ISSN: 2710-0723

The Diagenesis of Shanxi Group Shale and Its Impact on Pore Development

Lindong Shangguan[1,2]

[1] School of Earth Sciences and Engineering, Xi'an Shiyou University, Xi'an, Shaanxi, 710300, China

[2] Shaanxi Key Laboratory of Petroleum Accumulation Geology, Xi'an Shiyou University, Xi'an, China

Abstract

The Shanxi Formation, as a key marine-terrestrial transitional sedimentary stratum of the Permian in North China, exhibits shale porosity characteristics that directly govern its hydrocarbon storage and flow capacity. Diagenesis serves as the core factor regulating porosity evolution. This study focuses on the marine-terrestrial transitional shales of the Shanxi Formation. It systematically reviews the regional geological context, summarizes current domestic and international research on diagenesis and pore development within the formation, and outlines commonly used research methodologies. The analysis emphasizes the positive and negative impacts of major diagenetic processes-including compaction, cementation, dissolution, replacement, and organic matter evolution-on pore development. Utilizing indices such as vitrinite reflectance (Ro), and clay mineral transformation. It concludes by summarizing core findings and existing gaps in current research while proposing future research directions. Research indicates that diagenetic processes in the marine-terrestrial transitional shales of the Shanxi Formation are complex. Compaction and cementation are the primary causes of pore loss, while dissolution and organic matter evolution are key to secondary pore formation. The diagenetic stage primarily ranges from Middle Diagenetic Stage B to Late Diagenetic Stage, with the interaction of various diagenetic processes collectively determining the final pore development characteristics. This study provides theoretical reference and technical support for hydrocarbon exploration, development, and reservoir evaluation in the marine-terrestrial transitional shales of the Shanxi Formation.

Keywords

Shanxi Group; Shale; Diagenesis; Pore Development.

1. Introduction

With the continuous advancement of shale oil and gas exploration and development, marine-terrestrial transitional shales have gradually emerged as a hotspot in unconventional hydrocarbon research due to their abundant resource potential. Chinese marine-terrestrial transitional shale resources amount to approximately 19.8×10^{12} m^3, accounting for 25% of the nation's total shale gas resources, indicating immense exploration and development potential. The Shanxi Formation, extensively distributed across the North China Platform, represents a significant Permian marine-terrestrial transitional coal-bearing stratum. Its depositional environment reflects combined marine and continental tectonic influences. The deposited shales exhibit characteristics such as widespread distribution, substantial cumulative thickness, high organic matter content, and well-developed microfractures, making them potential high-quality reservoirs for transitional-phase shale gas[1-6].

ISSN: 2710-0723

Pores serve as the core medium for shale oil and gas accumulation and migration. Their development degree, pore types, and distribution characteristics directly influence the reservoir properties and gas potential of shale. The evolution of shale porosity is complex, governed by multiple factors including depositional environment, material composition, tectonic movements, and diagenesis. Diagenesis, occurring throughout the post-depositional evolution of shale, is the key factor determining the final porosity characteristics. It directly or indirectly regulates porosity formation, preservation, and destruction by altering the mineral composition, structural architecture, and degree of organic matter evolution within the shale[6,7].

To date, extensive research on Shanxi Formation shales has been conducted both domestically and internationally, primarily focusing on lithofacies types, geochemical characteristics, hydrocarbon evolution, and reservoir characterization. However, systematic investigations into the influence of diagenesis on pore development remain insufficient. Key gaps include unclear mechanisms of interaction among different diagenetic processes, inconsistent criteria for diagenetic stage classification, and limited research on the impact of regional diagenetic variations on pore development. Therefore, this paper takes the marine-terrestrial transitional shales of the Shanxi Formation as its research subject. It systematically reviews the influence of diagenesis on pore development, integrates existing research findings, clarifies the research trajectory, identifies current research gaps, and proposes future research directions. This study provides a theoretical basis for the efficient exploration and development of oil and gas resources in the Shanxi Formation shales[6,7].

2. Geological Setting

The Shanxi Group belongs to the Lower Permian System and is widely distributed across the North China Platform. It is primarily developed in the Ordos Basin, South North China Basin, Bohai Bay Basin, and other regions. Formed in a marine-terrestrial transitional environment during the Late Carboniferous to Early Permian, its sedimentary thickness generally ranges from 50 to 200 meters. The group exhibits a distribution pattern characterized by greater thickness in the east and south, and lesser thickness in the west and north. This stratigraphic unit occupies a critical transitional zone between marine and terrestrial environments, influenced by both marine and continental forces. Dominant sedimentary facies include tidal-controlled deltaic, tidal-controlled estuarine-bay, and barrier-island-lagoon-deltaic types, with localized swamp facies. The complexity of the depositional setting results in pronounced regional variations in shale lithology, mineral composition, and organic matter distribution[8,9].

Geochemically, the Shanxi Formation shales exhibit high organic matter abundance. In the Daning-Jixian area along the eastern margin of the Ordos Basin, the average total organic carbon (TOC) content is 4.06%, with humic (Type III) being the predominant organic type. The organic microfossils are mainly humic amorphous and vitrinite components, with vitrinite reflectance (Ro) ranging from 2.21% to 3.12% and averaging 2.61%. Overall, the shales are in an overmature stage of evolution, exhibiting high generative potential. Similarly, organic matter in the Shanxi Formation shales of the South North China Basin is predominantly Type III. Organic pores are less developed, with common organic margin shrinkage cracks. The surface porosity of pores within and around organic matter does not exceed 9.9% of the organic area[9,10].

Structurally, the Shanxi Formation underwent multiple tectonic episodes post-deposition, including the Indosinian, Yanshanian, and Himalayan orogenies. These movements altered burial depth and thermal conditions, catalyzing diagenetic processes while generating extensive microfractures that facilitated pore connectivity, indirectly influencing pore development and preservation. Specifically, the Shanxi Formation shales in the southeastern

ISSN: 2710-0723

Ordos Basin underwent four subsidence events and three uplift events after deposition. The burial depth reached its maximum around 104 Ma, followed by prolonged uplift that caused approximately 1600 m of stratigraphic gap, significantly affecting diagenetic evolution and pore development processes[8,10].

3. Current State of Research in China and Abroad

3.1. Current State of Research in China

Domestic research on diagenetic processes and pore development in the Shanxi Formation has primarily focused on core distribution areas such as the Ordos Basin and the South North China Basin. Studies have covered aspects including diagenetic types, pore characteristics, influencing factors, and diagenetic evolution. Regarding diagenetic processes, scholars generally agree that Shanxi Formation shales primarily underwent compaction, cementation, dissolution, replacement, and organic matter-related diagenesis. Among these, compaction and cementation are destructive diagenesis, while dissolution is constructive. Kaolinite and chlorite cementation exhibit certain pore-preserving properties.

Regarding porosity development characteristics, studies indicate that Shanxi Formation shales exhibit diverse pore types, primarily including organic pores, intergranular mineral pores, interlayer clay mineral pores, intergranular pyrite pores, and mineral dissolution pores. Significant differences in pore structures exist among different lithofacies shales. Among them, the high-TOC siliceous shale facies possesses the most favorable reservoir conditions, dominated by organic pore networks and intergranular mineral pores, exhibiting a generally favorable overall pore structure. Conversely, low-TOC clayey shale facies possess a poorer pore structure, primarily developed with intergranular pores and a small amount of organic microporosity.

Regarding the influence of diagenetic processes on porosity, most studies indicate that compaction is the primary factor causing loss of primary porosity, followed by cementation. Meanwhile, dissolution and organic matter evolution can generate secondary porosity, improving reservoir properties. Concurrently, the transformation of clay minerals also influences pore development. During the Middle Diagenetic Stage B to Late Diagenetic Stage, rapid conversion of kaolinite to illite-montmorillonite and illite significantly impacts pore volume and connectivity. Regarding diagenetic stage classification, different scholars have divided the Shanxi Formation shales into early, middle, and late diagenetic stages based on indicators such as Ro values, clay mineral transformation, and cement types. The Shanxi Formation shales in the Ordos Basin and the southern North China Basin primarily occur within the Middle Diagenetic Stage B to Late Diagenetic Stage.

Additionally, domestic researchers have explored correlations between lithofacies types, depositional environments, diagenesis, and pore development. Findings indicate that shallow marine bay-lagoon environments favor Type II_2 kerogen formation, readily producing abundant honeycomb-like organic gas bubbles. Biogenic silica enrichment enhances the preservation of various pore types and improves reservoir fracturability. Lagoon or swamp-type shales often adjoin coal seams, exhibiting macroporosity development, simple pore structures, high porosity volumes, and high connectivity-characteristics that make them favorable facies zones for developing high-quality reservoirs. However, current domestic research still has limitations, such as insufficient exploration into the interactive mechanisms of different diagenetic processes, weak investigation into the impact of regional diagenetic variations on pore development, and limited quantitative modeling of pore evolution.

3.2. Current State of Research in Abroad

Although no specific Shanxi Formation equivalent exists overseas, extensive research has been conducted on the diagenesis and pore development of transitional marine (marginal marine) shales. This has led to the development of a relatively mature theoretical framework and research methodology, whose findings hold significant reference value for studies on Shanxi Formation shales. International research primarily focuses on diagenetic mechanisms, pore evolution patterns, and quantitative characterization, emphasizing the coupling between organic matter evolution and diagenesis, as well as the influence of different diagenetic environments on pore development.

In diagenetic studies, foreign scholars investigating Cenomanian-Turonian Eagle Ford Group (EFG) mudstones found that the original porosity of these mudstones reached 70–80% during shallow burial stages. However, current porosity has decreased to approximately 10%, primarily due to burial-related diagenesis such as compaction and cementation. Concurrently, significant interactions exist between organic matter evolution and diagenetic processes in the mineral matrix, substantially influencing mudstone cementation-an effect more pronounced in mudstones than in sandstones or carbonates.

In pore evolution studies, international researchers emphasize the quantitative coupling of diagenesis with pore development. By establishing diagenetic evolution models and integrating thermal simulation experiments with porosity testing, they quantify the contributions of different diagenetic processes to pore loss and formation, identifying critical periods and controlling factors in pore evolution. For instance, by simulating the generation and migration of organic acids during organic matter maturation, they revealed the mechanism by which dissolution creates secondary pores. They concluded that the dissolution of minerals by organic acids is crucial for improving reservoir properties, and the intensity of dissolution is closely related to organic matter maturity and burial depth.

Additionally, foreign scholars have conducted in-depth studies on the diagenetic environments of marine-terrestrial transitional shales. They have clarified the influence of marine-terrestrial tectonic interactions on the types and intensity of diagenetic processes, proposing evolutionary models for diagenesis and pore development under different sedimentary environments. However, due to differences in the sedimentary background and material composition of foreign marine-terrestrial transitional shales compared to the Shanxi Formation, their research findings cannot be directly applied to the Shanxi Formation. Instead, they should be adapted and refined based on the specific geological characteristics of the Shanxi Formation.

4. Methodology

4.1. Sample Collection

A total of 100 shale samples of the S_2^3 submember of the Shanxi Formation were collected from the DJ3−4 well, which is located on the eastern margin of the Ordos Basin[11].

4.2. Geochemical and Mineralogical Characteristics

First, after pretreatment with hydrochloric acid (HCl) to remove carbonate minerals, the total organic carbon (TOC) contents of the Longtan Formation samples were determined using a LECO CS-230 carbon/sulfur analyzer. Meanwhile, vitrinite reflectance (Ro) was measured with a microscope photometer, and the maximum, minimum, and average values of vitrinite reflectance were recorded accordingly. Subsequently, all samples were ground into 200-mesh powder, and X-ray diffraction (XRD) analysis was carried out on a Bruker AXS D8 ADVANCE diffractometer in accordance with the industrial standard SY/T5163-2010, under conditions of 20 °C and 70% relative humidity. The operating voltage and current were set at 40 kV and 40 mA, respectively. Based on the standard powder diffraction data from the International Centre

ISSN: 2710-0723

for Diffraction Data (ICDD), the mineral compositions of the shale were identified. In addition, mineral contents were calculated from the diffraction patterns using the RIR method[12].

4.3. Scanning Electron Microscope (SEM) Observation

In this study, the shale samples were polished using a Leica EM TIC 3X triple ion beam milling system. The polishing voltage and current were set at 6 keV and 2 mA, respectively, with a polishing duration of 3-4h. The flat polished surfaces were oriented perpendicular to the bedding plane. Following polishing, a thin gold (Au) layer was deposited onto the samples using a Leica EM ACE600 high-vacuum coater to enhance electrical conductivity and improve the quality of SEM images. Finally, the microscopic pore structures were observed and characterized using a Zeiss Crossbeam 540 field emission scanning electron microscope (FE-SEM)[13].

5. Discussion

5.1. Types of Diagenesis

The diagenetic processes experienced by the marine-terrestrial transitional shales of the Shanxi Formation are complex, primarily involving compaction, cementation, dissolution, replacement, and diagenesis related to organic matter evolution. These processes interact and influence each other, collectively governing the evolution of shale porosity, with compaction, cementation, and dissolution being the most dominant diagenetic types[4,12,14].

(1) Compaction: The earliest diagenetic process occurring after the deposition of Shanxi Formation shales, compaction is the primary factor causing loss of primary porosity and persists throughout the entire diagenetic sequence. Compaction is primarily divided into mechanical compaction and chemical compaction (solubility compaction). Mechanical compaction mainly occurs during the early diagenetic stage. As burial depth increases, the pressure from overlying strata gradually intensifies, causing shale particles to become denser and more tightly packed. Primary intergranular pores are significantly compressed or even eliminated. Chemical compaction occurs primarily during the middle diagenesis stage and beyond. As burial depth increases further, elevated temperature and pressure conditions induce dissolution between shale particles. This process smooths particle edges, forming compaction-dissolution sutures that further reduce pore volume. The Shanxi Formation shales contain high clay mineral content with strong plasticity, making them prone to deformation under compaction and accelerating primary pore loss. Higher kaolinite and total clay content correlates with accelerated compaction-induced pore reduction rates.

(2) Cementation: As a destructive diagenetic process occurring primarily from late early diagenesis to mid-diagenesis, it involves the precipitation of minerals from pore water within the pore space. This forms cement that blocks pores, reducing porosity and permeability. The cementation types in Shanxi Formation shales primarily include siliceous cementation, carbonate cementation, clay mineral cementation, and pyrite cementation, with siliceous and carbonate cementation being the most common. Siliceous cementation primarily originates from the dissolution and resettlement of quartz grains and the transformation of biogenic silica. It predominantly exists as secondary quartz grains with enlarged edges and microcrystalline quartz, widely distributed throughout pore spaces, exerting a strong pore-blocking effect. Carbonate cementation primarily includes calcite and dolomite, predominantly forming during the diagenetic stage. Influenced by pore water chemistry, it concentrates in localized areas, severely blocking pores. Clay mineral cementation primarily involves kaolinite, illite, and chlorite. Kaolinite and chlorite cementation exhibit some pore-retaining properties, mitigating pore loss to a degree. Illite cementation, however, readily forms fibrous or lamellar aggregates that obstruct pores and throats. Pyrite cementation primarily occurs in reducing environments,

ISSN: 2710-0723

appearing as nodular or strawberry-like structures. While its impact on porosity is relatively minor, significant accumulation can also cause pore blockage.

(3) Dissolution: A constructive diagenetic process occurring primarily during the mesodiagenesis stage, where organic and inorganic acids in pore water dissolve soluble minerals within shale, creating secondary pores that enhance reservoir properties. In the Shanxi Formation shales, dissolution is closely linked to organic matter evolution. During maturation, organic matter generates substantial organic acids that enter pore water, dissolving soluble minerals like feldspar, carbonate minerals, and clay minerals to form dissolution pores. Concurrently, fractures generated by tectonic movements provide pathways for pore water migration, facilitating the initiation and progression of dissolution. Soluble pores in Shanxi Formation shales primarily include mineral-dissolved pores, intergranular dissolved pores, and intragranular dissolved pores. Mineral-dissolved pores are most common, formed mainly by the dissolution of feldspar and carbonate minerals. The intensity of dissolution is closely related to organic matter maturity, burial depth, and fracture development. Higher organic matter maturity and more developed fractures result in stronger dissolution and more developed secondary porosity. For instance, in the Shanxi Formation shales of the South China-North China Basin, a dissolution window forms at Ro=1.0%, improving reservoir properties. In the southern Ordos Basin, dissolution increased porosity to 3% in Shanxi Formation quartz sandstones composed of shale clasts.

(4) Replacement: Primarily occurring during the diagenetic stage, this process involves the replacement of original shale minerals by minerals from pore water, forming new minerals. While replacement itself has a minor direct impact on pore volume, it alters the mineral composition and structural fabric of shales, indirectly influencing pore development and preservation. Common metasomatic processes in Shanxi Formation shales include feldspar replacement by clay minerals, carbonate replacement by silica, and inter-clay mineral replacement. For instance, after feldspar is replaced by illite, the stability of mineral grains decreases, making them prone to deformation under compaction and leading to pore loss. Silicification of carbonate minerals forms siliceous minerals that enhance shale brittleness, reducing compaction damage to pores. Simultaneously, dissolution of siliceous minerals can further create secondary pores.

(5) Diagenesis related to organic matter evolution: Organic matter in Shanxi Formation shales is predominantly humic. During organic matter evolution, organic acids are generated, promoting dissolution processes while also forming organic pores. As organic matter matures, kerogen undergoes thermal cracking to form hydrocarbons. After hydrocarbon expulsion, numerous micropores and mesopores-termed organic pores-develop within the kerogen matrix. The degree of organic pore development correlates closely with organic matter abundance and maturity: higher abundance and maturity yield more developed organic pores. For example, the siliceous shale facies with high TOC content along the eastern margin of the Ordos Basin developed extensive honeycomb-like organic gas bubbles, significantly enhancing reservoir storage capacity. In contrast, the organic matter in the Shanxi Formation shale of the South North China Basin is predominantly Type III, exhibiting limited development of organic pores, primarily characterized by organic margin shrinkage cracks.

5.2. The Effect of Diagenesis on Pore Development

5.2.1. The Effect of Destructive Diagenesis on Pores

Compaction and cementation are the primary causes of pore loss in the Shanxi Formation shales. Together, they lead to a significant reduction in primary pores and inhibit the development of secondary pores. The destructive effects of compaction on pores manifest in two main ways: First, mechanical compaction causes particles to pack more tightly, compressing and closing primary intergranular pores. This is particularly pronounced in shales

ISSN: 2710-0723

with high clay mineral content, where particle deformation is significant and pore loss is more severe. Second, chemically induced compaction forms pressure-dissolution sutures, further reducing pore volume and decreasing connectivity. Studies indicate that by the end of the early diagenetic stage, primary porosity in quartz sandstones of the Shanxi Formation in the southern Ordos Basin decreased to 9.2%, while in clastic quartz sandstones and clastic sandstones it fell to 16.2%-primarily due to compaction. Through late diagenesis to the present, quartz sandstone porosity has continuously decreased to below 2%, driven by both compaction and cementation.

Cementation primarily damages pores through sedimentation within pore spaces, blocking pores and throats, thereby reducing porosity and permeability. Different cement types exhibit varying degrees of pore destruction: Siliceous cement, widely distributed, exerts the strongest blocking effect, potentially reducing porosity by 5%–10%. Carbonate cement concentrates locally, causing uneven pore blockage with regional reductions of 3%–8% in porosity. Fibrous aggregates formed by illite cementation not only block pores but also reduce pore connectivity; kaolinite and chlorite cementation cause relatively minor damage to pores and may even mitigate pore loss due to compaction to some extent, thereby protecting pore space.

5.2.2. The Effect of Constructive Diagenesis on Pores

Dissolution and diagenetic processes related to organic matter evolution are key factors in the formation of secondary pores in the Shanxi Formation shale. These processes effectively enhance reservoir properties, providing space for shale oil and gas accumulation. Dissolution dissolves soluble minerals, creating numerous secondary dissolution pores-primarily mesopores and macropores-with good connectivity. This significantly increases the shale's porosity and permeability. Studies indicate that in the southern Ordos Basin, quartz sandstones from the Shanxi Formation experienced a porosity increase from 16.2% during the early diagenetic stage to 3% in the late diagenetic stage due to dissolution. Although overall porosity remains low, dissolution significantly improved porosity. In the Shanxi Formation shales of the South and North China Basins, a dissolution window forms at Ro=1.0%, markedly improving reservoir properties. At Ro=1.5%, adsorbed gas reaches saturation, and at Ro=2.0%, both free and adsorbed gases become saturated.

Organic-related diagenetic processes enhancing porosity manifest in two primary ways: First, organic acids generated during organic matter maturation catalyze dissolution, indirectly creating secondary pores. Second, organic matter pores formed by the pyrolysis of organic matter itself-primarily micropores and mesopores-constitute one of the primary reservoir spaces for shale oil and gas. The Shanxi Formation shale exhibits an average TOC content of 4.06%, indicating relatively high organic matter abundance. As the Ro value increases, organic pores gradually develop. When Ro reaches approximately 2.61% (the overmature stage), the development of organic pores reaches a high level, significantly enhancing the reservoir properties of the shale. Additionally, organic matter adsorbs minerals from pore water, inhibiting the precipitation of cementation materials and indirectly protecting the pores.

5.3. Stages of Diagenesis

Based on the mineral composition, organic matter maturity, diagenetic types, and intensity of the Shanxi Formation's marine-terrestrial transitional shales, and referencing domestic and international diagenetic stage classification standards, the diagenetic stages of the Shanxi Formation shales are divided into three phases: Early Diagenetic Stage, Middle Diagenetic Stage, and Late Diagenetic Stage. The Middle Diagenetic Stage is further subdivided into Middle Diagenetic Stage A and Middle Diagenetic Stage B, with distinct diagenetic characteristics and pore evolution patterns observed across different stages[15-20].

(1) Early Diagenetic Stage: Ro<0.5%. This stage is dominated by mechanical compaction with weak chemical compaction. Cementation primarily involves clay minerals and minor carbonate

cementation, while dissolution is poorly developed. Shale particles are loosely arranged with well-developed primary intergranular pores, resulting in high porosity dominated by primary pores. Pore types are simple, and connectivity is good. Clay minerals are predominantly montmorillonite, showing no significant alteration. Organic matter remains in the immature to low-mature stage, with undeveloped organic pores and minimal influence on porosity from organic evolution. Pore evolution in this stage is primarily controlled by compaction. As burial depth increases, primary pores gradually diminish, and porosity slowly decreases.

(2) Middle Diagenetic Stage A: 0.5%≤Ro<1.3%. Mechanical compaction continues but with reduced intensity, while chemical compaction begins to manifest. Cementation is dominated by siliceous and carbonate cementation, with dissolution processes commencing. Clay minerals undergo preliminary alteration, with montmorillonite transitioning toward a montmorillonite-illite interlayer, and the illite interlayer ratio gradually increasing. Organic matter reaches low-mature to mature stages, initiating the formation of minor organic acids. These acids begin dissolving soluble minerals, creating limited secondary dissolution pores. Primary pores further diminish while secondary pores emerge, diversifying pore types. Porosity declines but at a slower rate. This stage marks the critical period for secondary pore formation, with pore evolution jointly controlled by compaction, cementation, and dissolution. Compaction and cementation remain the primary factors causing pore loss, while dissolution has a limited effect on pore improvement.

(3) Middle Diagenetic Stage B: 1.3%≤Ro<2.0%. During this stage, chemical compaction intensifies significantly while mechanical compaction weakens. Cementation reaches its peak, with widespread development of siliceous and carbonate cementation, and dissolution enters a vigorous phase. Clay minerals undergo further transformation: montmorillonite-illite interlayers convert to illite, with the montmorillonite-illite interlayer ratio gradually decreasing and illite content gradually increasing. Organic matter reaches the mature-to-high-mature stage, generating abundant organic acids and markedly intensifying dissolution. This forms extensive secondary dissolution pores while organic matter begins pyrolysis, creating minor organic pores. Primary pores largely disappear, with secondary pores becoming the dominant pore type. Porosity slightly recovers, and pore connectivity improves. This stage represents a critical period for pore development, where dissolution becomes the primary factor in pore formation. The destructive effects of cementation on pores are partially offset, with pore evolution primarily controlled by dissolution and cementation processes. For example, in the Shanxi Formation shales of the South North China Basin, clay minerals rapidly transform from kaolinite to the kaolinite-montmorillonite interlayer and illite during this stage, exhibiting a pattern of initial increase followed by decrease in porosity and specific surface area. In the southern Ordos Basin, quartz sandstones from the Shanxi Formation exhibit increased porosity during this stage due to dissolution.

(4) Late diagenetic stage: Ro≥2.0%. Mechanical and chemical compaction largely cease, cementation intensity weakens, dissolution persists but diminishes, and replacement processes become well-developed. Clay mineral transformation is largely complete, dominated by illite with low kaolinite content. Organic matter reaches a high-to-overmature stage with significant pyrolysis, developing abundant organic pores that become the primary pore type. Secondary dissolution pores further develop, though ongoing cement precipitation partially blocks these secondary pores. Porosity stabilizes, with pore connectivity primarily controlled by fracture development. The Shanxi Formation shales exhibit an average Ro of 2.61%, indicating an overall overmature evolutionary stage. Most areas are in the late diagenetic phase, characterized by organic pores and secondary dissolution pores as the primary pore types. Pore volume remains relatively low, yet the pore structure is complex. Reservoir properties are primarily determined by the development of organic pores and the connectivity of fractures.

ISSN: 2710-0723

6. Conclusion

The Shanxi Group marine-terrestrial transitional shales are widely distributed across the North China Platform, primarily developed in regions such as the Ordos Basin and the South North China Basin. Their sedimentary environments are dominated by tidal-controlled deltaic facies, tidal-controlled estuarine-bay facies, and barrier island-lagoon-deltaic facies. The mineral composition is characterized by quartz and clay minerals, with relatively high organic matter abundance. The average TOC content is 4.06%, with an average Ro of 2.61%. Overall, these shales are in the overmature stage, exhibiting high generative potential. Pore types are diverse, primarily including organic pores, intergranular mineral pores, interlayered clay mineral pores, and dissolution pores. Significant variations in pore development characteristics exist among different lithofacies and regions.

The Shanxi Formation shales primarily underwent diagenetic processes including compaction, cementation, dissolution, replacement, and organic matter evolution. Among these, compaction and cementation were the primary causes of pore loss, while dissolution and organic matter evolution were key factors in the formation of secondary pores. These various diagenetic processes interacted and influenced each other, collectively controlling the evolution of porosity. The diagenetic stages can be divided into the early diagenetic stage, middle diagenetic stage A, middle diagenetic stage B, and late diagenetic stage. The Shanxi Formation shales primarily reside within the middle diagenetic stage B to late diagenetic stage, which represents the critical period for pore development.

Diagenetic processes exerted distinct phased and differential influences on the development of shale porosity within the Shanxi Formation: The early diagenetic stage was primarily controlled by compaction, resulting in substantial loss of primary pores. The middle diagenetic stage was jointly governed by compaction, cementation, and dissolution, during which secondary pores gradually formed and developed. The late diagenetic stage was mainly controlled by organic matter evolution and dissolution, with organic pores becoming the predominant pore type and porosity tending toward stability.

References

[1] Wang X, Liu L, Wang Y, et al. Comparison of the pore structures of Lower Silurian Longmaxi Formation shales with different lithofacies in the southern Sichuan Basin, China[J]. Journal of Natural Gas Science and Engineering, 2020, 81: 103419.

[2] ZB. L. S. Diagenesis[J]. AAPG Bulletin, 1958, 42(11): 2692-2717.

[3] Rahman M J J, Worden R H. Diagenesis and its impact on the reservoir quality of Miocene sandstones (Surma Group) from the Bengal Basin, Bangladesh[J]. Marine and Petroleum Geology, 2016, 77: 898-915.

[4] Wang Y, Cheng H, Hu Q, et al. Diagenesis and pore evolution for various lithofacies of the Wufeng-Longmaxi shale, southern Sichuan Basin, China[J]. Marine and Petroleum Geology, 2021, 133: 105251.

[5] Summa L L. Diagenesis and reservoir quality prediction[J]. Reviews of Geophysics, 1995, 33(S1): 87-94.

[6] Zou C, Dong D, Wang S, et al. Geological characteristics and resource potential of shale gas in China[J]. Petroleum Exploration and Development, 2010, 37(6): 641-653.

[7] Loucks R G, Reed R M, Ruppel S C, et al. Spectrum of pore types and networks in mudrocks and a descriptive classification for matrix-related mudrock pores[J]. AAPG Bulletin, 2012, 96(6): 1071-1098.

[8] Cheng M, Li C, Yin J, et. al. Modeling of Burial History, Source Rock Maturity, and Hydrocarbon Generation of Marine-Continental Transitional Shale of the Permian Shanxi Formation, Southeastern Ordos Basin[J]. ACS Omega, 2024, 9(18): 20532-20546.

ISSN: 2710-0723

[9] Wang Y, Gu Y, Cai G, et al. Geological and Geochemical Characterization of Transitional Shale of the Permian Shanxi Formation in the Eastern Ordos Basin, North China[J]. Journal of Petroleum Geology, 2026, 49(1): 142-159.

[10] Zhao W, Wen Z, Zhang H, et al. Integrated Assessment of Marine-Continental Transitional Facies Shale Gas of the Carboniferous Benxi Formation in the Eastern Ordos Basin[J]. Energies, 2021, 14(24).

[11] Xue Y, Dang W, Zhang Q, et al. Lithofacies and Its Reservoir Characteristics of Marine–Continental Transitional Shales: A Case Study of Shanxi Formation in Eastern Ordos Basin[J]. Energy & Fuels, 2024, 38(19): 18441-18456.

[12] Xu L, Yang K, Wei H, et al. Diagenetic evolution sequence and pore evolution model of mesoproterozoic xiamaling organic-rich shale in zhangjiakou, hebei, based on pyrolysis simulation experiments[J]. Marine and Petroleum Geology, 2021, 132: 105233.

[13] Yue S, Yuqiang J, Xianyue X, et al. Lithofacies and sedimentary environment evolution of the Shan2 3 Sub-member transitional shale of the Shanxi Formation in the Daning-Jixian area, eastern Ordos Basin[J]. Coal Geology & Exploration, 2022, 50(9).

[14] Zhang J, Lin W, Li M, et al. Evolution Mechanism of Microscopic Pore System in Coal-Bearing Marine–Continental Transitional Shale with Increasing Maturation[J]. Minerals, 2023, 13(12).

[15] Wang X, Mou C, Wang Q, et al. Diagenesis of black shale in Longmaxi Formation,southern Sichuan Basin and its periphery[J]. Acta Sedimentologica Sinica, 2015, 36(9).

[16] Xie W, Wang M, Wang H, et al. Diagenesis of shale and its control on pore structure, a case study from typical marine, transitional and continental shales[J]. Frontiers of Earth Science, 2021, 15(2): 378-394.

[17] Lu L, Liu W, Wei Z, et al. Diagenesis of the Silurian Shale, Sichuan Basin: Focus on pore development and preservation[J]. Acta Sedimentologica Sinica, 2022, 40(1): 73-87.

[18] Tan X, Tian J, Li Z, et al. Diagenetic character and controling factor of reservoir of Kongdian Formation of Paleogene in Dongying basin[J]. Coal Geology & Exploration, 2010, 38(6).

[19] Lin S, Guo X, Li L, et al. Diagenetic Evolution and Formation Mechanism of Middle to High-Porosity and Ultralow-Permeability Tuff Reservoirs in the Huoshiling Formation of the Dehui Fault Depression, Songliao Basin[J]. Minerals, 2025, 15(3).

[20] Wang R, Hu Z, Bao H, et al. Diagenetic evolution of key minerals and its controls on reservoir quality of Upper Ordovician Wufeng-Lower Silurian Longmaxi shale of Sichuan Basin[J]. Petroleum Geology & Experiment, 2021, 43(6): 996-1005.