

Article

Gas–Water Distribution and Controlling Factors in a Tight Sandstone Gas Reservoir: A Case Study of Southern Yulin, Ordos Basin, China

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Abstract: The intricate gas–water distribution patterns in tight sandstone gas reservoirs significantly impede effective exploration and development, particularly challenging sweet spot prediction. In the Upper Paleozoic Shanxi Formation of the Ordos Basin, the complex and variable gas–water distribution characteristics remain poorly understood regarding their spatial patterns and controlling mechanisms. This study employs an integrated analytical approach combining casting thin sections, conventional porosity–permeability measurements, and mercury intrusion porosimetry to systematically investigate the petrological characteristics, pore structure, and physical properties of the Shan 2 member reservoirs in southern Yulin. Through the comprehensive analysis of production data coupled with structural and sand body distribution patterns, we identify three predominant formation water types: edge/bottom water, isolated lens-shaped water bodies, and residual water in tight sandstone gas layers. Our findings reveal that three primary factors govern water distribution in the Shan 2 member reservoirs: sand body architecture controlling fluid migration pathways; reservoir quality determining fluid storage capacity; and structural configuration influencing fluid accumulation patterns. This multi-scale characterization provides critical insights for optimizing development strategies in similar tight sandstone reservoirs.

Keywords: formation water; gas–water distribution; controlling factors; evolutionary model; Ordos Basin



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1. Introduction

Amid the escalating global energy demands and the declining production of conventional hydrocarbons, unconventional resources have become crucial components in the global energy mix, with tight sandstone gas emerging as a pivotal target for worldwide unconventional gas exploration [1–3]. The successful exploitation of tight sandstone gas reservoirs in the United States has significantly accelerated their global development, with total estimated resources exceeding 210 trillion cubic meters [4–6]. With the growing demand for energy and the depletion of shallow-layer hydrocarbon resources, the exploitation of tight sandstone reservoirs has been gradually shifting towards greater depths. In recent years, a notable trend of increasing exploitation depth has been observed. In major oil- and gas-producing regions, the average annual increase in the depth of hydrocarbon exploitation in tight sandstone reservoirs is moving towards deeper and ultradeep formations. This

trend is facilitated by advancements in drilling and extraction technologies, which have made it possible to access and develop deeper tight sandstone formations [7,8]. Tight sandstone reservoirs are characterized by ultralow porosity (less than 10% under overburden pressure) and negligible matrix permeability (less than 0.1 mD in situ) [9,10], exhibiting substantially inferior petrophysical properties and smaller pore throat radii compared to conventional reservoirs. China boasts substantial tight sandstone gas reserves totaling 21.85 trillion cubic meters, predominantly distributed in the Sichuan, Ordos, Songliao, and Tarim Basins [11–14]. Among these, the Ordos Basin stands out as China's most prolific gas-bearing basin, demonstrating exceptional exploration potential, particularly in its Upper Paleozoic strata. Notable discoveries such as the Sulige, Yulin, and Daniudi fields have yielded substantial proven reserves [5]. However, the exploration progress in the eastern Upper Paleozoic formations of the Ordos Basin lags significantly behind the advancements made in the northern regions.

Tight sandstone reservoirs exhibit pronounced heterogeneity and complex pore architectures, posing significant challenges in characterizing fluid occurrence states. The intricate gas–water configurations within these reservoirs constitute critical petroleum geological features. In particular, widespread water production in Upper Paleozoic tight gas sandstone reservoirs, especially within the Shanxi Formation of the Ordos Basin, presents substantial obstacles to gas exploration and development [15–18]. Various studies have demonstrated that the gas–water distribution patterns in these reservoirs are strongly correlated with lithological properties, reservoir quality, and structural configurations. Additional controlling factors include reservoir typology, diagenetic evolution, intense heterogeneity, the genetic mechanisms of reservoir tightness, and depositional facies, all of which critically influence gas accumulation and formation water distribution [19–23]. For instance, Dou et al. [15] observed that hydrocarbon generation intensity governs the distribution patterns of gas and water in the Sulige gas field, while regional tectonics exhibit a lesser influence. Chen et al. [17] postulated that stratigraphic water intrudes along basin margins, resulting in varying degrees of water production across formations from the Benxi to Shanxi groups in the Shenmu gas field, with the scale and volume of stratigraphic water gradually increasing from west to east, accompanied by rising salinity. Berry et al. [24], in their research on the San Juan Basin of New Mexico and Colorado, USA, suggested that hydrodynamic sealing formed by stratigraphic water flowing down dip is the primary mechanism underlying the inverted gas–water distribution observed in low-pressure gas reservoirs within the region. Berkenpas [25] identified buoyancy, capillary force, and differential pressure as the three primary forces controlling the displacement of stratigraphic water by natural gas during reservoir formation and proposed a kinetic equilibrium perspective to elucidate these processes and mechanisms. Despite these advancements, current research disproportionately focuses on the central–northern sectors of the basin, leaving critical knowledge gaps regarding the following: (1) formation water typologies in the eastern Shanxi Formation; (2) differential controls on gas–water distribution patterns across basin regions; and (3) comparative mechanisms shaping gas–water distributions between eastern and central–northern domains.

This study adopts an integrated methodology, leveraging well logging, mud logging, and gas testing data to meticulously delineate gas–water contacts. By conducting a comprehensive analysis of gas–water distribution patterns across multiple scales, ranging from individual wells to cross-sectional and areal distributions, we systematically characterize the spatial relationships, classifications, and unique features of gas–water configurations. Additionally, we delve into the primary controlling factors that govern the distribution of formation water within the Shanxi Formation by examining its structural architecture, sand body distribution patterns, and reservoir characteristics.

2. Geological Setting

As one of China's most significant geological features, the Ordos Basin ranks as the nation's second-largest sedimentary basin and holds vast reserves of tight sandstone gas, with estimated natural gas resources surpassing 1000 billion cubic meters [26–28]. This expansive basin occupies a strategic position within the regional tectonic framework, spanning across several major geological domains, including the Songliao Basin, Yangtze Platform, Tarim Block, Tibetan Plateau, and Qaidam Block, forming a substantial cratonic basin within the continental interior [29,30]. Based on its tectonic framework, the basin can be delineated into six primary tectonic units: the Yimeng Uplift, the Western Thrust Zone, the Tianhuan Depression, the Shaanbei Slope, the Weibei Uplift, and the Jinshaan tectonic zone [31,32]. Sedimentary accumulations within the basin reach remarkable thicknesses of up to 10 km, reflecting its long and complex geological history. The Caledonian Orogeny played a pivotal role in shaping the basin's evolution, causing significant uplift that created a stratigraphic gap spanning approximately 160 million years, from the Upper Ordovician through the Upper Carboniferous periods. Stratigraphic analysis reveals distinct thickness variations: (1) the Lower Paleozoic strata range in thickness from 300 to 600 m, whereas (2) the Upper Paleozoic strata measure approximately 900 m in thickness.

Limestone formations developed in the southern portion of the southeastern Ordos Basin during the formation of the Benxi Formation and Taiyuan Formation, which is situated within the western North China Platform. Subsequently, during the formation of the Middle Permian Shanxi Formation, these limestone formations transitioned into coal-bearing strata. From the Middle to Late Permian periods, sandstone and mudstone interbeds became extensively developed throughout the region [33]. This geological evolution highlights the complex and dynamic tectonic history of the Ordos Basin, contributing to its rich natural gas resources.

Covering an extensive area of 7541 km² within the eastern Yishan–Shaanxi Slope region, the investigated zone incorporates the Mizhi, Zizhou, and Qingjian gas fields (Figure 1). Stratigraphically, the Shanxi Formation is divided into two principal units: the Shan 1 and Shan 2 members. The latter unit displays a three-tiered subdivision, with its structural configuration demonstrating a northeast–southwest-oriented monoclinal dip. This geological feature exhibits a gradual inclination, displaying slope gradients between 6 and 14 m/km. Horizontal stress plays a dominant role and varies with depth and location in the Ordos Basin. This indicates that horizontal stress has a significant impact on the stress state of the formation and is closely related to wellbore stability. The current maximum horizontal principal stress direction of the Shanxi Formation strata (buried at a depth of about 2000–3500 m) is NE 60–85°, with a stress gradient range of 0.017–0.021 MPa/m, consistent with the regional tectonic compression background [34,35].

The structural complexity is further accentuated by the presence of multiple low-amplitude, arcuate uplift features distributed throughout the region. The structural features of the top surfaces of these three sub-layers are similar, demonstrating good inheritance, which reflects stable deposition and tectonic conditions during the Shan 2 depositional stage. Among them, Shan 23, situated at the base of the Shan 2 member, although composed of highly compact and poor-quality lithology, remains a significant exploration target in the Ordos Basin. Over years of natural gas exploration and exploitation, it has been observed that the Shan 22 and Shan 23 sub-layers produce a considerable amount of water.

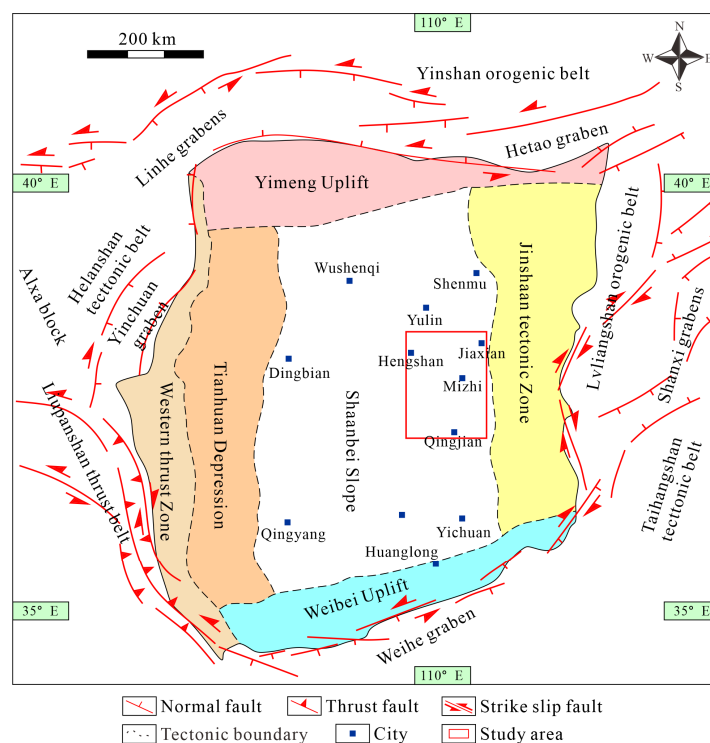


Figure 1. The division of tectonic units and the location of the research area in the Ordos Basin.

3. Methods

Thin sections and scanning electron microscopy from 2000 images, the reservoir porosity and permeability of 3494 samples from 125 wells, and gas test results from four layers in 614 wells were also collected. The formation water salinity of 11 wells was analyzed, while logging data from 1200 wells was collected. The data collected were obtained from the Research Institute of Petroleum Exploration and Development of the Changqing Oilfield Company, PetroChina.

3.1. Reservoir Physical Properties

Residual hydrocarbon and salt were removed from the samples through solution extraction. This was followed by oven-drying the samples at 100 °C for 24 h. The samples were then processed to a constant weight to measure their porosity and permeability. Helium has a relatively small molecular volume; it can enter smaller pores and will not be adsorbed in the pores. Currently, it is the most accurate medium for porosity measurement. A standard volume with a known size is used based on Boyle's law. Under a set initial pressure, the gas undergoes isothermal expansion into the core chamber at a normal pressure. The gas diffuses into the pores of the core. By using the change in pressure and the known volume, and according to the ideal gas equation, the effective pore volume and the skeletal volume of the tested rock sample can be calculated, and thus the porosity of the rock sample can be obtained. The permeability can be obtained by applying Darcy's law and conducting multiple measurements under different pressures.

3.2. Analysis of Formation Water

The water sample analysis and testing work was completed by Changqing Oilfield Company, PetroChina. $K^+ + Na^+$, Ca^{2+} , Mg^{2+} , SO_4^{2-} , Cl^- , CO_3^{2-} , HCO_3^- , and total dissolved solids (TDSs) were determined. Inductively coupled plasma emission electron spectrometry measured ions including $K^+ + Na^+$, Ca^{2+} , and Mg^{2+} ; SO_4^{2-} and Cl^- were determined by ion chromatography. We used acid-base titration to determine CO_3^{2-} .

and HCO_3^- . We analyzed the water type through these ions according to the Surin classification.

4. Results and Discussion

4.1. Reservoir Characteristics

Petrological analysis of the Shan 2 member in the investigated region reveals a dominant quartz arenite composition, frequently containing lithic fragment inclusions, with litharenite occurring as a secondary component. The stratigraphically adjacent Shan 1 member displays an inverse lithological distribution, being principally composed of litharenite with subordinate occurrences of sublitharenite, as illustrated in Figure 2. The primary clastic components of the reservoirs in both members are quartz and chert, with average quartz grain contents of 61.3% for Shan 2 and 61.4% for Shan 1. The secondary clastic components are dominated by metamorphic rock fragments, accompanied by an extremely low feldspar content and a relatively high content of interstitial materials, averaging 16.45%. The most common cement types observed are siliceous cementation and iron calcite cementation, while the matrix is predominantly composed of hydromica and kaolinite, contributing to the overall geological composition of the study area.

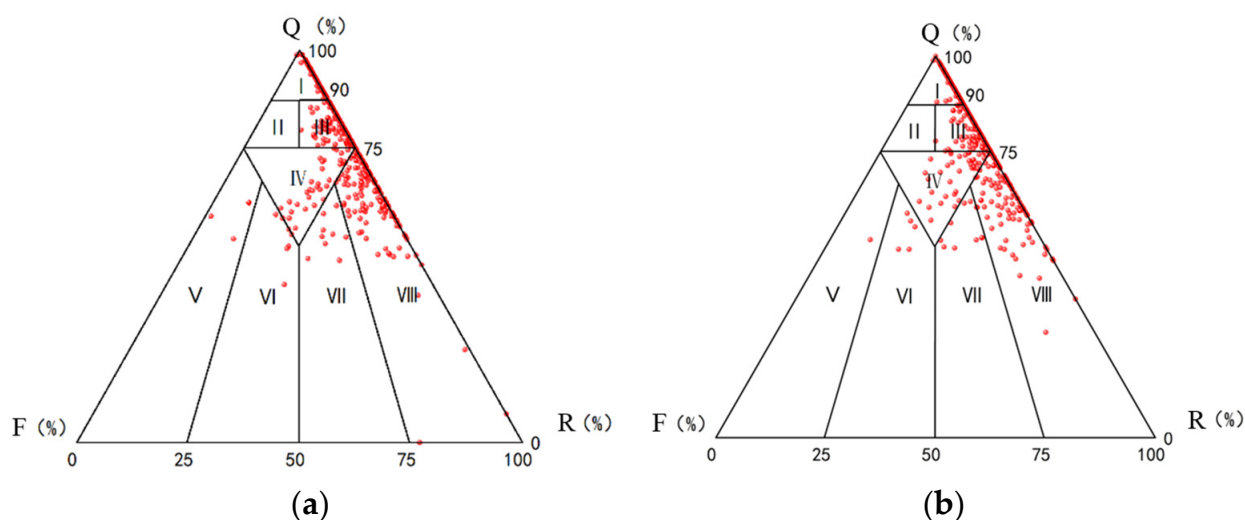


Figure 2. Classification of reservoir rocks in study area (Q: quartz; F: feldspar; R: rock fragment). (a) Shan 1; (b) Shan 2.

Petrophysical analysis of the Shanxi Formation reservoirs in the investigated region indicates generally unfavorable storage and flow characteristics, with porosity and permeability values falling within low ranges. The measured porosity spans from 0.05% to 15.1%, with a mean value of 4.62%, while permeability measurements range between 0.002 mD and 241.74 mD, averaging 1.16 mD. These reservoirs exhibit significant diagenetic modification, with secondary porosity development primarily through feldspar dissolution and kaolinite intercrystalline pore formation. Microscopic examination of thin sections reveals several diagnostic features, including deformed mica flakes, extensive cementation, and quartz overgrowth phenomena (Figure 3). Analysis of pore throat characteristics shows a broad size distribution from 0.01 to 3 mm, though smaller pore throats predominate. Mercury injection capillary pressure data indicate maximum saturation values ranging from 39.25% to 97.95%, with an average of 78.38%, while the principal distribution of maximum pore throat radii falls between 0.165 and 4.34 mm.

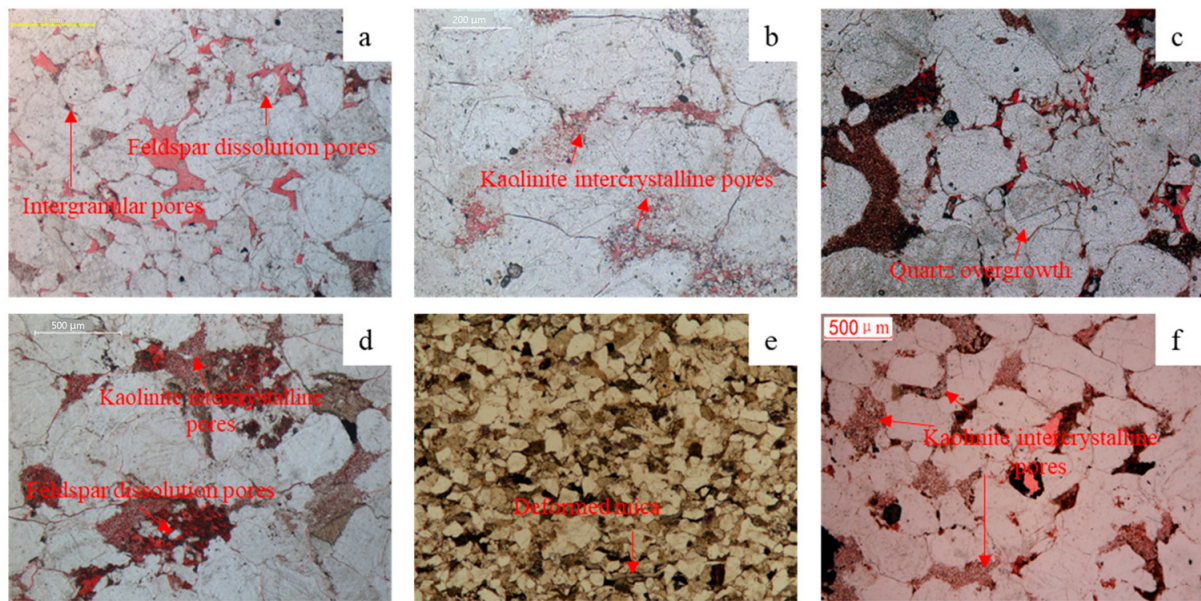


Figure 3. Thin sections of the sandstone reservoirs in the study area: (a) Intergranular pores and feldspar dissolution pores, Q11, 2734 m. (b) Kaolinite intercrystalline pores, Q38, 2784 m. (c) Quartz overgrowth, Y55, 2579 m. (d) Feldspar dissolution pores and kaolinite intercrystalline pores, Y108, 2404 m. (e) Deformed mica, M60, 2104 m. (f) Kaolinite intercrystalline pores, M68, 2537 m.

Overall, these data suggest intense diagenesis within the study area's Shanxi Formation, poor pore throat sorting, uneven pore throat distribution, and limited pore throat connectivity, all of which contribute to the challenging reservoir conditions.

The collective dataset demonstrates that the Shanxi Formation reservoirs have experienced substantial diagenetic alteration, resulting in several challenging characteristics: (1) the poor sorting of pore throat sizes; (2) the heterogeneous spatial distribution of pore networks; and (3) limited connectivity between pore systems. These factors collectively contribute to the complex reservoir quality observed in the study area, presenting significant challenges for hydrocarbon exploration and production.

4.2. Geochemical Characteristics of Formation Water

The formation water within the Shanxi Formation of the study area exhibits characteristics of brine, being devoid of HCO_3^- and SO_4^{2-} ions. It possesses a relatively high salinity, with mineralization values ranging from 23 to 206.63 g/L, averaging at 171.76 g/L. Among the conventional ionic components, the cation concentration decreases in the order of Ca^{2+} , the sum of $\text{K}^+ + \text{Na}^+$, and Mg^{2+} . Conversely, the anion concentration decreases from Cl^- and SO_4^{2-} to HCO_3^- . Notably, chloride concentrations span from approximately 21,902.20 to 12,000 mg/L. The mineralization degree and the concentrations of primary cations and anions in the stratigraphic water surpass those of present-day seawater. Ca^{2+} , $\text{K}^+ + \text{Na}^+$, and Cl^- dominate the ionic composition, resulting in a water type classified as CaCl_2 (Table 1). This water type is favorable for the accumulation and preservation of natural gas.

The sodium chloride coefficient ($\text{Na}^+ / \text{Cl}^-$) of formation water in the Shanxi Formation is relatively low, primarily ranging from 0.15 to 6.23 with an average of 0.77. Statistical analysis reveals that $\text{Na}^+ / \text{Cl}^-$ for the majority of wells is less than 0.50, indicating that the stratigraphic water in the study area is within a closed and reducing environment, which is conducive to the accumulation and preservation of gas reservoirs [36]. The metamorphic coefficient ($(\text{Cl}^- - \text{Na}^+) / \text{Mg}^{2+}$) varies between -0.118 and 1440.5 , averaging at 184.04 , suggesting that the majority of the reservoirs are well-sealed, favorable for gas accumula-

tion and preservation [27,37]. Comprehensive analysis suggests that the tight sandstone gas reservoirs in the Shanxi Formation exhibit good sealing properties, characterized by prolonged water–rock interaction in the sedimentary water, deep circulation, stagnant or slowly alternating runoff, concentration, and positive metamorphism.

Table 1. Hydrochemical characteristics of the Shanxi Formation strata in southern Yulin.

Well	(K ⁺ + Na ⁺)/ (mg/L)	Ca ²⁺ / (mg/L)	Mg ²⁺ / (mg/L)	Cl [−] / (mg/L)	HCO ₃ [−] / (mg/L)	SO ₄ ^{2−} / (mg/L)	Salinity/ (g/L)	Water Type
Y6	26,059	32,011	362	101,949	0	0	168.725	CaCl ₂
Y53	4690	10,060	296	25,949	0	0	40.61	CaCl ₂
Y44	22,310	47,977	3375	130,278	0	0	206.63	CaCl ₂
Y29	22,915	41,313	60	109,347	0	0	175.763	CaCl ₂
Y47	15,199	41,328	1446	102,851	0	0	165.072	CaCl ₂
Y40	25,759	33,566	1386	105,377	0	0	170.771	CaCl ₂
Y29	20,947	33,491	1417	96,355	0	0	153.625	CaCl ₂
F9	8.1	570	57.6	1.3	0	71	23	CaCl ₂
Y80	14,200	10,700	660	43,200	0	0	70.5	CaCl ₂
Y60	32,400	32,400	2610	12,000	0	0	200	CaCl ₂
Y54	18,098	29,038	3315	90,220	0	0	143.51	CaCl ₂

4.3. Occurrence State and Types of Formation Water

The spatial distribution and retention of formation water within reservoir systems are predominantly controlled by three key petrophysical parameters: matrix porosity, pore throat architecture, and the surface adsorption characteristics of mineral constituents. These factors collectively influence fluid storage capacity and phase behavior through their interactions with the rock–fluid system. The spatial distribution of water-producing wells is scattered, and the vertical gas–water relationships are complex. Formation water exhibits diverse occurrence states, as documented in previous studies [38–40]. Based on the characteristics of formation water distribution, it can be further classified into edge/bottom water, isolated lens-shaped water bodies, and residual water trapped within tight sandstone gas layers. This classification provides insights into the complex interplay between reservoir geometry, fluid distribution, and fluid flow behavior within the study area.

Edge/bottom water refers to free water present within the reservoir interval (Figure 4). Under the action of the production of differential pressure, liquid water bodies in the reservoir flow into the wellbore and are subsequently moved to the surface during production. Isolated lens-shaped water is associated with reservoir heterogeneity, where isolated water-rich sand bodies exist within impermeable intervals in the formation. The limited energy of natural gas is unable to displace this original water body within the tight impermeable layers during the reservoir formation process, resulting in isolated lenticular bodies of water with high water saturation (Figure 5). Residual water in tight sandstone gas layers refers to sandstone reservoirs that are initially water-saturated. Due to pressure increase from hydrocarbon generation during the peak hydrocarbon generation period, gas desorbs and becomes free gas, promoting the downward migration of water bodies (Figure 6). Gas migrates preferentially through high-permeability zones (gas-displacing-water phase) during early accumulation. Later structural adjustment induces aquifer invasion (water-displacing-gas phase), establishing dynamic equilibrium. However, when encountering denser sandstone intervals, it lacks the energy to displace the water, leading to the formation of “trapped water saturation zones” within the sandstone.

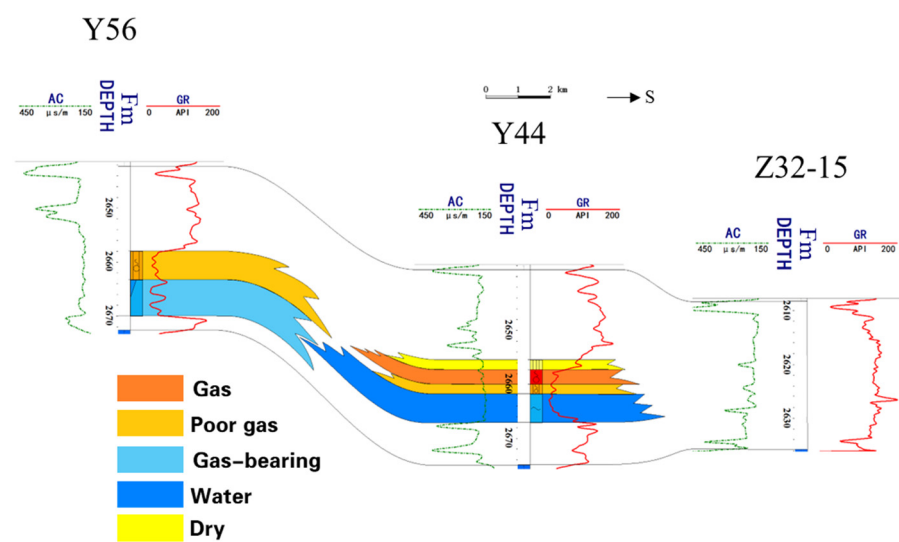


Figure 4. Edge/bottom water distribution characteristics.

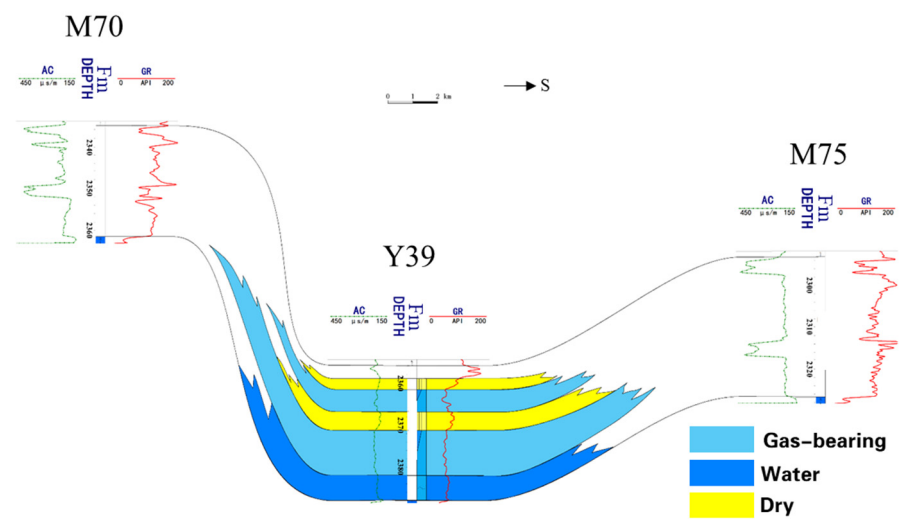


Figure 5. Isolated lens-shaped water bodies' distribution characteristics.

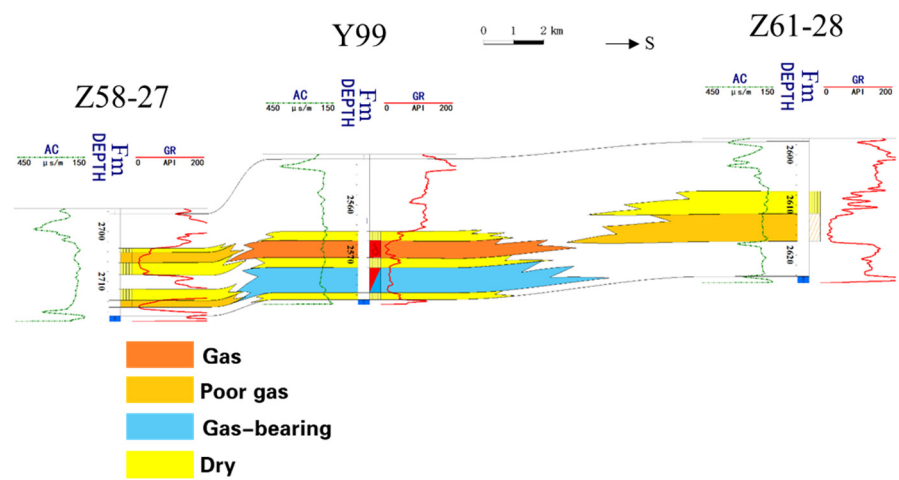


Figure 6. Distribution characteristics of residual water in tight sandstone gas layers.

Hydrodynamic analysis of the Shan 23 reservoir interval reveals two principal aqueous phases: edge/bottom water and isolated lens-shaped water, complemented by localized residual water occurrences within tight gas-bearing sandstones at particular well sites. Edge/bottom water predominantly follows paleochannel margins, while isolated lens-shaped water exhibits dispersed patterns concentrated within central channel facies. Spatially, hydrodynamic analysis reveals isolated lens-shaped water in western, southwestern, southern, and eastern sectors, with lenticular water displaying particularly fragmented distributions focused in central regions. Within the Shan 22 sub-member, isolated lens-shaped water constitutes the dominant aqueous phase, showing irregular distribution patterns concentrated along eastern and western block margins. These water-bearing sand bodies are hydraulically isolated by low-permeability barriers (e.g., argillaceous strata), creating hydraulic compartmentalization that prevents inter-sand body communication, resulting in self-contained lenticular geometries with bilateral termination features. The intricate spatial configuration of aqueous phases and their correlation with reservoir heterogeneity indices underscores the operational complexities in water control strategies for these low-permeability gas-bearing systems. This fluid distribution architecture demonstrates strong genetic relationships with (1) depositional facies architecture; (2) diagenetic modification intensity; and (3) structural compartmentalization patterns.

4.4. Gas–Water Distribution

From a cross-sectional perspective, the Shan 23 reservoir is deemed a high-quality reservoir in comparison to the Shan 22 and Shan 21 reservoirs. Within sand bodies exhibiting favorable physical properties, there is a common distribution of gas zones and gas–water zones. Notably, edge/bottom water constitutes the highest proportion in the Shan 23 reservoir. Within the same gas–water system in the cross-section, water bodies are situated at structurally lower or relatively low positions. Additionally, isolated lens-shaped water bodies are typically found in intervals with relatively superior physical properties, surrounded by impermeable layers such as mudstone. Consequently, these water-bearing sand bodies remain disconnected from surrounding sand bodies, manifesting in an isolated form, as illustrated in Figure 7. Conversely, formation residual water primarily occurs in reservoir sand bodies characterized by poor physical properties and is predominantly located in dry layers. This intricate arrangement of gas, water, and physical properties within the Shan 23 reservoir underscores the importance of detailed reservoir characterization for effective exploration and production strategies. The distribution of gas and water in the Shanxi Formation is relatively complex. Natural gas is distributed throughout the Shanxi Formation, but it can be seen that the gas is mainly distributed in the Shan 2 member, appearing as discontinuous blocks or strips. The distribution areas of formation water and natural gas are interwoven, mainly distributed in the Shan 22 and Shan 23 sub-members, without obvious regularity. The coexistence of the two in different layers indicates that the distribution of gas and water in the Shanxi Formation is not simply a layered state but rather a complex interlocking relationship.

4.5. Controlling Factors of Gas–Water Distribution

In the development of coalbed methane in the eastern margin of the Ordos Basin, the frequency of microseismic events induced by the gas–water mutual drive is positively correlated with the fluctuation in formation pressure [41]. Meanwhile, triaxial compression experiments have shown that with the growth of water content, sandstone rocks show a decreasing trend in strength and tend to experience gentle damage with relatively fewer fractures [42], indicating that the distribution of gas and water has a potential impact on rock mechanics, leading to a series of natural disasters. Therefore, it is necessary to

clarify the genesis mechanism and distribution law of formation water in the research area and analyze the gas–water relationship, which is of great significance for the rational arrangement of development well locations and the improvement of production capacity.

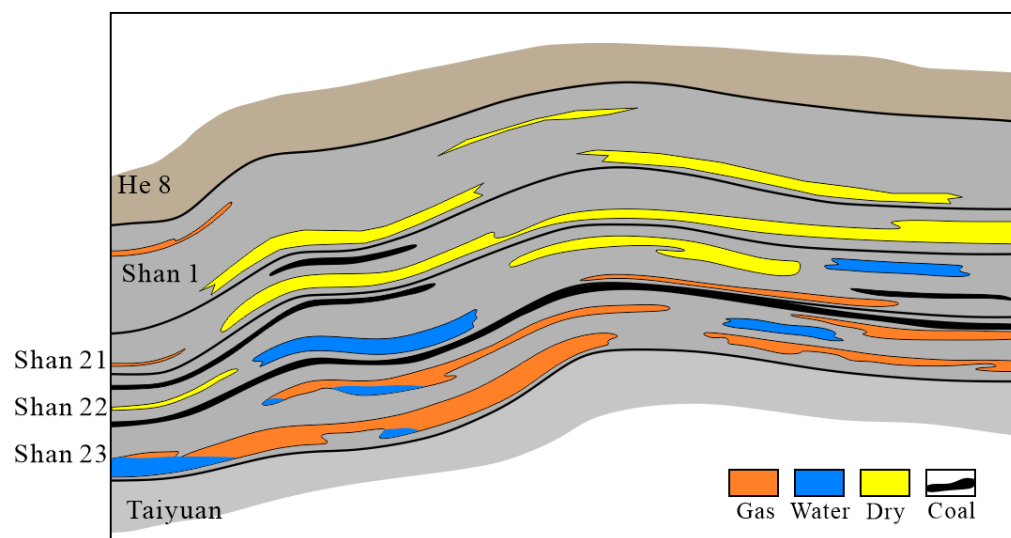


Figure 7. Distribution pattern diagram of formation water in Shanxi Formation.

4.5.1. Geological Structure

Located within the eastern portion of the Shaanbei Slope, the investigated region experienced significant tectonic reorganization during the Yanshan orogenic event. This geological episode fundamentally altered the structural framework, transforming the previously eastward-dipping strata into their current southwest-inclined monoclinical arrangement, a structural disposition that has remained stable since its formation. This structural characteristic facilitates the westward and southwestern migration of formation waters during hydrocarbon migration. The structural architecture of the Shan 2 reservoir interval demonstrates a consistent northeast–southwest-oriented monoclinical dip, with measured inclination angles corresponding to slope gradients of 6 to 14 m/km, reflecting a relatively low-angle structural disposition. Multiple rows of low, gentle, nose-like uplifts, trending nearly northeast, are developed within this structure, with widths spanning from 2.5 to 5.8 km and amplitudes varying between 9.5 and 19.5 m. The concentrated distribution of formation waters in structurally low areas and the relatively simple, gentle topographic features of the west, south, and southwest suggest significant macroscopic control by structural characteristics. As natural gas migrates, it displaces formation waters, causing them to accumulate in adjacent low areas, particularly in the west and southwest of the study area. Consequently, relatively water-rich zones and smaller water-rich points emerge in the eastern region, as illustrated in Figure 8. This complex interplay between structural features and fluid migration patterns underscores the importance of a detailed understanding of geological structures in reservoir characterization and fluid distribution modeling.

In summary, the existing structural characteristics play a pivotal role in constraining the distribution of gas and water, exerting macroscopic and predominant control over these fluid distributions. Specifically, the relatively low structural areas serve as the primary water-rich zones. Furthermore, within relatively independent gas–water systems, the microstructural lows also emerge as the main areas where water bodies are distributed. This underscores the significance of structural geology in determining the spatial arrangement of hydrocarbons and aqueous fluids within subsurface reservoirs.

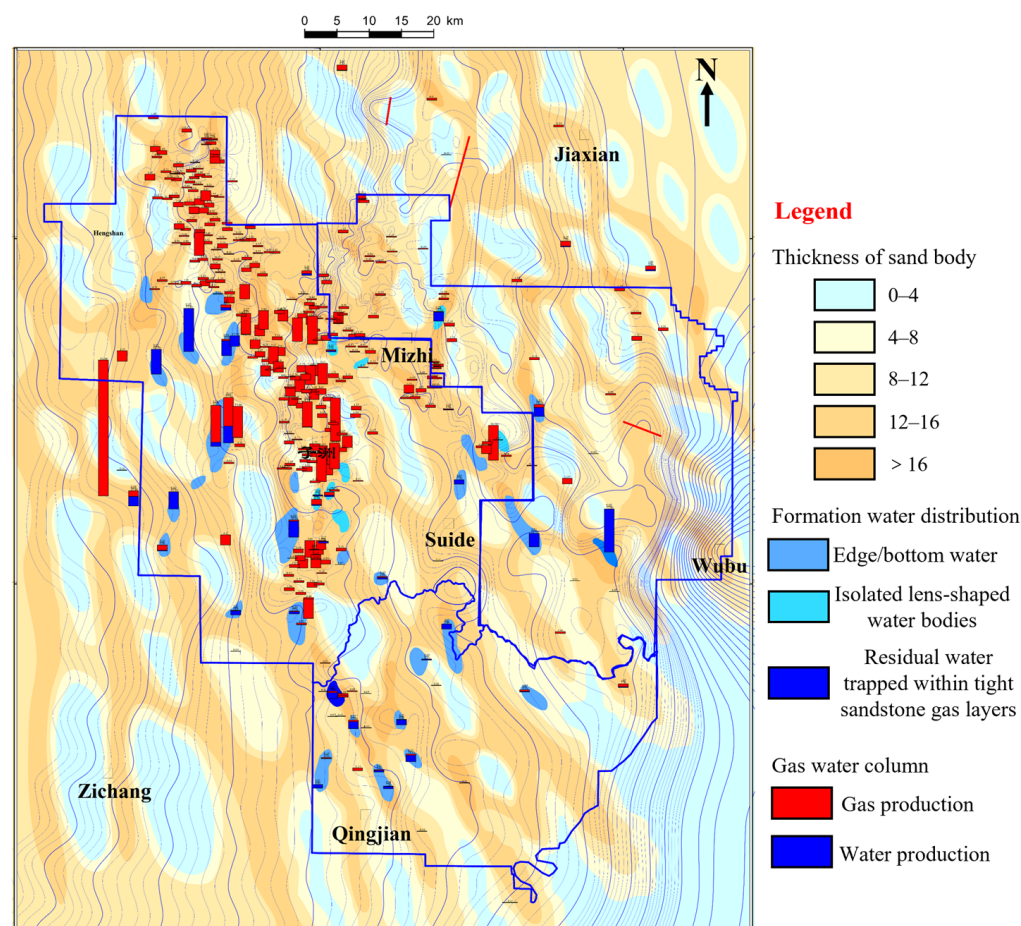


Figure 8. Composite plan view of water bodies, sand bodies, and top surface structures in Shan 23 member. The distribution of sand body thickness, with the blue line representing the structure, showing an overall structural characteristic of being high in the east and low in the west. The formation water is mostly concentrated in the lower part of the formation.

4.5.2. Distribution Conditions of Sand Bodies

The study area is located within a delta-front depositional setting, characterized by sediment input primarily from near-north and northwest directions. This results in a general enrichment and southward distribution of sand bodies. Horizontally, the Shan 2 member is characterized by well-developed sand bodies extending from north to south. Vertically, these sand bodies are stacked in multiple layers, displaying horizontal continuity and a composite, contiguous nature, indicative of good lateral continuity. The spatial arrangement of these sand bodies constitutes a fundamental factor influencing the distribution of gas and water. Notably, zones where sand bodies exhibit bending and pinch-out features are identified as critical areas for the accumulation of formation water, as illustrated in Figure 9. This intricate relationship between sand body distribution and fluid occurrence highlights the importance of sedimentological processes in shaping the fluid distribution patterns within subsurface reservoirs.

4.5.3. Reservoir Properties

The spatial distribution of aqueous phases within the reservoir system is significantly controlled by petrophysical characteristics, with the investigated area displaying intricate gas–water-phase relationships. These complex fluid distributions are fundamentally linked to three key factors: the deltaic depositional environment, suboptimal reservoir quality parameters, and restricted connectivity between sand body elements.

The Shan 23 member's gas reservoir exhibits an average porosity of 5.47% and an average permeability of 0.461 millidarcy (mD). Conversely, the water reservoir within the same member has an average porosity of 6.21% and an average permeability of 0.341 mD. Analysis reveals no significant correlation between the porosity of the sand bodies and their associated water production. However, a certain correlation is observed between water production and permeability, with a tendency for water production to decrease as permeability increases. Specifically, the porosity of sand bodies in the water-producing layers primarily falls within the range of 5% to 9%, while the permeability predominantly spans from 0.1 to 0.65 mD (Figures 10 and 11). These observations highlight the sophisticated interactions among reservoir quality parameters and fluid phase behavior, emphasizing the challenges in predicting and managing water production in low-permeability systems.

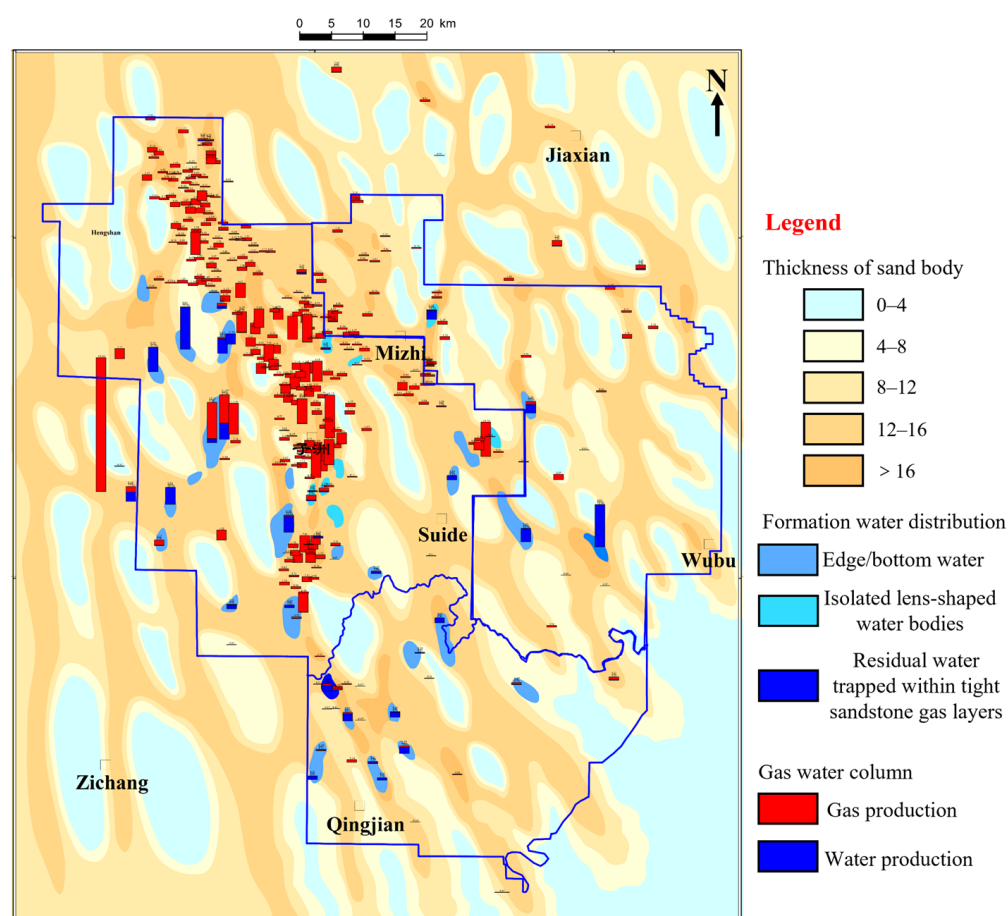


Figure 9. Composite plan view of water bodies and sand bodies in Shan 23 member. Sand bodies zone exhibit bending and pinch-out features are identified as critical areas for the accumulation of formation water.

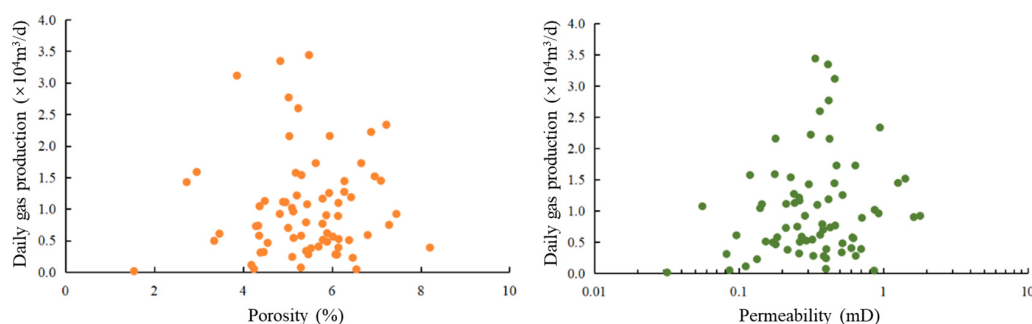


Figure 10. Intersection plot of daily gas production and porosity–permeability in Shan 23 member.

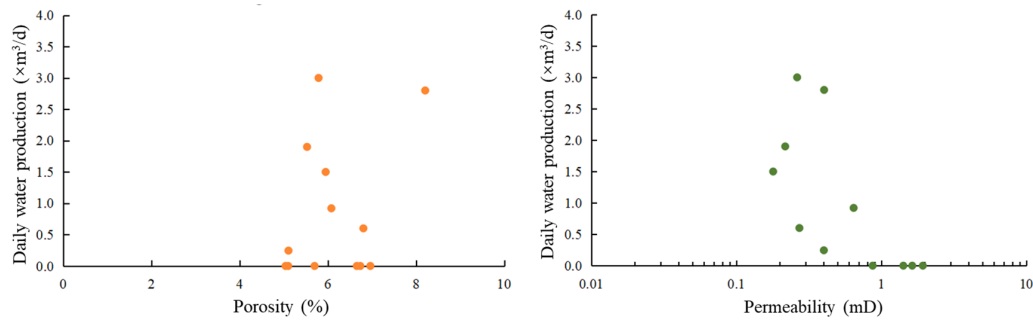


Figure 11. Intersection plot of daily water production and porosity–permeability in Shan 23 member.

Mobile water in larger pores is readily displaced by natural gas, whereas mobile water in smaller pores tends to remain. Additionally, the Shanxi Formation contains carbonate cementation, which causes water to become the wetting phase and natural gas to become the non-wetting phase in the reservoir. As a result, water readily enters small pores but is difficult to be displaced by natural gas. Consequently, reservoir conditions directly influence the extent to which natural gas migrates into the reservoir and displaces water, thereby affecting the amount of mobile water within the reservoir.

5. Conclusions

This investigation presents a comprehensive analysis of petrological characteristics and pore network architecture within the Shanxi Formation of the southern Yulin region, the Ordos Basin, integrating a detailed examination of formation water types and their distinctive features through dynamic reservoir data interpretation. The stratigraphic unit represents a transitional depositional system between marine and continental environments, with delta-front facies development comprising three principal subfacies such as subaqueous distributary channels, interdistributary bays, and swamps. In terms of reservoir lithology, the Shan 2 member is predominantly composed of sublitharenites with minor occurrences of litharenite, whereas the Shan 1 member is dominated by litharenite, followed by sublitharenites. Notably, both members exhibit low porosity and low permeability characteristics, indicating challenging reservoir conditions.

Through integrated analysis of well log interpretations and production data, combined with the spatial distribution patterns of aqueous phases in the investigated reservoirs, three distinct formation water types are identified within the Shan 2 interval: edge/bottom water, isolated lens-shaped water bodies, and residual water in tight sandstone gas layers. Significantly, all three aqueous phases coexist within the Shan 2 member, with edge/bottom water being predominantly concentrated in the Shan 23 sub-reservoir system. By integrating structural and reservoir characteristics, the distribution patterns of formation water in the Shan 2 member of the study area are analyzed. The primary controlling factors for the distribution of formation water include sand body conditions, reservoir properties, and structural features. Formation water tends to accumulate in areas where sand bodies exhibit bending or pinch-out features and in structurally low or relatively low positions. Furthermore, due to reservoir heterogeneity, formation-trapped water and isolated lenticular water bodies are more likely to accumulate in parts of the reservoir with inferior physical properties or in sand bodies with poor interconnections. These findings provide critical insights for water management strategies in heterogeneous tight gas reservoirs, particularly regarding the prediction and mitigation of aqueous-phase interference during production operations. We could explore the implications of gas–water interaction in the context of natural hazards such as rock bursts in the future, which were not within the scope of the present research but could offer valuable insights for enhancing safety and resource management in related industries.

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