 39.5% and 30.4% lower than those of the Yulin Gas Field, and 44.1% and 37.6% lower than those of the Shenmu Gas Field, respectively (Table 1). In terms of planar distribution (Fig. 2), the sand bodies in the Mizhi Gas Field mostly occur as isolated lens-shaped or short strip-shaped distributions, with lateral extensions generally ranging from 0.5 to 2.0 km. The connectivity between sand bodies is poor, and the area of individual sand bodies is mostly less than 1 km^2. The small scale and poor continuity of sand bodies result in limited effective reservoir space, making it difficult to form large-scale contiguous gas-bearing zones. Typically, single wells encounter 1–3 effective sand layers, with individual effective thickness generally less than 3 m. This contrasts markedly with the Yulin Gas Field, where single wells commonly intersect 5–8 effective sand layers with individual thicknesses of 3–5 m [14-16].

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Table 1. Comparison of sand body Thickness in the main reservoirs of Mizhi Gas Field and the gas fields in the Northern adjacent Area

Gas field name	Horizon	Sand body thickness range(m)	Average sand body thickness(m)
Mizhi Gas Field	Member Shan 2	3.5~8.2	5.2
	Member He 8	4.0~10.5	7.8
Yulin Gas Field	Member Shan 2	6.8~12.5	8.6
	Member He 8	8.5~15.2	11.2
Shenmu Gas Field	Member Shan 2	7.2~13.8	9.3
	Member He 8	9.0~16.5	12.5

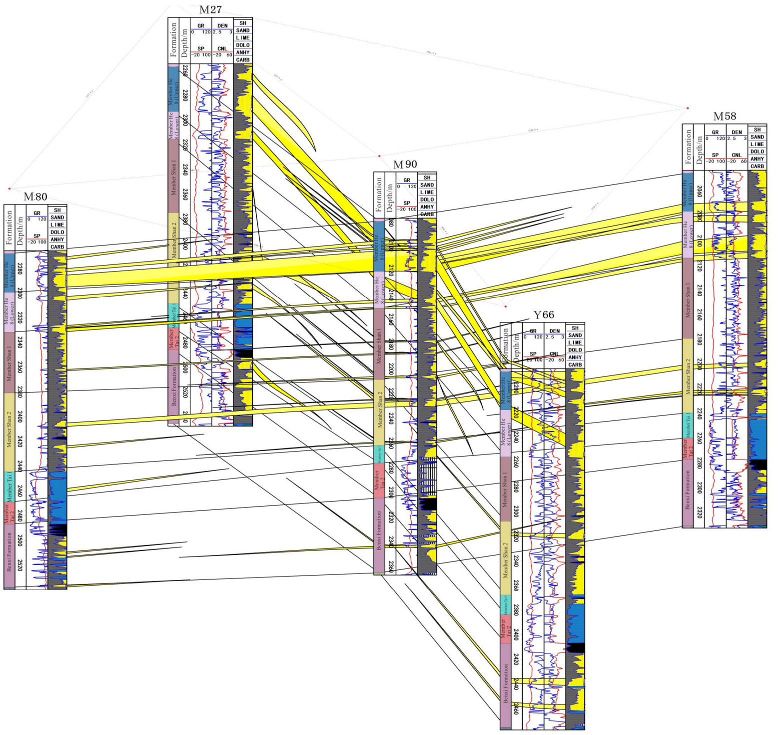

Fig. 2 In the 82-meter well area, meters 80- 90- Yu 66- Yu 133 Grid diagram of well cluster sand body

Table 2. Comparison table of physical properties of the main reservoirs between the Mizhi Gas Field and the gas fields in the northern adjacent area

Gas field name	Horizon	Porosity range(%)	Average porosity(%)	Permeability range(mD)	Average permeability(mD)
Mizhi Gas Field	Member Shan 2	1.77~10.72	4.77	0.01~1.58	0.15
	Member He 8	3.8~9.2	6.5	0.02~1.5	0.48
Yulin Gas Field	Member Shan 2	4.5~11.8	7.9	0.05~3.6	0.92
	Member He 8	5.2~12.6	8.7	0.08~4.2	1.15
Shenmu Gas Field	Member Shan 2	5.0~13.2	8.5	0.06~4.8	1.38
	Member He 8	5.6~14.5	9.3	0.10~5.5	1.62

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The reservoirs in the Shan-2 and He-8 members of the Mizhi Gas Field are generally characterized by low porosity, low permeability, and complex pore-throat structures, with petrophysical parameters significantly lower than those of gas fields in adjacent northern areas (Table 2). The average porosity of the main productive layer, the Shan-2 member, is approximately 4.77%, and the average permeability is about 0.15 mD. The average porosity of the secondary productive layer, the He-8 member, is about 6.5%, and the average permeability is around 0.48 mD. Both are classified as ultra-low porosity and ultra-low permeability reservoirs [16-17].

4. Genesis of Low-Abundance Gas Reservoirs

4.1. Abundant Gas Supply Provides the Fundamental Material Basis for the Formation of Gas Reservoirs.

The Upper Paleozoic of the Ordos Basin was deposited in a transitional marine-continental sedimentary environment under warm and humid climatic conditions, developing a widely distributed set of coal-measure hydrocarbon source rocks. The gas is jointly supplied by coal and dark mudstone from the Carboniferous–Permian Taiyuan, Shanxi, and Benxi formations [18]. Both the coal and dark mudstone are extensively developed throughout the basin; however, due to topographic and depositional environmental factors, the characteristics of the source rocks vary to some extent across different regions. The thickness of gas source rocks is greatest in the eastern part of the basin, and the Mizhi Gas Field, located in this eastern region, is a typical coal-derived gas accumulation. Among these, coal acts as an efficient and high-intensity core gas source rock, while dark mudstone serves as a widely distributed and foundational supplementary gas source rock. Together, they form an optimal "source-reservoir coexistence" system in space, jointly controlling the enrichment and distribution of natural gas in the Mizhi Gas Field. Overall, the Upper Paleozoic gas source rocks in the Mizhi Gas Field study area are dominated by coal-measure strata of the Shanxi, Taiyuan, and Benxi formations. The coals in the Benxi and Taiyuan formations were primarily formed in swamp or lagoon environments, whereas the coals in the Shan-2 member of the Shanxi Formation were mainly deposited in wetland swamp settings.

The controlling effect of gas source conditions on gas reservoir distribution is primarily reflected in the influence of source rock thickness and hydrocarbon generation intensity on reservoir distribution. Since hydrocarbon generation intensity is proportional to source rock thickness, their controlling effects on gas reservoir distribution are consistent. Following the aforementioned stratigraphic division scheme, with the 8# coal seam as the top boundary of the Benxi Formation, this coal layer is the most stable and thickest among all coal seams. Due to its extensive distribution, it can be described as having an "extensive distribution" pattern. In the study area, the 5# coal seam in the Shanxi Formation is widely distributed and relatively thick (Figs 3-4). In the Mizhi Gas Field study area, the source rocks are predominantly coal-measure strata, characterized by strong hydrocarbon generation capacity, wide distribution, and relatively large thickness [19]. Sufficient gas supply ensures adequate natural gas charging into the reservoirs, serving as a prerequisite for gas accumulation in the Mizhi Gas Field. Therefore, the gas source is not a limiting factor for the low abundance of the Mizhi Gas Field; on the contrary, it constitutes a favorable background condition.

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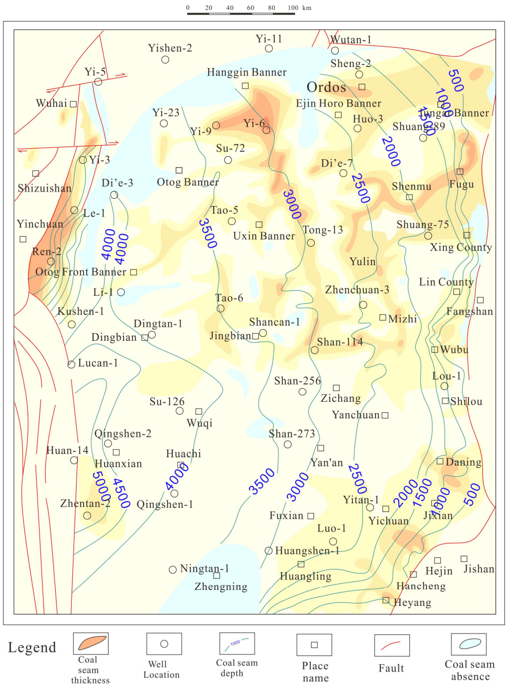

Fig. 3 Superimposed Map of Coal Seam Thickness and Burial Depth for No. 5 Coal Seam in the Shanxi Formation of the Basin

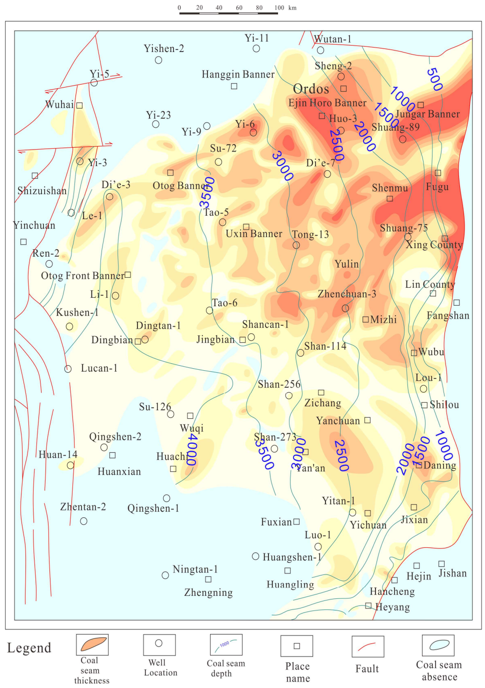

Fig. 4 Superimposed Map of Coal Seam Thickness and Burial Depth for No. 8 Coal Seam in the Benxi Formation of the Basin

4.2. Poor Reservoir Quality Constrains Gas Enrichment.

The reservoir quality of the main producing intervals in the Mizhi Gas Field is constrained by both the depositional environment and diagenesis, resulting in thin sand bodies, poor continuity, and inferior physical properties. These factors have become key constraints on natural gas enrichment [20].The depositional environment restricted sand body development. The Mizhi Gas Field is located far from the northern Yinshan provenance area, with a straight-line distance of 180–220 km, significantly greater than the distances of the Yulin and Shenmu gas fields from the provenance area [21]. The intensity of sediment supply diminishes with increasing transport distance, leading to insufficient supply of clastic particles during the deposition of the main intervals in the Mizhi Gas Field and a weakening of depositional energy, which limited the scale of sand body development.During the deposition of the Shan-2 Member, the main part of the gas field was situated in a delta plain subfacies, where distributary channels were relatively narrow with limited lateral migration capacity, resulting in thin individual sand bodies and short lateral extensions. In the southern transition zone, influenced by the delta front subfacies, sand bodies were separated by inter-distributary bay mudstones, further reducing their continuity.During the deposition of the He-8 Member, the gas field entered a delta front subfacies environment, where underwater distributary channels frequently shifted and bifurcated. Sand bodies exhibited lenticular or lobate distributions with even poorer lateral connectivity. In some areas, sand bodies pinch out, forming "isolated sand bodies," making it difficult to develop large-scale, connected reservoir systems.In contrast, the northern Yulin and Shenmu gas fields are closer to the provenance area. During deposition, they were located in the core area of the delta plain.

Diagenesis further deteriorates reservoir physical properties. The main reservoir intervals in the Mizhi Gas Field have undergone complex diagenetic evolution, with compaction and cementation being the primary diagenetic processes leading to the deterioration of reservoir quality [22-23], while dissolution has provided only limited improvement. In terms of compaction, the reservoir sand bodies are relatively fine-grained and experienced strong early compaction. Grains are predominantly in point-line or line contact (Figs. 5a, 5b), with concavo-

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convex contacts occurring in some areas. This resulted in substantial loss of primary intergranular pores, with compaction-induced porosity reduction ranging from 28% to 35%, accounting for approximately 65–75% of the total porosity loss. Regarding cementation, the interstitial material content in the reservoir is high, ranging from 18% to 28%. It mainly consists of clay minerals such as illite and kaolinite, along with carbonate cements including ferrodolomite and siderite. Among the clay minerals, illite (Fig. 5d) often occurs in hair-like or curved-sheet forms coating pore surfaces, blocking pore throats. Kaolinite (Fig. 5c) forms aggregates within pores, further reducing pore connectivity. Carbonate cements typically occur as poikilitic or pore-filling types, directly filling both primary and secondary pores, leading to a sharp decrease in effective pore space. Cementation has caused porosity reduction of 12–18% [24], accounting for about 25–35% of the total porosity loss. In terms of dissolution, although the reservoir contains relatively high feldspar content and low lithic fragment content, its greater burial depth (2,800–3,600 m for the main intervals) restricts acidic fluid activity, resulting in relatively weak dissolution. This process has only generated a limited number of secondary dissolution pores (Figs. 5e, 5f), with porosity enhancement of merely 3–8%, which is insufficient to compensate for the porosity losses caused by compaction and cementation.

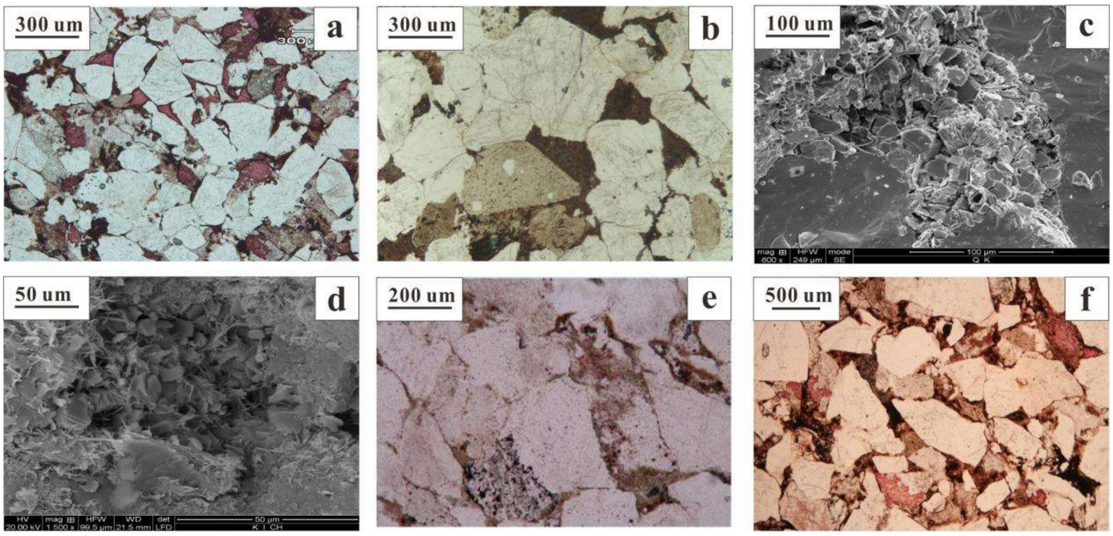

Fig. 5 Microscopic Characteristics of Diagenesis in the Mizhi Gas Field

a. Grain contact, Well Mi 35-15, 2262.98 m, He 8 Member; b. Rigid grain rupture, Well Mi 67, 2280.25 m, Shan 2 Member; c. Book-like kaolinite, Well Mi 65, 2388.53 m, Shan 2 Member; d. Chlorite and illite, Well Mi 65, 2315.87 m, He 8 Member; e. Intragranular dissolution pores in lithic fragments, Well Mi 89, 2176.28 m, He 8 Member; f. Partial dissolution of lithic fragments, Well Mi 70, 2191.30 m, He 8 Member.

In summary, the limited sand body development resulting from the depositional environment, coupled with the deterioration of physical properties due to diagenesis, collectively leads to poor reservoir quality in the main producing intervals of the Mizhi Gas Field. This makes it difficult to achieve large-scale natural gas enrichment and constitutes the fundamental intrinsic factors contributing to the low-abundance characteristics of the gas reservoirs.

4.3. Tectonic Inversion Leads to Unfavorable Gas-water Distribution.

The tectonic burial history of the Ordos Basin is synchronous with the evolution of natural gas accumulation [25]. The structural inversion of the basin since the Late Cretaceous has played a crucial role in reshaping the accumulation process of the Mizhi Gas Field. From the late Yanshan Movement at the end of the Late Cretaceous to the Himalayan Movement, tectonic inversion occurred in the Ordos Basin. This led to differential uplift between the eastern and western

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parts of the basin—intense uplift in the east, forming the Lüliang Mountains and the Jinxi Flexural Fold Belt, while the west experienced continued subsidence. As a result, the basin structure transformed from an early Mesozoic east-dipping monocline to the present-day west-dipping monocline (Fig. 6), fundamentally altering the basin's tectonic framework. This structural inversion triggered a redistribution of gas and water in the Upper Paleozoic reservoirs. Prior to the inversion, the basin was an east-dipping monocline, and natural gas migrated and accumulated toward the higher eastern parts under buoyancy, forming gas-rich accumulations in the eastern high positions. At that time, the Mizhi Gas Field area was situated in a high structural position, with thorough gas-water separation and high gas saturation.

After the structural inversion, the basin became a west-dipping monocline [26]. The original pressure system of the gas reservoirs was disrupted, and the direction of gas migration reversed, shifting toward the western long axis. This adjustment was not a complete, one-time replacement, resulting in incomplete displacement of formation water by natural gas in the Mizhi area. Consequently, the original water saturation in the reservoirs remained generally high. High water saturation occupies significant pore space, greatly reducing the effective storage capacity (i.e., gas saturation) for natural gas, which manifests as low gas reservoir abundance. This also explains why many gas layers in the Mizhi Gas Field produce a certain amount of formation water. Simultaneously, formation water converged toward the original high positions in the east under gravity. Located in the eastern part of the basin, the Mizhi Gas Field became a relatively low structural position after the inversion, situated at the intersection where gas migrates westward and formation water converges eastward, forming a gas-water transition zone. Therefore, it can be concluded that the gas-water redistribution induced by structural inversion ultimately shaped the low-quality gas reservoirs in the Mizhi Gas Field study area.

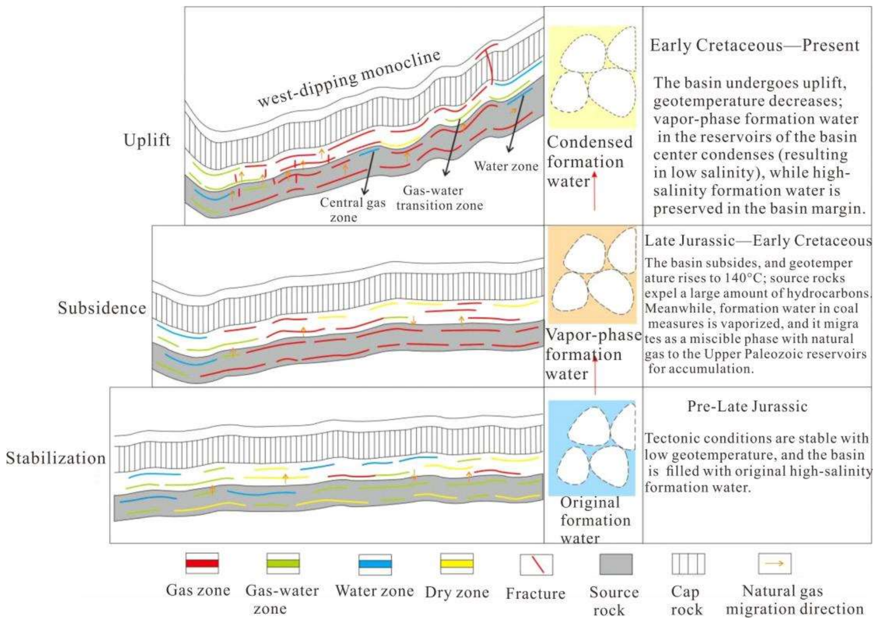

Fig. 6 The formation water genesis model in the eastern Ordos Basin

The formation of the gas-water transition zone has led to a significant increase in the original water saturation of the gas reservoirs. According to well-log interpretation data, the original water saturation of the Shan-2 member gas reservoir in the Mizhi Gas Field ranges from 38% to 52%, with an average of 45.6%; for the He-8 member gas reservoir, it ranges from 35% to 48%, with an average of 41.8%. In contrast, the northern Yulin and Shenmu gas fields are located in relatively higher structural positions in the western part of the basin, where gas-

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water separation is thorough and the original water saturation is lower. The average original water saturation for the Shan-2 and He-8 members in the Yulin Gas Field is 28.5% and 26.2%, respectively, while in the Shenmu Gas Field, it is 26.8% and 24.5%, both significantly lower than those in the Mizhi Gas Field (Table 3).

Table 3. Comparison table of the original water saturation of the main layer between the Mizhi Gas Field and the gas fields in the northern adjacent area

Gas field name	Horizon	Range of initial water saturation(%)	Average initial water saturation(%)
Mizhi Gas Field	Member Shan 2	38~52	45.6
	Member He 8	35~48	41.8
Yulin Gas Field	Member Shan 2	25~36	28.5
	Member He 8	23~34	26.2
Shenmu Gas Field	Member Shan 2	22~33	26.8
	Member He 8	20~31	24.5

4.4. Fault Development Compromises Gas Reservoir Preservation Conditions.

Widely developed faults in the Ordos Basin play important roles in its tectonic framework, the distribution and evolution of source rocks, hydrocarbon migration and redistribution, and ultimately in hydrocarbon accumulation and preservation [27]. The Mizhi Gas Field is located in the eastern fault-developed zone of the Ordos Basin. Influenced by regional tectonic stress, faults are relatively well-developed in the gas field, primarily consisting of NE- and NW-trending conjugate fault sets (Fig. 7), with locally developed nearly E-W trending faults, forming a complex fault network system. Overall, the fault system in the Mizhi Gas Field is generally characterized by "weak overall activity, localized development, small scale, and old episodes." Tectonic activity has generated multiple faults of varying sizes in the region. The fault system in the Mizhi Gas Field exhibits "segmentation and inheritance," with faults having short extension distances and small throws, mainly classified as fourth-order faults. The faults within the gas field are mostly small to medium-sized thrust or normal faults, with lengths ranging from 1 to 10 km and throws between 5 and 30 m. Some faults cut through the main Upper Paleozoic reservoirs of the Shanxi and Shihezi Formations and extend upward into the Shiqianfeng Formation or even Mesozoic strata, compromising the vertical sealing integrity of the gas reservoirs. Based on seismic interpretation and drilling data, the fault density within the gas field ranges from 0.8 to 1.5 faults/km^2, which is higher than that of the northern Yulin Gas Field (0.3–0.6 faults/km^2) and Shenmu Gas Field (0.2–0.5 faults/km^2). The widespread development of faults serves as a primary pathway for gas escape.

The destruction of gas reservoir preservation conditions by faults is mainly manifested in two aspects. On one hand, faults act as conduits for vertical migration of natural gas, leading to the escape of originally accumulated gas into overlying strata. The presence of gas shows in shallow formations such as the Shiqianfeng Formation within the gas field confirms the upward leakage of natural gas along faults, with some shallow gas accumulations being secondary reservoirs formed by gas escaping from the underlying main reservoirs. On the other hand, faults connect the gas reservoirs with overlying aquifers or the surface, resulting in pressure release and the formation of low-pressure gas reservoirs. The pressure coefficient of the main reservoirs in the Mizhi Gas Field ranges from 0.75 to 0.92, averaging 0.83, classifying them as low-pressure reservoirs [28]. In contrast, the pressure coefficients of the Yulin Gas Field and Shenmu Gas Field in the north range from 0.95 to 1.05 and 0.98 to 1.12, respectively, both representing normal pressure systems (Table 4). The significant loss of natural gas and the reduction in reservoir pressure directly lead to decreased gas reserves and lower abundance in the main reservoirs, constituting a key external controlling factor for the formation of low-abundance gas reservoirs.

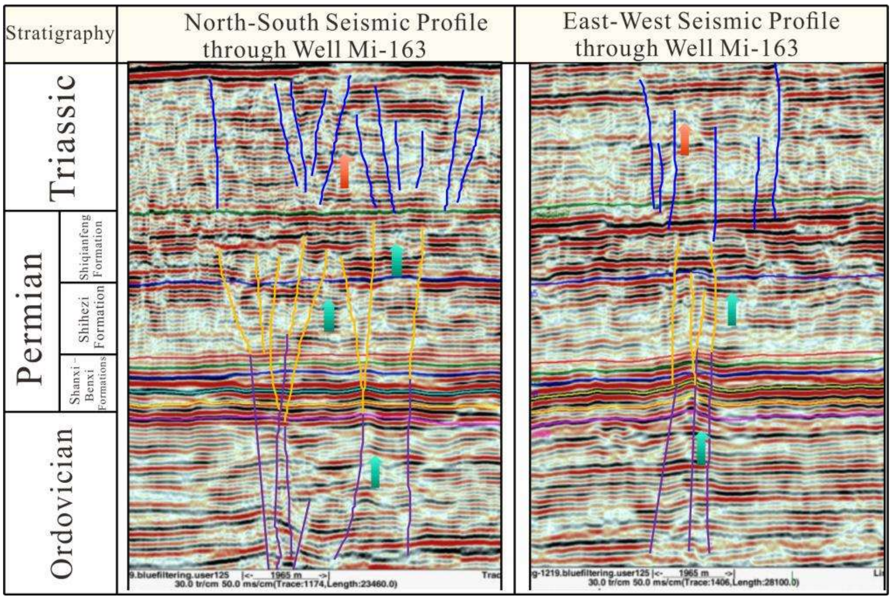

Fig. 7 Seismic Fault Profile of the Mi-163 Well Area

Table 4. Comparison of Pressure Coefficients in the Main Pay Zones of the Mizhi Gas Field versus Those in Northern Adjacent Gas Fields

Gas field name	Horizon	Range of pressure coefficient	Average pressure coefficient
Mizhi Gas Field	Member Shan 2	0.78~0.92	0.85
	Member He 8	0.75~0.89	0.81
Yulin Gas Field	Member Shan 2	0.95~1.03	0.99
	Member He 8	0.96~1.05	1.01
Shenmu Gas Field	Member Shan 2	0.98~1.10	1.04
	Member He 8	1.00~1.12	1.06

5. Natural Gas Accumulation Model.

The formation of low-abundance gas reservoirs in the Mizhi Gas Field is a complex process characterized by "multi-stage accumulation and later-stage adjustment and modification."

Source Rocks and Early Accumulation: The Upper Paleozoic coal-measure source rocks entered their peak gas generation period during the Jurassic to Early Cretaceous. The large volumes of natural gas generated migrated and accumulated in underlying or laterally up-dipping sandstone bodies, driven by overpressure [29]. Before the Late Cretaceous tectonic inversion, natural gas primarily migrated toward the up-dip direction in the eastern basin, forming early-stage gas accumulations within the tight sandstone reservoirs of the Shan-2 and He-8 members in the Mizhi area. Tectonic Inversion and Gas-Water Redistribution: The Late Cretaceous tectonic inversion transformed the regional structural framework from an east-dipping monocline to a west-dipping monocline, leading to a reorganization of the gas-water distribution pattern [30]. This event fundamentally altered the accumulation setting of the early-stage gas that had accumulated in the eastern part (the Mizhi area) [31]. The gas

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reservoirs underwent adjustment, with natural gas migrating toward the new up-dip direction (west). The Mizhi area transitioned into a gas-water transition zone, resulting in increased water saturation within the reservoirs and a reduction in effective gas-bearing space. Fault Activity and Gas Escape: Accompanying the tectonic inversion or later tectonic activity, the fault system developed in the eastern part of the basin cut through the Upper Paleozoic reservoir-seal assemblages. These faults provided pathways for the vertical escape of natural gas, leading to partial loss of gas from the original reservoirs, a decrease in reservoir pressure, and the formation of low-pressure gas reservoirs. Final Accumulation: Following the two significant stages of "post-accumulation modification" – namely, the gas-water redistribution caused by tectonic inversion and the gas loss induced by faulting – the natural gas remaining within the relatively poorer reservoirs of the Shan-2 and He-8 members in the Mizhi area ultimately formed the present-day low-abundance, normal- to low-pressure gas reservoirs (Fig. 8). Their low-abundance characteristics are the result of the combined effects of "inherent deficiencies" (poor reservoir quality) and "post-accumulation destruction" (tectonic inversion and fault-related gas escape).

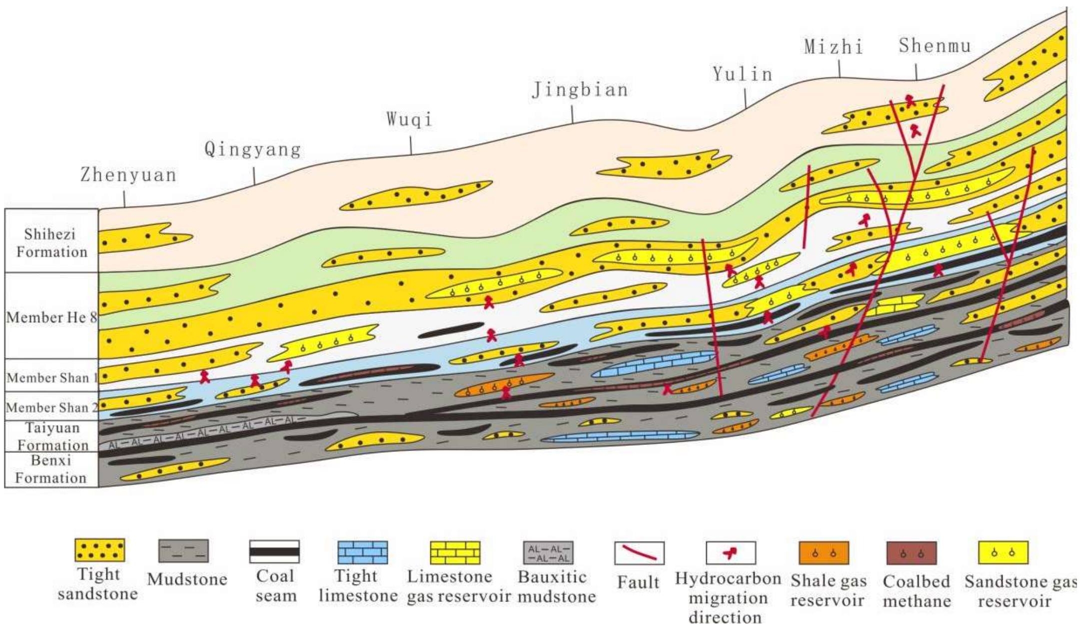

Fig. 8 Hydrocarbon Accumulation Model Map of the Upper Paleozoic in the Ordos Basin

6. Conclusion

Based on a systematic study of the genesis of low-abundance gas reservoirs in the main Upper Paleozoic intervals of the Mizhi Gas Field in the Ordos Basin, the following main conclusions and understandings are drawn:

(1) The main Upper Paleozoic gas reservoirs in the Mizhi Gas Field possess sufficient gas supply conditions. The coal seams and dark mudstones of the Shanxi Formation exhibit high hydrocarbon generation intensity, providing a substantial material foundation for reservoir formation. However, the low-abundance characteristics of the reservoirs are collectively controlled by reservoir quality, tectonic evolution, and preservation conditions. Due to the long distance from the provenance area, the main reservoir intervals feature thin sand bodies with poor continuity. Furthermore, influenced by intense compaction and cementation, their physical properties are inferior, constituting the core internal factor for the low abundance of the gas reservoirs.

(2) The Late Cretaceous tectonic inversion of the basin and the development of faults are key external factors contributing to the low abundance of the gas reservoirs. The tectonic inversion placed the gas field within a gas-water transition zone, resulting in elevated original water saturation and reduced effective gas-bearing space. The widespread development of faults compromised the sealing integrity of the reservoirs, allowing natural gas to escape upward along the faults and leading to a decrease in reservoir pressure, which further exacerbated the insufficient degree of gas enrichment.

(3) The low-abundance gas reservoirs in the Mizhi Gas Field are the product of the coupling between a "favorable accumulation background" and "unfavorable reservoir and preservation conditions." Their accumulation model can be summarized as follows: against a background of sufficient gas supply, natural gas preferentially charged relatively higher-quality reservoir bodies to form early-stage accumulations. Subsequently, these accumulations experienced intense late-stage modifications, including gas-water redistribution induced by tectonic inversion and seal failure along with gas escape caused by faulting. Ultimately, against a background of relatively poor reservoir quality, this process resulted in residual, low-abundance gas reservoirs.

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