Hindawi
Geofluids
Volume 2021, Article ID 9015041, 17 pages
https://doi.org/10.1155/2021/9015041

Research Article

Pore Structure Differentiation between Deltaic and Epicontinental Tight Sandstones of the Upper Paleozoic in the Eastern Linxing Area, Ordos Basin, China

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Received 8 May 2021; Revised 22 July 2021; Accepted 11 August 2021; Published 31 August 2021

Academic Editor: Afshin Davarpanah

Research on tight gas reservoirs in the eastern margin of the Ordos Basin, China, has recently become a hot spot. This paper mainly studies the reservoir characteristics of tight sandstone in the north-central area close to the provenance in eastern Linxing. Cast thin section, scanning electron microscopy, high-pressure mercury injection, and X-ray diffraction (XRD) were applied to discriminate the tight sandstone reservoir differences between the Permian Taiyuan and Shanxi formations in the study area. The results show that the deltaic tight sandstones in the Shanxi Formation are dominated by lithic quartz sandstone and lithic sandstone with an average porosity of 2.3% and permeability of 0.083 mD. The epicontinental tight sandstones in the Taiyuan Formation are mainly lithic sandstone and lithic quartz sandstone, with average porosities and permeabilities of 6.9% and 0.12 mD, respectively. The pore type is dominated by secondary dissolution pores, containing a small number of primary pores, and fractures are not developed. The capillary pressure curves of the Taiyuan Formation sandstone are mainly of low displacement pressure, high mercury saturation, and mercury withdrawal efficiency, while the Shanxi Formation sandstone is mainly of high displacement pressure, low mercury saturation, and withdrawal efficiency. The diagenetic evolution of sandstone in the Shanxi Formation is in meso-diagenesis stage A, and the Taiyuan Formation has entered meso-diagenesis stage B. The siliceous cement in the Taiyuan Formation sandstone enhanced the sandstone resistance to compaction and retained some residual intergranular pores. The pore types in the Shanxi Formation sandstone are all secondary pores, while secondary pores in the Taiyuan Formation sandstone account for approximately 90%. The results can be beneficial for tight gas production in the study area and similar basins.

1. Introduction

Tight sandstones have great development potential within coal measures on the eastern margin of the Ordos Basin [1, 2]. Even though all coal-bearing formations show potential tight gas production layers, their sedimentary environments are different [3]. The sandstones in the Taiyuan Formation were deposited in an epicontinental environment, while the Shanxi Formation was deposited in a deltaic environment [4, 5]. The sandstones have different pore structures influenced by both the sedimentary environment and complex diagenetic processes [6]. Tight gas is now being produced from all Upper Paleozoic sandstones, and clarifying the sandstone properties of different formations is crucial for favorable spot selection and well design.

Diagenesis refers to a series of physicochemical processes that are experienced after sediment deposition until metamorphism or repositioning due to tectonic movement [7–9]. Diagenesis is tightly correlated with clastic particle compaction in sandstone, the transformation of primary pores, and the formation of secondary pores, which greatly affect its porosity and permeability [10–12]. The diagenetic evolution process is mainly influenced by the original clastic particle composition, sedimentary environment, geological fluid, stratum temperature, pressure, basin tectonic setting, and sedimentary burial process, which reflects the long geological process of interaction between inorganic minerals and organic matter [13, 14]. Diagenesis mainly includes compaction (mechanical compaction and chemical compaction), cementation, dissolution, metasomatism, recrystallization, and mineral polymorphism, in which compaction, cementation, and dissolution are of great significance in the process of reservoir physical transformation [15–17].

This study examined samples from 6 tight gas wells in the eastern Linxing area on the eastern margin of the Ordos Basin for a comprehensive study. There are differences in the composition, pore structure, and diagenesis of tight reservoirs in the Upper Paleozoic delta-continental margin sedimentary facies. This information is designed to predict the dominant reservoirs in the study area and lay a solid foundation for subsequent exploration and development of similar blocks.

2. Geological Setting

The Linxing area on the eastern margin of the Ordos Basin, which belongs to the Lvliang area, spans two tectonic units, the Yishan slope and the Jinxi flexural fold belt [1]. The structure of the area is relatively simple, the strata are gentle (the dip angle is generally less than 1°), and nose-like structures with a small range are mainly developed (Figure 1) [18]. The Carboniferous-Permian coal-bearing rock series in the eastern margin of the Ordos Basin is formed in a marine-continental transitional facies sedimentary environment. The Early Permian Taiyuan Formation strata are formed in an epicontinental sedimentary environment, and the study area is dominated by barrier coastal sedimentary systems, with river deltas, tidal flats, barrier sand bars, and other sedimentary environments developed in sequence from north to south. In the late early Permian, the sea in the study area retreated on a large scale and gradually transitioned to a continental sedimentary environment. The Shanxi Formation was dominated by river delta deposits [19–21].

3. Methods

In this paper, samples of the Shanxi Formation and Taiyuan Formation were tested by experimental analysis methods, such as casting thin section, scanning electron microscopy, high-pressure mercury intrusion, and X-ray diffraction (XRD), mainly to identify and classify rock types, pore types, diagenesis types and stages, and mineral compositions. After that, the porosity and permeability of tight sandstone were quantitatively analyzed by an E-HYFZ-00062 Autopore IV 9500 (maximum pressure: 228 MPa, pore diameter:5∗ $10^{-}3\,\mu$m~103 μm) high-pressure mercury injection experiment, and the pore structure characteristics of tight sandstone were inferred by testing the displacement pressure (P_d), maximum pore throat radius ($r_{\max}$), withdrawal efficiency, porosity, and permeability, and other data [22].

Then, the reservoir differences between the Taiyuan Formation and Shanxi Formation can be determined. Moreover, D/max-2600 X-ray diffraction (XRD) was adopted to analyze the total detrital content and the relative clay mineral content of the samples. To study diagenesis and pore structure accurately, Leica DM4P thin sections were impregnated for observation. An FEI Quanta FEG 450 (FCG-004) scanning electron microscope (SEM) was adopted to observe the mineral composition and to understand the evolution of the mineral process. Then, the influence of the sedimentary environment and diagenesis on reservoir differences can be clarified [23, 24].

4. Results

4.1. Sandstone Petrology

4.1.1. Sandstone Composition. According to thin section identification, the debris content of the Taiyuan Formation sandstone samples in the study area was 58.0% ~85.0%, with an average of 74.5%, and the interstitial content was 8.0% ~34.0%, with an average of 22.0%. Among the crumb particles, the relative content of quartz particles is 26.0% ~41.0%, the average content is 35.4%, and the relative content of feldspar particles (potassium feldspar and plagioclase) is low, ranging from 5% to 27%, with an average of 14.1%; the lithic content is 35.0% ~66.0%, and the average content is 50.5%. According to the Folk (1974) sandstone triangle classification, the Taiyuan Formation sandstone samples are dominated by litharenite and feldspathic litharenite, followed by litharenite. The sandstone samples of the Shanxi Formation are dominated by litharenite and feldspathic litharenite (Figure 2).

The lithotripsy content of the coal-bearing sandstone in the study area is relatively high. The Taiyuan Formation sandstone is dominated by metamorphic rock cuttings, followed by volcanic rock cuttings and sedimentary rock cuttings and mica fragments, and is dominated by igneous rock cuttings and volcanic clastic rock cuttings in the Linxian area. The sandstone debris content of the Shanxi Formation is significantly higher than that of the Taiyuan Formation, mainly dominated by metamorphic rock cuttings, followed by igneous rock cuttings, mica fragments, and sedimentary rock cuttings (Figure 3).

The coal-bearing sandstones in the study area also have high interstitials, mainly including matrix and cement, and the matrix is mainly muddy. The average mud content of the Taiyuan Formation was 14.8%, and the mud content increased from 3% to 36% from bottom to top, reflecting the gradual transition of the sedimentary environment to the continental phase. The average mud content in the Shanxi Formation is 46.3%, which is much higher than the mud content of the Taiyuan Formation. The types of cement mainly include siliceous, clay minerals, calcite, and siderite. The cements of the Taiyuan Formation are mainly siderite and clay minerals, with contents of 4.0% to 16.0% and an average value of 8.5%. The cements in the Shanxi Formation are 3.0% ~19.0%, with an average of 9.5%, and are mainly composed of siderite and ferrocalcite.

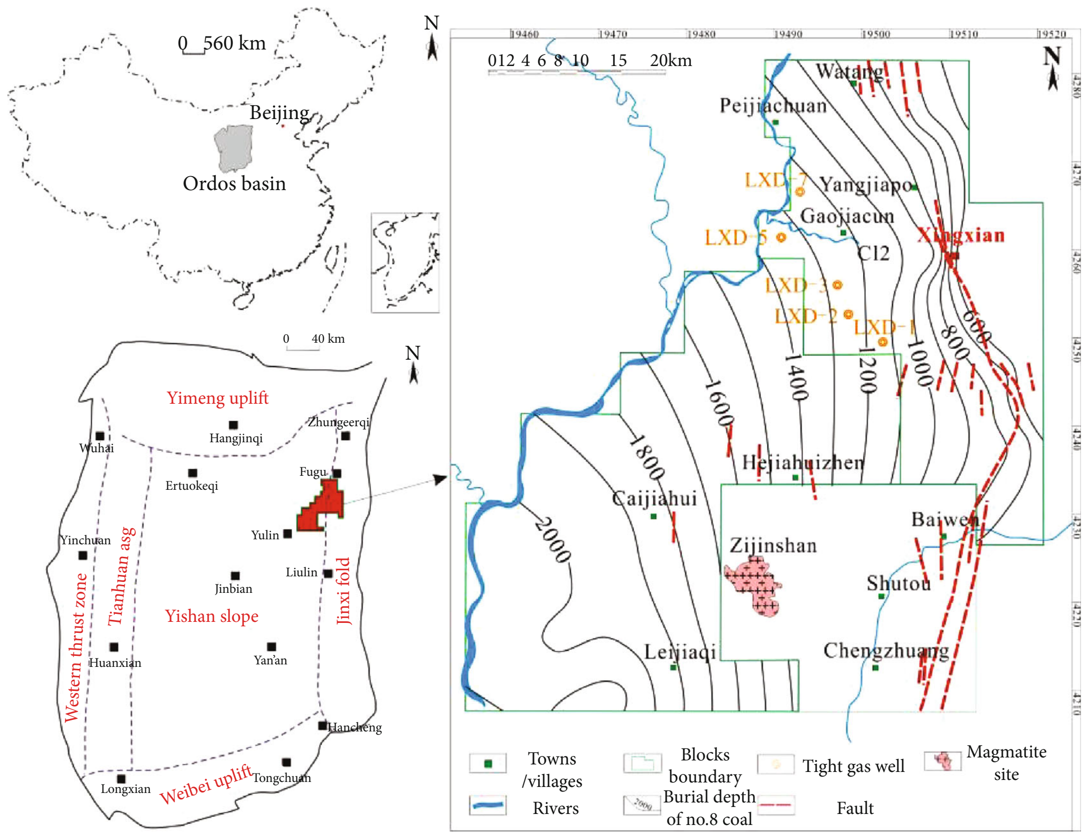


Figure 1: Location of the Linxing area, northeastern Ordos basin, modified after [4].

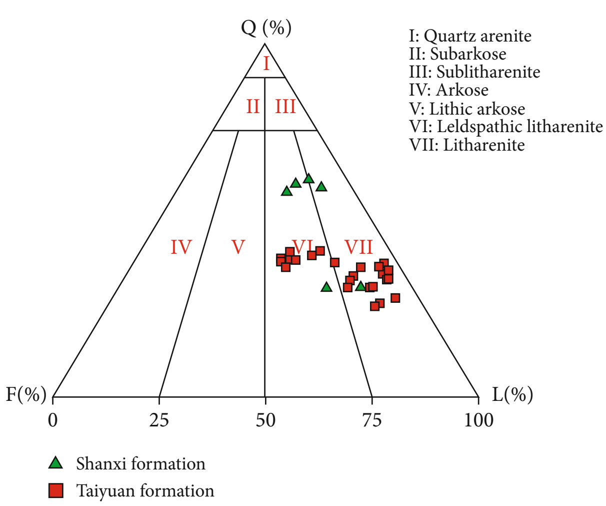


Figure 2: Ternary diagram of coal-measure tight sandstone types in the study area.

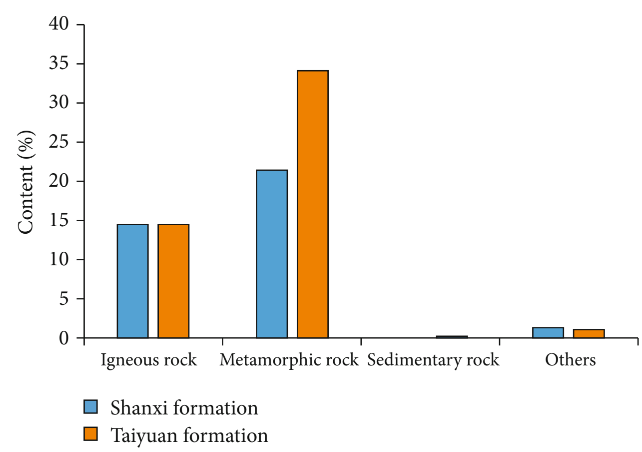


Figure 3: The types of rock fragments in coal-measure sandstones.

Overall, the Taiyuan Formation sandstone has a high content of litharenite and fewer quartz particles, and their composition is moderately mature. The sandstone quartz particles and feldspars in the Shanxi Formation are relatively high in content, and their component maturity is high. Among them, the high content of litharenite and miscellaneous in sandstone provides a material basis for the dissolution of secondary pores.

4.1.2. Texture of Detrital Grain. The sandstone structure of the Taiyuan Formation is dominated by medium-thick sand size, and the northern and southern margins are coarser in grain size and gradually decrease toward the middle and are dominated by medium-coarse sandstones in the study area. The sorting property is also gradually improved from both sides to the inside. Among them, feldspar lithic sandstone has good sorting properties, lithic sandstone has moderate sorting, and the clastic particles are mostly subcircular and subangular, with pore-type cementation as the main

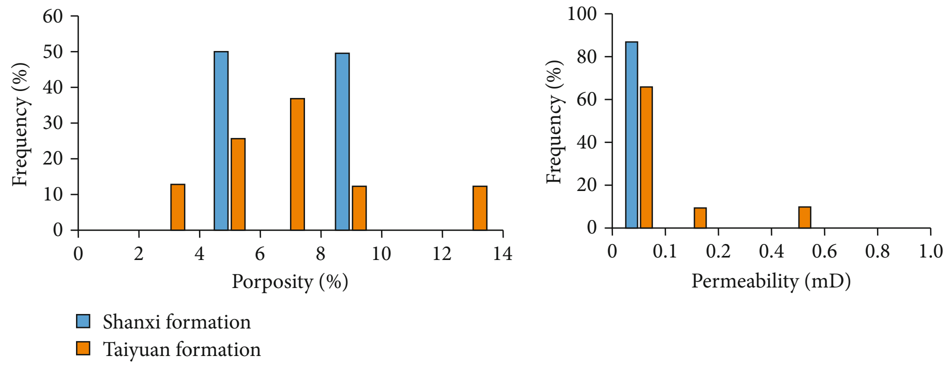


Figure 4: The porosity and permeability distribution of coal-measure sandstone in the study area.

component, line contact, and point-line contact between the particles. The sandstone structure of the Shanxi Formation is dominated by fine-grained and medium-grained structures, with moderate sorting, and the particles are mainly subcircular and subangular, with pore cementation as the main cementing types. The particles are mainly in line contact. The maturity of the sandstone structure of the Taiyuan Formation is lower than that of the Shanxi Formation sandstone. However, overall, from top to bottom, the structural maturity of the coal-bearing sandstone gradually increases.

4.2. Porosity and Permeability. Overall, the coal-bearing sandstones on the eastern margin of the basin are generally poor in physical properties. According to the results of gas measurement porosity, the porosity of the Taiyuan Formation sandstone is 2.3% ~12.2%, the average value is 6.9%, the permeability is 0.018~0.514 mD, and the average value is 0.12 mD; the sandstone porosity of the Shanxi Formation is 2.0% ~2.5%, the average value is 2.3%, the permeability is 0.071~0.95 mD, and the average value is 0.083 mD. The porosity and permeability of sandstone samples show a single polarization distribution (Figure 4). Among them, the porosity of the Taiyuan Formation sandstone is less than 10%, accounting for more than 90% of the total samples, while the porosity of the Shanxi Formation sandstone samples is less than 10%. The permeability of the Taiyuan Formation sandstone sample is less than 0.1 mD, accounting for more than 70%, and the Shanxi group is less than 0.1 mD, accounting for 100%. The physical properties of the Taiyuan Formation and the Shanxi Formation sandstone in the study area are poor, both of which belong to dense to ultratight sandstone, but the percolation conditions of the Taiyuan Formation are significantly better than those of the Shanxi Formation.

4.3. Pore Structures. The pore structure is the size, shape, distribution, and connectivity of the pores and throats within the reservoir [25]. In general, the size and distribution of pores determine the porosity of the reservoir, and the size and distribution of the throat control the permeability of the reservoir. For conventional reservoirs, it is feasible to evaluate the reservoir only by porosity and permeability. For low-permeability reservoirs, pore structure characteristics are the key factors determining reservoir performance [26]. In this paper, the pore type, size, shape, and distribution characteristics of sandstone samples in the study area were observed and counted in detail by casting thin sections and scanning electron microscopy. Typical sandstone samples were selected for high-pressure mercury intrusion experiments to study the pore structure characteristics of coal-bearing sandstones.

4.3.1. Microscopic Observation Results. Through the microscopic observation of the sandstone samples in the study area, it is found that the pore type of the coal-bearing sandstone reservoir in the study area is dominated by secondary pores and contains a small number of primary pores (Figure 5). Secondary pores include interparticle dissolution pores, intragranular dissolution pores, and intercrystalline pores of clay mineral aggregates, which are mainly formed by dissolution and metasomatism, in which interparticle dissolution pores are formed by an intergranular matrix or cement is dissolved. Intragranular dissolution pores are mainly composed of feldspar, lithic, and quartz particles, which are formed by the erosion of sandstone skeleton particles. The intercrystalline pores of clay minerals are mainly found in clay mineral aggregates, which are mainly composed of kaolinite intercrystalline pores. Primary pores are mainly residual intergranular pores after compaction and cementation damage, some residual intergranular pores are further enlarged under late dissolution, and it is difficult to distinguish the difference in the dissolved pores, which is unified into the category of dissolution pores. In addition, some samples can be seen as microfracture development.

According to the statistical results of the cast thin sections, samples of the Taiyuan Formation are mainly composed of secondary pores and contain a small amount of residual intergranular pores. The secondary pores accounted for 95.6% of the total surface porosity, and the residual intergranular pores accounted for 4.4%. The secondary pores are mainly composed of the dissolution pores of cuttings, quartz, and feldspar particles, followed by the intercrystalline pores. The interparticle dissolution pores account for 48% of the secondary pores, the intragranular dissolved pores account for 49%, and the intercrystalline pores of clay minerals account for 3%. Microcracks were visible in individual samples, and the number was small and not counted (Table 1).

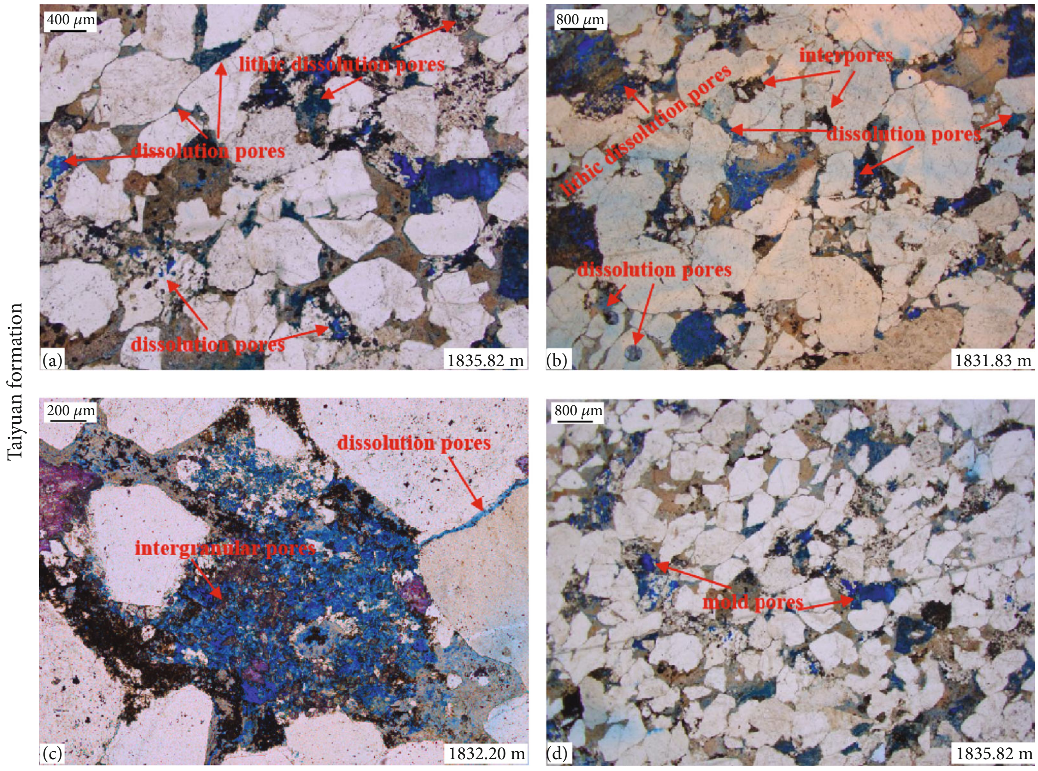


Figure 5: Pore type of coal-measure sandstone. All the sections were selected from well LXD-2, which is located in the central part of the study area, and the depths are marked. (a) Lithic dissolution pores and dissolution pores; (b) lithic dissolution pores, dissolution pores, and interparticle pores; (c) dissolution pores and intergranular pores; (d) mold pores.

Table 1: Proportion of pore types in coal-measure sandstone.

Layer	Residual intergranular pores (%)	Interparticle dissolution pores (%)	Intragranular dissolution pores (%)	Intercrystalline pores (%)	Rate (%)
Shanxi Formation	0	0.50	1.25	0.25	2.00
Taiyuan Formation	0.46	4.77	4.92	0.31	10.46

All of the Shanxi Formation sandstone samples were secondary pores, and no preserved primary pores were observed under the microscope. The secondary pores are mainly intragranular dissolved pores formed by the dissolution of feldspar and cuttings, followed by the interparticle dissolution pores formed by the dissolution of the intercrystalline pores and interstitials of the kaolinite aggregate, in which the intragranular dissolved pores accounted for 62.5%, the interparticle dissolution pores accounted for 25%, and the kaolinite intercrystalline pores accounted for 12.5% (Table 1).

4.3.2. Mercury Intrusion Porosimetry Results. The pore structure is the shape, size distribution, and connectivity of the pores and throats between the debris particles, reflecting the reservoir's reservoir and seepage capacity. High-pressure mercury intrusion experiments are one of the most effective methods for studying the pore structure of tight sandstone. Compared with the conventional mercury intrusion experiment, the maximum pressure of mercury in the high-pressure mercury intrusion experiment is larger (up to 200 MPa), and the range of test pores is larger, up to the nanometer scale. Structural parameters such as pore throat size and distribution of sandstone samples can be calculated from the relationship between capillary pressure and mercury influx.

The capillary pressure curves of the Taiyuan Formation samples can be divided into three categories (Figure 6(a)): class I curve (sample T1), the displacement pressure (Pd) is lower than 1.0 MPa, the curve of the middle curve of the mercury inlet curve is near level, and after the mercury saturation exceeds 70%, the curve rises sharply, the maximum mercury saturation is greater than 90%, the residual mercury saturation is 55.44%, and the withdrawal efficiency is 34.78%. The curve shows that the effective throat distribution of the reservoir is wide and unevenly distributed, the pore throat is larger, and the pore structure is better; class II curve (sample T2), the displacement pressure is approximately 3 MPa, the mercury inflow curve is near the horizontal step, with a sharp shift to the upper right, and the maximum mercury saturation is 73.0%. The residual mercury saturation is 71.4%, and the withdrawal efficiency is

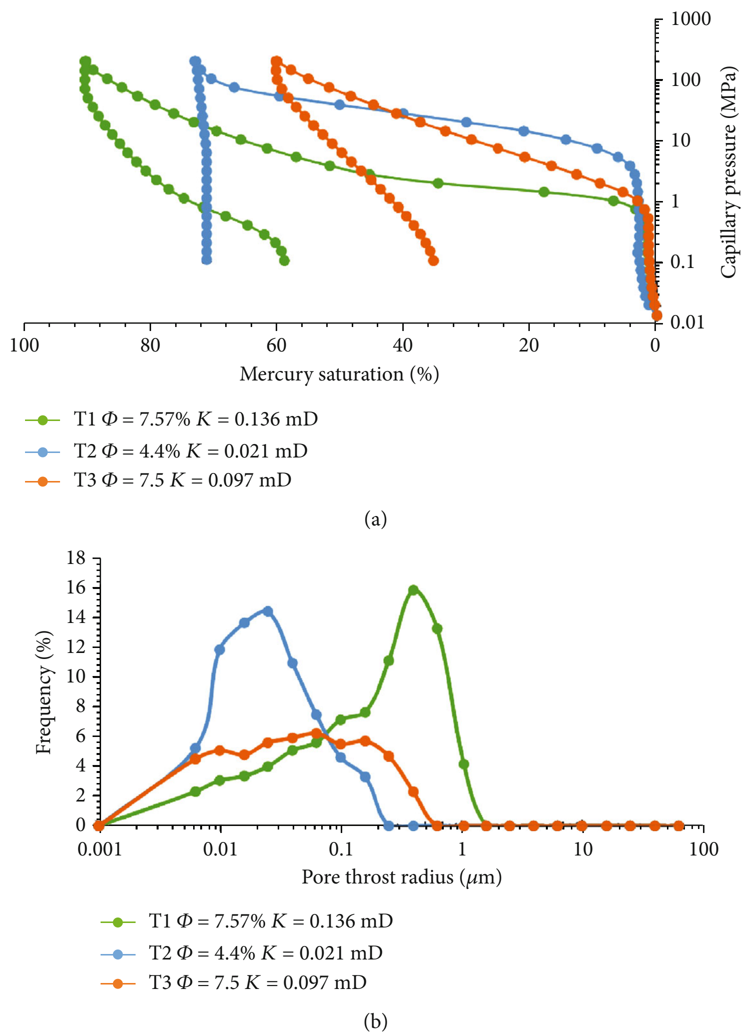


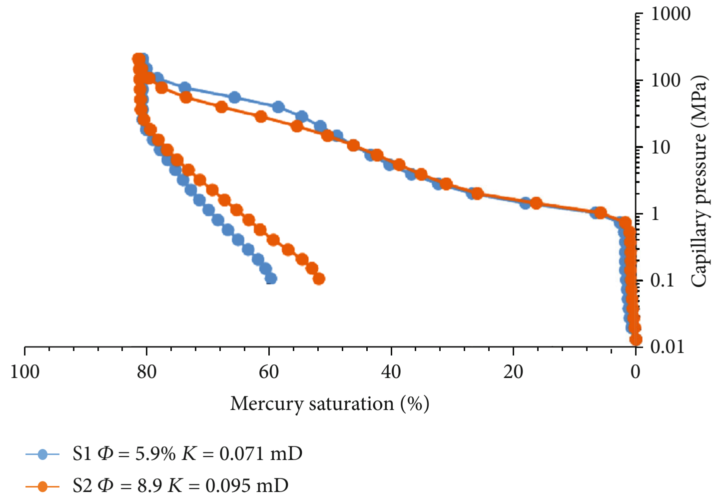
Figure 6: Capillary pressure curve and pore throat distribution of sandstone in the Taiyuan Formation.

low at 2.6%. The curve shows that the effective throat distribution of the reservoir is narrow, the pore throat is small, and the pore structure is poor. The class III curve (sample T3) has a displacement pressure of approximately 1 MPa, the mercury intrusion curve is nearly horizontal, the inclination to the upper right is not obvious, the maximum mercury saturation is approximately 60%, the residual mercury saturation is approximately 20%, and the withdrawal efficiency is approximately 40%. The curve shows that the effective throat distribution of the reservoir is narrow, the pore throat is larger, and the pore structure is better.

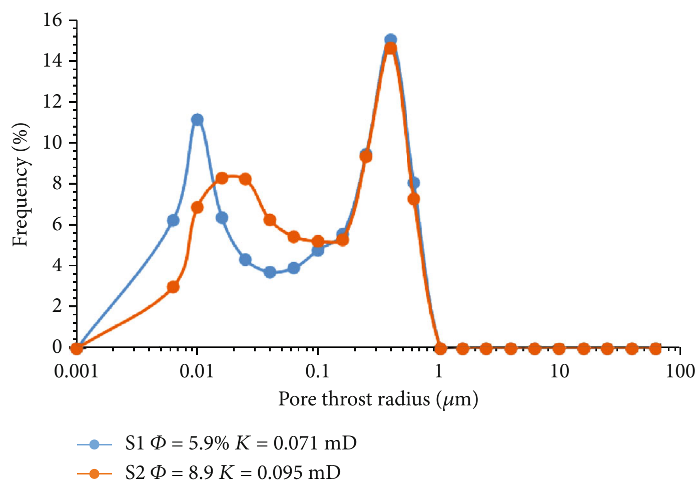
According to the capillary pressure curve, the pore throat distribution characteristics of the Taiyuan sandstone samples can be obtained (Figure 6(b)), and class I curve pore throat distribution range is wide, the radius is divided into 0.006 μm~1.048 μm, which is monomodal, with the peak to the right, and the maximum peak corresponding to the throat is 0.4 μm; the radius of the throat of the class II curve is mostly between 0.006 μm and 0.16 μm, the distribution range is narrow, and the radius of the throat of the main peak is 0.025 μm; the class III curve has a narrow range of pore throat distribution, which is concentrated between 0025 μm and 0.04 μm. There is little difference between the maximum and minimum values, and the pore throat radius distribution is relatively uniform.

The capillary pressure curve of the Shanxi Formation sandstone samples is similar to that of Taiyuan Formation III (Figure 7(a)), and the discharge pressure is approximately 0.76 MPa. The mercury intrusion curve rises steadily with a small slope and shifts to the upper right. The maximum mercury saturation is slightly higher than 80%, with an average of 81.05%. The remaining mercury saturation is 45.2% ~53.3%, with an average of 49.25%. The mercury removal efficiency is 26.0% ~36.2%, with an average of 31.1%. The curve shows that the effective throat distribution of the reservoir is narrow, the pore throat is small, and the pore structure is poor.

According to the capillary pressure curve, the pore throat distribution characteristics of the Shanxi Formation sandstone samples can be obtained (Figure 7(b)). The pore throat radius of the tight reservoir in the study area is mainly distributed between 0.006 μm and 0.63 μm, and the distribution range



(a)



(b)

Figure 7: Capillary pressure curve and pore throat distribution of sandstone in the Shanxi Formation.

is narrow, showing a double-peak distribution. The main peak corresponds to a pore throat radius of 0.4 μm.

The capillary pressure curve of the Taiyuan Formation in the study area is dominated by class I, and there are fewer class II and class III curves. The Shanxi Formation sandstone is mainly curve III, and the pore structure of the Taiyuan Formation sandstone is better than that of the Shanxi Formation.

4.4. Diagenetic Sequences. The coal-bearing tight sandstones in the eastern margin of the basin have undergone various diagenesis transformations, and the diagenesis is strong, which is of great significance for the formation of current sandstone reservoir characteristics. In this paper, through microscopic observation, scanning electron microscopy, and XRD analysis of rock flakes, the diagenesis types and characteristics of coal-bearing sandstones in the study area are systematically studied. The diagenesis experienced by the coal-bearing tight sandstones in the study area mainly includes compaction, cementation, dissolution, and metasomatism.

4.4.1. Compaction. The coal-bearing sandstones in the eastern margin of the basin experienced intense compaction (Figure 8), and the primary pores were severely damaged. The specific performance is that the sandstone debris particles are closely arranged, and the contact mode is mainly line contact and bump contact. Plastic cuttings and mica fragments are severely deformed by extrusion, and cracks appear on the surface of rigid particles. Due to the difference in tectonic evolution, compaction is becoming more intense from north to south.

The sandstones of the Shanxi Formation are formed in an epicontinental sedimentary environment, with high contents of heterogeneous and plastic cuttings. The intergranular pores are most severely modified by compaction, and the particles are closely arranged and contain no primary intergranular pores. The Taiyuan Formation sandstone quartz has a high content of rigid particles and less heterogeneous and plastic cuttings, and the overall compaction resistance of the sandstone is stronger than that of the Shanxi Formation. The compaction transformation causes slightly less

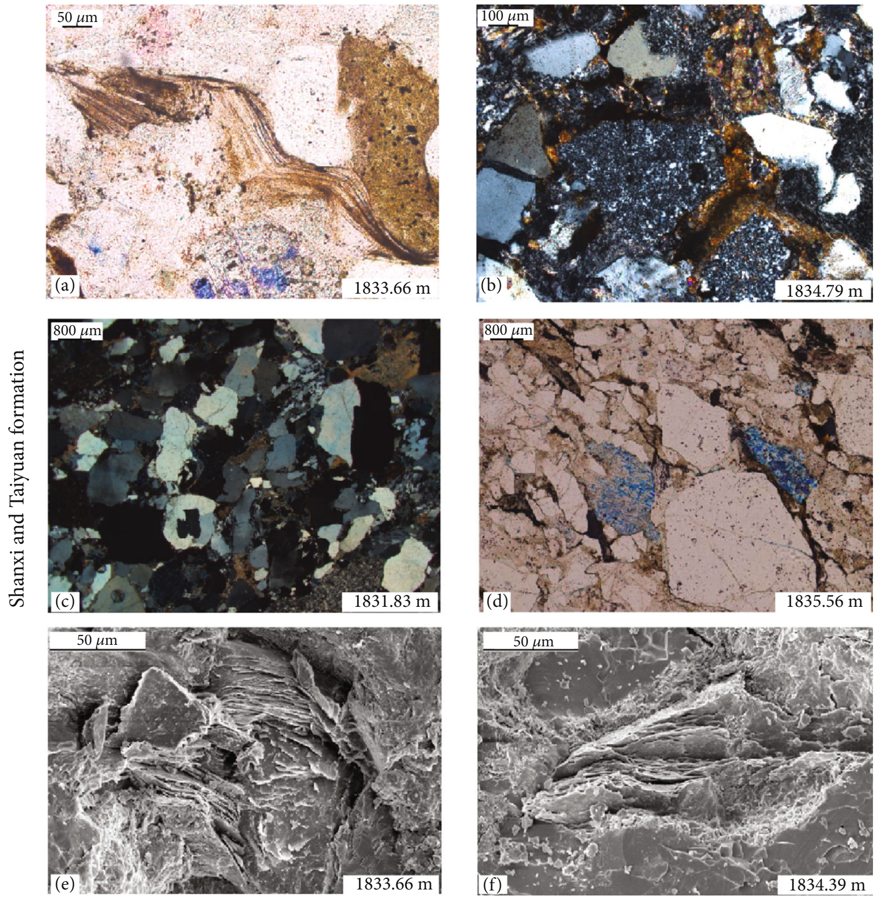


FIGURE 8: The compaction characteristics of coal-measure sandstone. All the sections were selected from the Taiyuan Formation of well LXD-2, which is located in the central part of the study area, and the depths are marked. (a) Mica extrusion deformation; (b) lithic extrusion deformation; (c) closely arranged quartz particles are in linear contact; (d) closely packed quartz particle bump contact; (e) and (f) Mica pieces under scanning electron microscopy (SEM) bending deformation.

physical damage to the reservoir than the Shanxi Formation, and some of the original intergranular pores are retained.

4.4.2. Cementation. Cementation mainly refers to the minerals precipitated from the pore solution cementing the crumb particles together so that the loose sediments are consolidated into rocks. It can occur in various periods of diagenesis and is one of the main factors leading to the decrease of reservoir porosity and permeability. In addition to filling the pores and blocking the throat and reducing the porosity and permeability of the sandstone, some cementation has the ability to enhance the compaction resistance of the sandstone skeleton particles and to some extent reduce the damage of the physical properties of the reservoir by compaction. This type of cementation is called retentive diagenesis [27]. For example, the early chlorite film wrapped the edge of quartz particles, hindering the secondary increase of quartz, enhancing the strength of early sediments, and slowing the damage of reservoir properties by compaction. Silica cementation is the most common cementation of coal-bearing sandstones in the eastern margin of the basin, followed by clay mineral cementation and carbonate cementation.

(1) Siliceous cementation

There are three main forms of siliceous cementation in the study area. The first is the secondary enlargement around the quartz crumb particles. Under the polarizing microscope and the scanning electron microscope, the contour of the original debris can be easily discerned by the clay film at the edge of the original crumb particles, and the optical orientation of the secondary enlarged side is consistent with the original quartz particles (Figures 9(a)–9(c)). This phenomenon of secondary quartz enlargement is very common in flakes, and the second-stage secondary side can be seen at most. The second type is quartz cement filled in the pores, which is generally cryptocrystalline or small granular. Under a scanning electron microscope, crystal-like self-generated quartz particles can be clearly seen and filled in the intergranular pores (Figure 9(d)). The third type is vermiculite cement, which can be epitaxially grown on the edge of quartz particles. Vermiculite cement is similar to secondary enlargement, but its extinction angle is inconsistent with quartz particles. This type is composed of many tiny plaque crystals, alternating between light and dark under orthogonal mirrors; it can also appear as a tiny crystal aggregate in the matrix. This type is as clean and smooth as a quartz

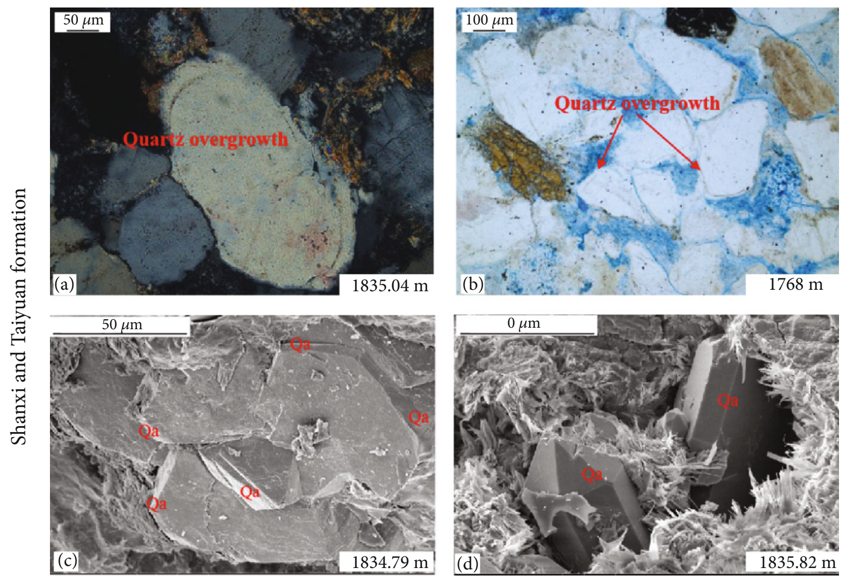


Figure 9: The quartz cement characteristics of coal-measure sandstone. All sections were selected from wells LXD-2 and LXD-5, which are located in the central part of the study area, and the depths are marked. (a) Quartz overgrowth (Taiyuan Formation); (b) quartz overgrowth (Shanxi Formation); (c) quartz secondary enlargement, crystal shape is better (Taiyuan Formation); (d) pore-filling authigenic quartz that is euhedrally crystallized (Taiyuan Formation).

particle under a single polarizer, and the tiny crystals are alternately arranged in light and dark under an orthogonal mirror. Vermiculite cement is often found under the microscope that siliceous cements often appear together with authigenic clay minerals, with authigenic quartz associated with illite and kaolinite, which indicates that the siliceous cement is derived from the conversion between kaolinite and clay minerals of feldspar. In the distribution, the Taiyuan Formation silicic cementation is more developed than the Shanxi Formation. In the Taiyuan Formation quartz sandstone flakes, pore cementation between the quartz particles was observed, and quartz secondary growth was particularly developed and mosaic (Figure 9(b)). The presence of siliceous cement in either form will reduce the radius of the primary intergranular pores and pore throats, which will greatly reduce the porosity and permeability of the coal-bearing sandstone in the study area. However, siliceous cementation also increases the grain strength of sandstone while reducing the porosity of sandstone, which makes some of the original intergranular pores in the Taiyuan Formation sandstone, which reduces the damage to reservoir physical properties to some extent.

(2) Clay cements

XRD analysis showed that (Table 2) the clay mineral content in the coal-bearing sandstone in the study area is high, and the clay mineral content of the Taiyuan Formation sandstone is 6% ~96%, with an average of 32.74%, in which illite has the highest relative content, followed by kaolinite and chlorite content, and I/S mixed clay is the lowest. The content of clay minerals in the sandstones of the Shanxi Formation is 51% ~73%, with an average of 60.25%. The relative content of illite is the highest, followed by kaolinite, and the chlorite content and I/S mixed clay content are the lowest. On the whole, the coal-bearing sandstones in the eastern margin of the basin have higher clay mineral contents, mainly kaolinite, followed by illite and chlorite contents, and the I/S mixed clay content is lower.

The clay minerals in the sandstone are both biosynthesized and self-generated. The microscopic and scanning electron microscopic observations are all self-generated clay minerals, and the mineral morphology can be clearly observed. These clays are cements; the deposited clay minerals are weathered from the parent rock, and the mineral species and morphology cannot be distinguished under the microscope. They are called argillaceous interstitials. The kaolinite in the sandstone of the eastern margin of the basin is mostly altered by feldspar or volcanic rock, and the crystal self-formation is higher. The single crystal is in the shape of a pseudohexagonal plate. The aggregates are mostly book-like, worm-like, filled in the intergranular pores, dissolution pores, or mold pores, the kaolinite aggregates are loosely arranged, and the intercrystalline pores are developed (Figures 10(a) and 10(b)).

The chlorite in the sandstone is generally produced as a film wrapped around the edge of the particle or in the form of a pore lining. In the sandstone samples of the study area, chlorite film or lining chlorite is rarely seen, and residual chlorite film is visible only at the edge of the grain or on the secondary side of the quartz, which is mainly due to the high content of organic matter in the coal system. The large number of organic acids formed during the diagenesis process erodes the early formation of chlorite film.

The illite fills the intergranular pores or wraps around the edges of the particles in the form of hair, honeycombs, and bridging under the microscope (Figures 10(d)–10(f)). There are two sources of illite in the study area: The first is

Table 2: Relative content of clay minerals in sandstones in coal measure.

Formation		Clay (%)	K (%)	I (%)	Ch (%)	I/S (%)	S/(I/S) (%)
Shanxi	Content	51-73	25-44	15-26	22-36	8-25	20-20
	Average	60.25	31.33	22.33	27.34	19	20
Taiyuan	Content	6-96	1-86	3-99	0-29	0-20	0-24
	Average	32.74	42.11	47.26	7.47	3.16	1.47

Clay: clay minerals; K: kaolinite; I: illite; Ch: chlorite; I/S: I/S mixed clay; *S*% (I/S): I/S mixed-layer rate.

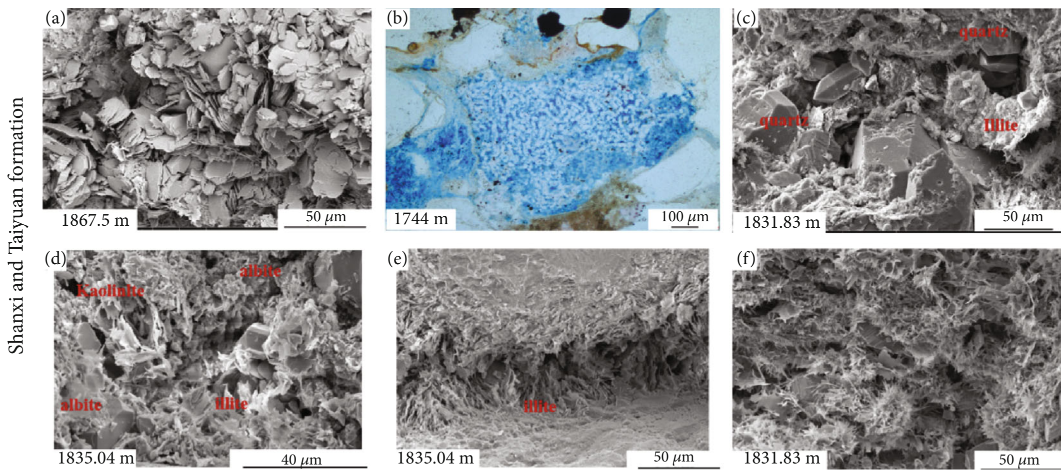


Figure 10: Shape characteristics of clay minerals in coal-measure sandstone. All sections were selected from wells LXD-2 and LXD-5, which are located in the central part of the study area, and the depths are marked. (a) Arranging loose flake kaolinite, intergranular pore development (Taiyuan Formation); (b) dissolution pores and worm-like kaolinite (Shanxi Formation); (c) authigenic quartz occurring with illite (Taiyuan Formation); (d) autogenous albite occurring together with filamentous illite and kaolinite (Taiyuan Formation); (e) bridging illite (Taiyuan Formation); (f) fibrous illite (Taiyuan Formation).

the transformation of smectite, in which the I/S mixed layer clay is the transition product of smectite to illite conversion, the honeycomb illite is transformed from the I/S mixed layer mineral, second, kaolinite and potassium feldspar in acidic conditions can occur in kaolinite Yili petrochemical (formula 1). The reaction can promote the dissolution of K-feldspar to form secondary pores and improve the physical properties of the reservoir, but the excess silica in the conversion process can provide a material source for siliceous cementation and has a certain negative impact on the reservoir properties. Scanning electron microscopy often shows fine authigenic quartz particles near illite. Illite does provide a source of siliceous cement when formed (Figures 10(c) and 10(d)). Luo et al. [27] studied the genetic origin of authigenic illite in the coal-bearing sandstone of the Xujiahe Formation in Sichuan. It is believed that the illite envelope can prevent the secondary increase in quartz during diagenesis, which has a positive impact on the protection of sandstone reservoir properties [27].

$$KAl_2Si_3O_8 + Al_2Si_2O_5(OH)_4 = KAl_3Si_3O_{10}(OH)_2 + 2SiO_2 + H_2O. \quad (1)$$

The I/S clay is a product of the conversion of smectite to illite, which is generally filled in the pores in the form of a honeycomb or attached to the edges of the granules. In the early days of diagenesis, smectites were altered by volcanic tuff or volcanic rock. As the diagenesis deepens, the smectite gradually transforms into illite, and the smectite content in the mixed minerals gradually decreases until the smectite is completely converted into illite.

(3) Carbonate cements

The carbonate mineral test results show that the carbonate cement content is 1.0% ~18.0%, and the average value is 5.5%. The content is higher in the vicinity of the limestone or the contact surface with the mudstone, the content of the sand body is lower, and no carbonate rock debris is found in the flake, indicating that the carbonate cement is mainly exogenous. Sandstone thin section identification results show that the carbonate cement in the study area mainly includes calcite (mainly iron calcite), iron dolomite, and siderite. Under the microscope, iron calcite cement filled the dwarf dissolved pores, and feldspar dissolved pores to enclose the quartz secondary enlarged edges (Figures 11(a) and 11(b)), and no signs of calcite dissolution were observed. This finding indicates that calcite cementation occurs in the later stage of diagenesis after the dissolution of lithic and feldspar and the secondary increase in quartz. Iron dolomite is dyed by ruthenium, which is light blue

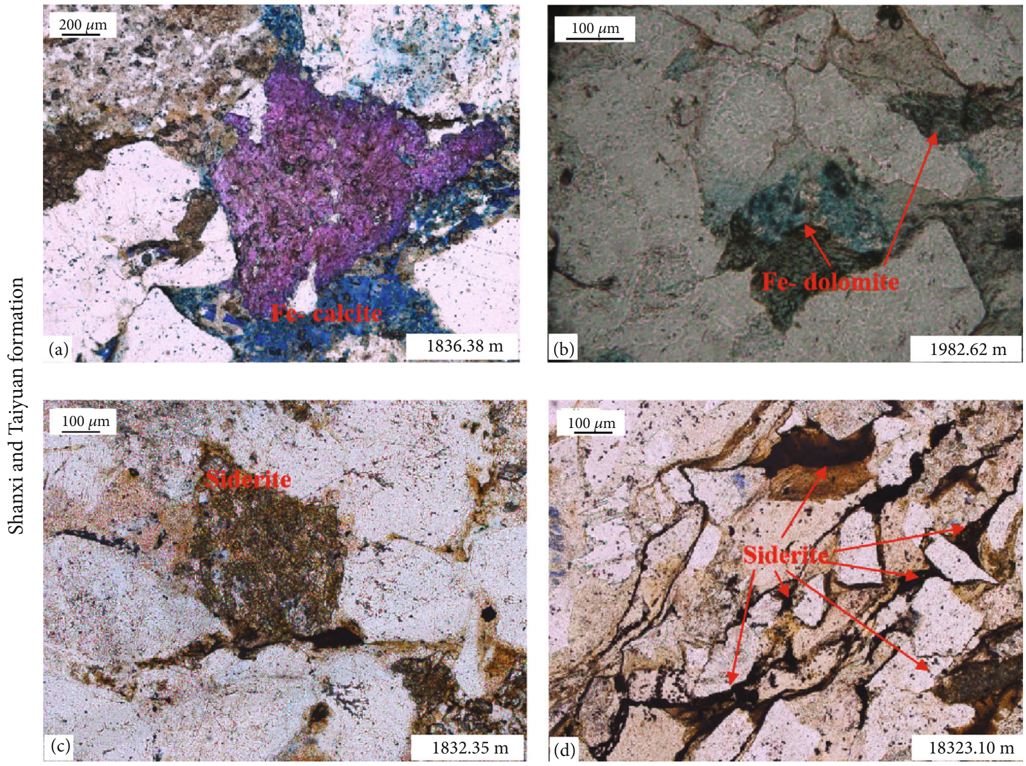


FIGURE 11: Characteristics of carbonate cements in coal-measure sandstone. All the sections were selected from the Taiyuan Formation of well LXD-2, which is located in the central part of the study area, and the depths are marked. (a) Fe-calcite fills the dissolution pores; (b) Fe-dolomite cementation; (c) clustered siderite; (d) siderite with a zonal distribution.

under the microscope, the shape is mostly rhomboid, and the surface is cleaved and fills the pores (Figure 11(b)). The siderite is generally a collection of mud crystals, which are in the form of a mass and spread in layers (Figures 11(c) and 11(d)). In the black mudstones of the Shanxi Formation and the Taiyuan Formation, which are close to the sandstone in the field profile, many of the siderites are also distributed along the bedding, and the genesis should be related; the content of dolomite cement is small, and it is mostly filled with fine crystals.

4.4.3. Dissolution. Dissolution is an important constructive diagenesis. Any debris, miscellaneous, or authigenic minerals in sandstone reservoirs can undergo different degrees of dissolution in certain diagenetic environments. The formation of secondary pores improves the porosity and permeability of sandstone, making it a good reservoir. According to the nature of the fluid causing dissolution, it can be divided into the dissolution of atmospheric leaching water and the dissolution of organic acids. The former is mainly for the dissolution of carbonic acid, the dissolution ability is small, and the organic acid has a strong ability to dissolve, which is the main reason for the formation of secondary pores [28, 29].

The dissolution of the study area is very developed and is a key factor for the development of tight sandstones in coal-bearing strata. Under the microscope, there are mainly feldspar, cuttings, and interstitial dissolution. In the Taiyuan Formation samples, quartz particles or secondary enlarged edges are observed (Figure 12).

(1) *Feldspar Corrosion*. The dissolution of feldspar is mostly carried out along the cleavage plane to form intragranular dissolved pores, and further, the entire feldspar particles are eroded away to form larger mold pores. In the mirror, almost no intact feldspar particles are seen, most of the kaolinite aggregates retain the shape of the feldspar particles, or the feldspar particles that have been dissolved along the cleavage surface are preserved by later calcite cementation. Therefore, dissolution is one of the reasons for the low content of sandstone in the area. After the feldspar is dissolved, only the dissolved material is transported out to maximize the reservoir physical properties. However, after feldspar is dissolved, clay minerals are formed in situ, which has many effects on the reservoir physical properties

(2) *Corrosion of the Interstitium*. The interstitium between the skeleton particles forms intergranular dissolved pores under the dissolution of the organic acid or enlarges the residual intergranular pores, or the interstitial alterations form a loosely arranged kaolinite aggregate. All of the above factors can increase the porosity of the reservoir and improve the permeability of the reservoir

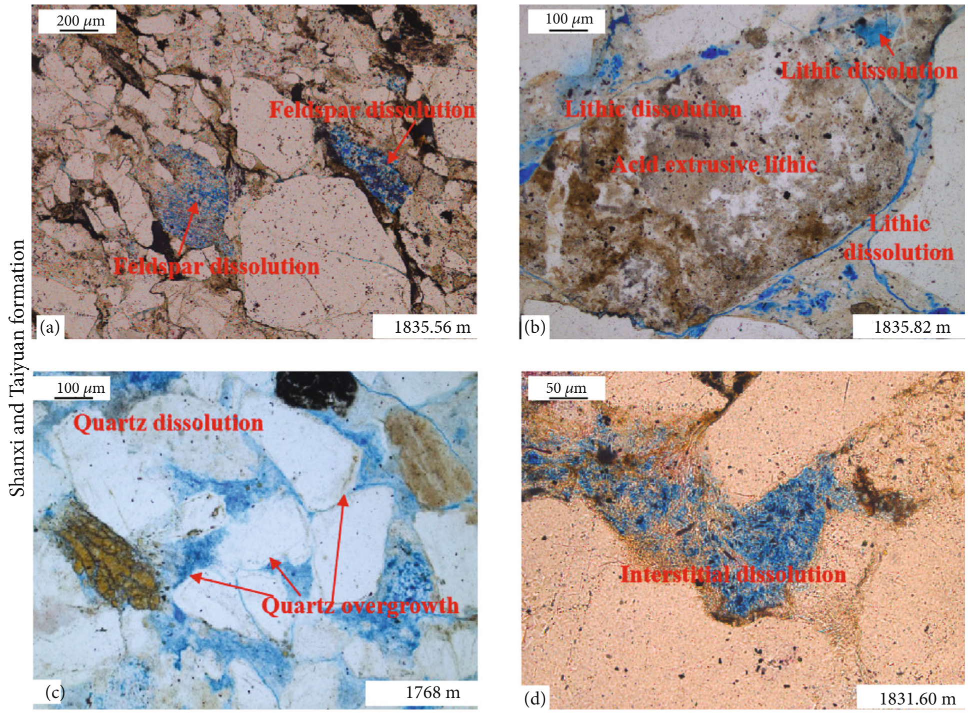


FIGURE 12: Characteristics of dissolution in coal-measure sandstone. All the sections were selected from the Taiyuan Formation of well LXD-2 and Shanxi Formation of well LXD-5, which is located in the central part of the study area, and the depths are marked. (a) Feldspar dissolution (Taiyuan Formation); (b) acid extrusive lithic dissolution (Taiyuan Formation); (c) quartz particle dissolution (Shanxi Formation); (d) interstitial dissolution (Taiyuan Formation).

(3) *Deposition of Cuttings*. Under the microscope, it can be seen that the cuttings are dissolved to form intergranular dissolved pores and mold pores

(4) *Corrosion of Quartz*. The dissolution of quartz particles in the sandstone of the Taiyuan Formation in the study area formed intragranular dissolved pores, and the secondary enlarged edges of quartz were eroded into a harbor shape, which increased the residual intergranular pores and improved the reservoir properties

4.5. Diagenetic Stages. The diagenetic evolution process of clastic rocks undergoes a series of complex diagenetic events, and different types of diagenesis occur in different diagenetic stages, which are arranged in chronological order to form the diagenetic sequence of a regional clastic rock. The division of the diagenetic stage and the establishment of diagenetic sequences are an important part of reservoir evaluation, which is of great significance for understanding the physical properties of clastic reservoirs, the evolution of pore structures, and the prediction of favorable reservoir space.

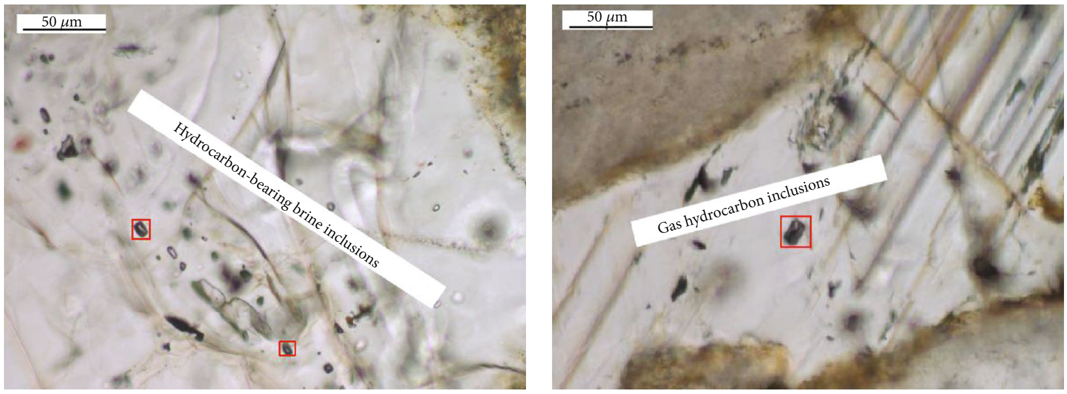
The classification marks of diagenetic stages are different in different diagenetic environments, "Code for the Division of Diagenetic Stages of Clastic Rocks" (SY/T 5477–2003) can be divided into freshwater–brackish water, diagenetic stage classification under acidic, and alkaline environments according to the acidity and alkalinity of pore water in clastic rocks [30]. During the diagenetic evolution of coal-bearing strata, the formation of organic acids makes the pore water of the clastic rocks acidic, and the diagenetic evolution of clastic rocks in the coal-bearing rock series is an acidic medium environment. According to the paleotemperature, illite content in the I/S mixed layer, authigenic mineral combination characteristics, skeleton particle contact type, and pore type, the diagenesis stage is divided into five stages: syngenetic rock stage, early diagenetic stage, medium diagenetic stage, late diagenetic stage, and surface-generated rock stage.

(1) Rock structure and pore type

The coal-bearing sandstone structure in the study area is dense, and the skeleton particles are closely arranged. The contact relationship is mainly line contact and concave-convex contact, and cracks are visible on the surface of the particles. The pore type is dominated by secondary pores, and the intergranular pores are less preserved.

(2) Clay mineral combination

The clay minerals in the coal-bearing sandstones in the study area are mainly kaolinite and illite. The proportion of smectite in the clay minerals of the I/S layer is approximately 20%. In the I/S clay, the proportion of smectite increases from Taiyuan to Shanxi, showing an increasing trend; the Taiyuan Formation is approximately 1.47%, and the Shanxi Formation is approximately 20%.



(a) (b)

Figure 13: Shape of fluid inclusions in coal-measure sandstones. (a) Hydrocarbon-bearing brine inclusions in quartz grain cracks; (b) carbon dioxide gaseous hydrocarbon inclusions in calcite fractures.

(3) Spontaneous mineral distribution

In the sandstone sample sheets of the whole study area, the secondary increase in quartz is very developed, and the secondary growth of the two phases is common. The secondary quartz of the local sample is especially developed, so the quartz particles are mosaic. Compared with the stone box formation, there are more carbonate cements, mainly iron calcite, iron dolomite is visible, and siderite is developed in different layers.

(4) Fluid inclusion uniform temperature

The formation of fluid inclusions in sandstone is closely related to the diagenesis process. Information on the composition and temperature of geological fluids in the original diagenesis process is an important means to study the evolution process of diagenesis. In the coal-sedimentary sandstones of the study area, a large number of fluid inclusions are developed in the secondary marginal, healing, and carbonate cements of quartz, mainly in brine inclusions and hydrocarbon inclusions, which are distributed in a beaded or strip shape (Figure 13).

The uniform temperature of fluid inclusions in coal-bearing sandstones in the study area is mainly distributed between 20°C and 130°C, showing two concentrated distribution intervals: 28°C ~38°C and 104°C ~130°C, indicating that there are two stages of geological fluids in the diagenetic evolution process. Among them, in the interval of 28°C ~38°C, it is mainly the fluid inclusions in the fracture zone of calcite, which is dominated by brine inclusions, indicating that the secondary increase of quartz in this stage is formed in the stage A of the diagenetic stage; in the interval of 104°C ~130°C, it is mainly the liquid hydrocarbon inclusions and a small amount of accompanying brine inclusions in the second-stage secondary and healing joints of quartz, indicating that the secondary quartz enlargement in this period is also formed in the stage A of the diagenetic stage.

According to the comprehensive evaluation and analysis of sandstone sample structure, pore development, authigenic mineral distribution, mixed layer ratio of I/S clay, and uniform temperature of fluid inclusions, the coal-bearing sandstone in the study area has entered the meso-rock stage.

4.6. Diagenesis Sequence. During the evolution process of litharenite and feldspathic litharenite in the study area, the destructive effects of compaction, cementation, and constructive effects of dissolution are mainly experienced. Suppose the diagenesis sequence is consolidation diagenesis—compaction—cementation—dissolution (Figure 14). Conversely, when consolidating in diagenesis, the primary porosity of the litharenite is 31.3%; after that, the compaction lost 23.8%, the cementation loss is 7.4%, the dissolution increased by 6.7%, and the final porosity is 6.8%.

The primary porosity of feldspathic litharenite, consolidating diagenesis, is 27.8%, compaction and cementation lose all pores, dissolution increases the porosity by 2.3%, and the final porosity is 2.3% (Table 3).

5. Discussions

The sedimentary environment affects the composition of sandstone, controls the quality of the primary reservoir, and then affects the diagenetic evolution and later transformation of the reservoir. The effects of diagenesis on the physical properties of sandstone reservoirs can be divided into three categories. The first type is destructive, changing the pore structure of sandstone and reducing the porosity and permeability of sandstone, making it more compact, mainly including compaction and cementation. The second type is constructive. During the diagenesis process, new pores are generated, and the porosity and permeability of the reservoir are improved, mainly with dissolution. The third type is protective, which can increase the strength of the sandstone reservoir skeleton particles during diagenesis, thereby reducing or slowing the damage of the sandstone reservoir porosity and permeability by destructive diagenesis. To a certain extent, this type is a kind of protection for reservoir porosity and permeability, mainly for cementation around sandstone particles, such as early ring-shaped chlorite cement.

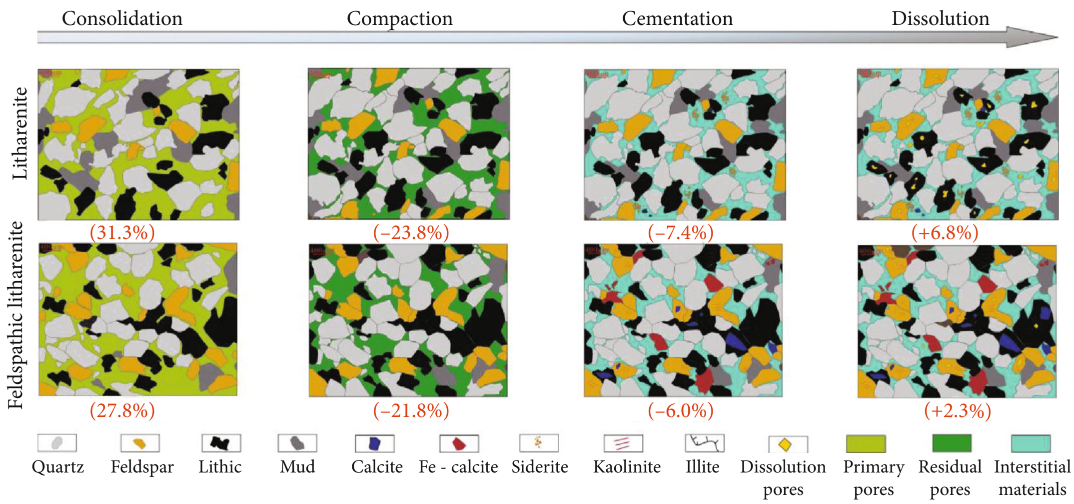


FIGURE 14: Diagenetic sequence of lithic arenite and feldspathic lithic arenite.

TABLE 3: Pore evolution process of lithic arenite and feldspathic lithic arenite.

Sandstone type	Primary porosity (%)	Compaction porosity loss (%)	Cementation porosity loss (%)	Dissolution increased porosity (%)
Lithic arenite	31.3	23.8	7.4	6.8
Feldspathic lithic arenite	27.8	21.8	6.0	2.3

The Taiyuan Formation and the Shanxi Formation sandstones in the study area are developed in coal-bearing strata and are affected by coal-bearing organic acid fluids during diagenesis. The presence of organic acids does not simply enhance the strength of the dissolution and improve the porosity and permeability of the reservoir. At different stages of diagenetic evolution, the effects of organic acids on diagenesis and reservoir properties are different.

5.1. Sedimentary Environment Effect on Primary Reservoir Quality. Tight sandstones of the Taiyuan Formation in the study area are mainly developed in barrier islands and tidal phases and are affected by tides (Figure 15). These sandstones are mainly medium-coarse-grained mud-bearing lithic arenite and coarse-grained and feldspathic lithic arenite, rock sorts medium, and the roundness is low; the delta phase of the Shanxi Formation has relatively weak hydrodynamic force, and the main deposits are extremely fine: fine-grained feldspathic lithic arenite, rock sorting is medium, and the roundness is low (Figure 15). In the Taiyuan Formation, sandstone has low maturity, relatively good pore structure, and large porosity, and its primary reservoir quality is better, but lower quartz fragments result in a weak resistance to compaction, and high feldspar and lithic contents lay the foundation for dissolution. In contrast, the Shanxi Formation has poor primary reservoir quality, strong compaction resistance, and weak dissolution.

5.2. Compaction and Cementation Effect on Reservoir Physical Properties. Compaction is a typical destructive diagenesis. Under the pressure of the overlying strata, the sandstone skeleton particles are rearranged and become increasingly compact, resulting in a decrease in reservoir porosity and permeability. Compaction, including mechanical compaction and chemical compaction, is an irreversible effect that increases with depth. The coal-bearing sandstone in the study area experienced a maximum burial depth of 1900 m. The particles were in contact with the bumps, indicating that the compaction experienced was strong. The primary pores of the Shanxi Formation sandstone were destroyed. The Taiyuan Formation sandstone retained only some residual intergranular pores.

Cementation is mainly wrapped at the edge of the particles or filled in the pores. The influence on the physical properties of the reservoir is complicated. The stage or occurrence state of the reservoir is different, and the impact on the reservoir is completely different. Most of the cementation blocks the pores, reduces the porosity and permeability of the reservoir, and causes damage to the reservoir. The secondary sandstone quartz in the Taiyuan Formation has a large number of secondary cementations, which reduces the intergranular pore volume, makes the pore throat smaller, and reduces the porosity and permeability of the sandstone reservoir. There is also a favorable side for the general secondary increase in quartz particles, which makes the sandstone particles mosaic, enhances the anticompacting ability between the particles, and retains some residual intergranular pores. To a certain extent, it has a protective effect on reservoir properties.

5.3. Dissolution Effect on Reservoir Property. Dissolution is a typical constructive diagenesis, producing secondary pores during diagenesis, which greatly improves reservoir physical

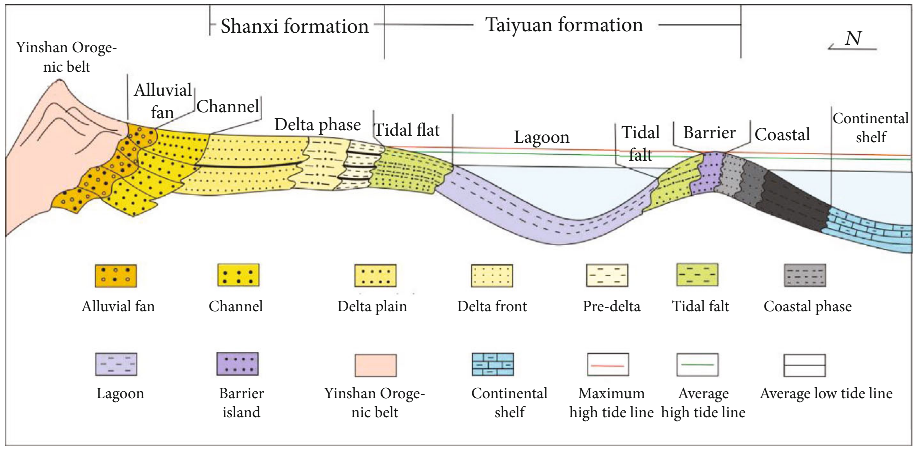


FIGURE 15: Sedimentary pattern of Linxing area.

properties. The coal-bearing strata have high organic matter content. The organic matter of the Shanxi Formation matures in middle diagenetic phase A and releases a large amount of organic acids, which causes the sandstone in this area to strongly dissolve and produce a large number of secondary pores, which improves the physical properties of the reservoir in the study area. The dissolution of quartz particles in the Taiyuan Formation sandstone in the B-stage alkaline water medium in the middle diagenetic stage also has a positive impact on reservoir physical properties. The statistical results of the cast thin slices show that the existing pores in the Shanxi Formation sandstone are all secondary pores, and there are no residual intergranular pores. The secondary pores in the Taiyuan Formation sandstone account for approximately 95.6% of the total pores, and the residual intergranular pores only account for 4.4%. Therefore, dissolution is a key factor in the development of coal-bearing sandstones in the region.

5.4. Sedimentary Environment and Diagenesis Comprehensively Affect Reservoir Characteristics. The sedimentary environment and diagenesis have an important influence on tight reservoirs. The sedimentary environment mainly controls the primary reservoir conditions, which in turn affects the evolution of diagenesis and the transformation of reservoirs. The sedimentary environment has an important influence on the composition of clastic rocks. Generally, with a strong hydrodynamic force, the clastic materials deposited in areas have a large grain size, low maturity, moderate deviation in sorting, and low quartz content, and the roundness is mainly angular or subangular-subcircular, so the original quality of the reservoir is relatively good. However, under weak hydrodynamic conditions, after long-term transportation, the debris components have good maturity, fine particle size, and preference for sorting. The particles are mainly subcircular or subangular-subcircular, the primary pores are poor, and the primary quality of the reservoir is poor. The tight sandstones formed in the barrier islands and tidal flats have large and many primary pores, but under the combined influence of burial depth and rigid minerals, there are almost no residual pores in the study area. However, due to the relatively high contents of feldspar and rock fragments in barrier islands and tidal flats with turbulent water environments, dissolution is relatively developed, secondary pores are developed, and the porosity and permeability conditions are improved. Therefore, the quality of the reservoir of the Taiyuan Formation is better.

6. Conclusions

The tight sandstones of the coal-bearing in the study area are mainly feldspathic lithic sandstone and lithic sandstone. The Taiyuan Formation is dominated by lithic sandstone and feldspathic lithic sandstone, followed by feldspathic lithic sandstone. The average porosity is 6.9%, and the average permeability is 0.12 mD. The Shanxi Formation is dominated by lithic quartz sandstone and feldspathic lithic sandstone with an average porosity of 2.3% and an average permeability of 0.083 mD, all of which are tight sandstone reservoirs.

The pore type is dominated by secondary dissolution pores, containing a small number of primary pores, and fractures are not developed. The pore structure is poor, and the pore throat radius distribution is narrow, mainly between 0.0025 μm and 1.048 μm. The capillary pressure curves of the Taiyuan Formation sandstone are mainly of low displacement pressure, high mercury saturation, and mercury withdrawal efficiency, while the Shanxi Formation sandstone is mainly of high displacement pressure, low mercury saturation, and withdrawal efficiency.

The diagenetic evolution of sandstone in the Shanxi Formation is in stage A of meso-diagenesis, and the Taiyuan Formation has entered stage B of meso-diagenesis. The development of siliceous cement in the Taiyuan Formation sandstone enhanced the sandstone's resistance to compaction and retained some residual intergranular pores. The pore types in the Shanxi Formation sandstone are all secondary pores. The secondary pores in the Taiyuan Formation sandstone account for approximately 90% of the total pores.

The structural maturity of the lithic sandstone in the tidal flat and barrier phases is relatively low, the original reservoir quality is better, and dissolution is relatively developed. The feldspar lithic sandstone in the delta front deposition phase has a high structural maturity, the original reservoir quality is poor, and the dissolution development is weak.

Data Availability

Data has been included in the manuscript.

Conflicts of Interest

None of the authors have any conflicts of interest.

Acknowledgments

This study was supported by the National Science Foundation of China (Grant no. 42072194) and the Major National Science and Technology Project of China (nos. 2016ZX 05066001-002 and 2017ZX05064-003-001), and we thank the Research Institute of Petroleum Exploration and Development and Tarim Oil Co. of CNPC for providing testing samples and our colleagues for beneficial suggestions.

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