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Article

Pore Development Mechanisms and Controlling Factors in Tight Sandstone Reservoirs —A Case Study of the Shihezi–Shanxi Formations in the Sulige Gas Field

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Abstract: Core analytical data, including petrographic and epoxy-impregnated thin sections and scanning electron microscopy (SEM), were used to investigate in detail the mechanisms of pore development in the Lower Shihezi–Shanxi tight sandstone reservoirs of the Sulige Gas Field. The results show that the reservoir sandstones contain abundant lithic fragments and mineralogically complex framework and interstitial components, resulting in marked differences in diagenesis and pore development among rocks with different mineral assemblages. Depositional environment, rock composition and texture, and diagenesis interact with and constrain one another, jointly controlling the preservation of primary pores and the development of secondary pores. Coarse-grained sandstones deposited under high-energy hydrodynamic conditions and enriched in rigid components (quartz minerals plus quartzite lithic fragments) effectively resist compaction and therefore constitute favorable lithofacies for the preservation of primary pores. Moderate amounts of interstitial materials, such as grain-rimming chlorite coatings or micaceous matrix, can suppress quartz overgrowths and resist compaction, thereby playing an important role in preserving primary pores. Superimposed dissolution and alteration of multiple minerals directly generate secondary pores. Among these processes, extensive dissolution of quartz-rich components (quartz grains and quartzite fragments) makes the largest contribution to reservoir pore space. Feldspar is relatively scarce and is mainly altered to kaolinite, producing intercrystalline micropores and minor intragranular dissolution pores. The reservoirs also contain micaceous matrix derived from tuffaceous alteration and kaolinite as interstitial material; these components include unstable, readily soluble constituents, and their dissolution produces intergranular dissolution pores, while kaolinite contributes intercrystalline pores, substantially improving porosity and permeability. Structural microfractures, diagenetic

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shrinkage fractures, residual primary pores, and matrix micropores together form flow pathways for mineral-dissolving fluids, thereby facilitating dissolution of the various mineral constituents.

Keywords: tight sandstone; reservoir pore-development mechanism; multi-mineral composition; primary pores; secondary pores; Sulige Gas Field; Shihezi–Shanxi formations

1. Introduction

Tight sandstone gas reservoirs are widely distributed in the Ordos, Sichuan, Songliao, and other basins in China and have become an important target for domestic natural-gas exploration and development in recent years. The Sulige Gas Field has been developed into the largest integrated tight sandstone gas field in China [1]. Accelerating the efficient development of tight sandstone gas is strategically important for national energy security. However, the tight nature of these reservoirs, strong heterogeneity, and difficulty in predicting high-quality reservoir intervals severely constrain economic development [2]. Consequently, a detailed understanding of pore-development mechanisms in tight sandstone reservoirs is essential for predicting favorable reservoir distribution and guiding development deployment.

Previous studies have addressed several aspects of tight sandstone reservoirs in the Sulige Gas Field and the Ordos Basin. Gong et al. [3] quantitatively described the causes of reservoir densification and differential diagenesis in the second member of the Lower Permian Shanxi Formation in the Su 77 Block. Li et al. [4] selected multiple parameters and applied a genetic artificial neural-network method to quantitatively classify diagenetic reservoir facies in low-permeability sandstones, enabling rapid reservoir-quality evaluation. Li et al. [5] analyzed the densification of Upper Paleozoic tight sandstone reservoirs and the genesis of high-quality reservoirs in the southern Ordos Basin from the perspective of diagenetic evolution. Gao et al. [6] investigated how petro-mineralogical characteristics of tight sandstones in the He 8 Member of the Tianhuan area affect reservoir quality. Wang et al. [7] analyzed the causes of differential densification of Permian sandstones in the eastern Sulige Gas Field based on diagenetic processes and evolutionary pathways in different sandstone types. Liu et al. [8] used acid-dissolution simulation experiments to investigate the origin of secondary pores in the He 8 tight sandstones of the Ordos Basin. These studies have focused mainly on reservoir characteristics, diagenesis, and pore evolution, whereas pore-development mechanisms in the Sulige tight sandstones remain comparatively underexplored. Because these reservoirs contain diverse mineral components and exhibit differential diagenesis, their pore-forming mechanisms and controlling factors are complex. To improve understanding of pore development and support prediction of favorable reservoir distribution, this study integrates petrographic and epoxy-impregnated thin sections with SEM observations to investigate reservoir composition, pore-development mechanisms, and pore-structure characteristics in the Lower Shihezi–Shanxi formations of the Sulige Gas Field.

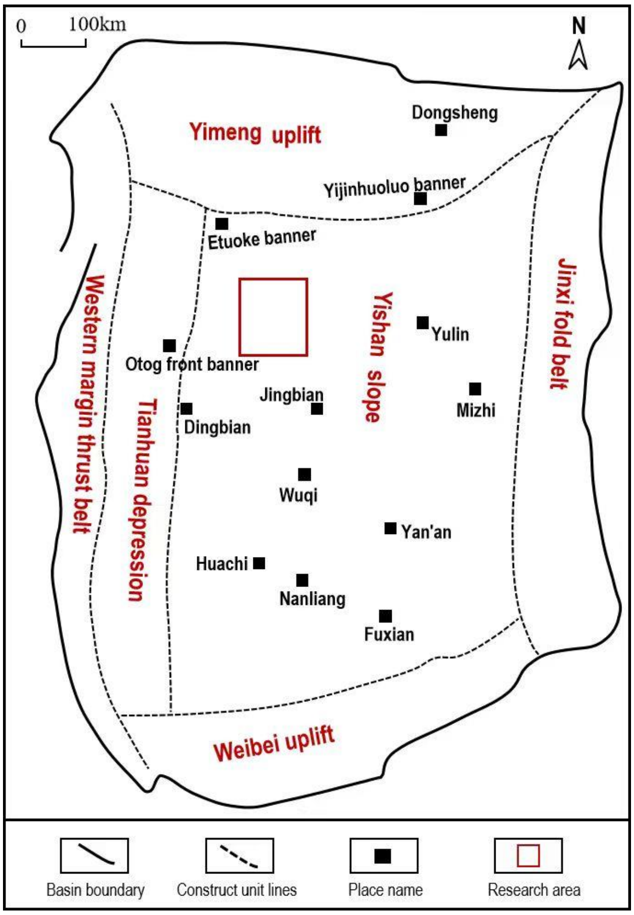


Figure 1. Location of the study area.

2. Regional Geological Setting

The Sulige Gas Field is located in the central-northern part of the Yishaan Slope in the Ordos Basin (Figure 1). Structurally, it forms a monocline dipping from northeast to southwest. The Paleozoic succession comprises, from bottom to top, the Carboniferous Benxi and Taiyuan formations and the Permian Shanxi, Shihezi, and Shiqianfeng formations. The He 8 Member of the Shihezi Formation and Member 1 of the Shanxi Formation are the principal gas-bearing intervals. Reservoir burial depths are approximately 3,200–3,500 m. The depositional system is dominated by fluvial facies, and the reservoirs generally have poor physical properties, characterized by low permeability, low pressure, and low abundance (the “three-low” characteristics). They therefore represent typical lithologic-trap tight sandstone gas reservoirs. Reservoir porosity in the study area is mainly 4%–10%, with an average of 6.74%. Permeability is mainly 0.04–1 × 10^{-3} μm², with an average of 0.18 × 10^{-3} μm², confirming their typical tight-sandstone character.

3. Petrographic and Pore Characteristics

3.1 Reservoir Petrographic Characteristics.

Thin-section statistics (Figure 2) show that the target intervals are dominated by lithic sandstones, with a minor proportion of lithic quartz sandstones. Average contents are 38.52% lithic fragments, 58% quartz, and 3.48% feldspar. Lithic fragments are abundant and compositionally diverse, including metamorphic fragments such as quartzite, phyllite, and slate; igneous fragments such as granite and volcanic rocks; and sedimentary fragments such as claystone, siltstone, and carbonate rock. Quartzite fragments are the most abundant lithic type (Table 1).

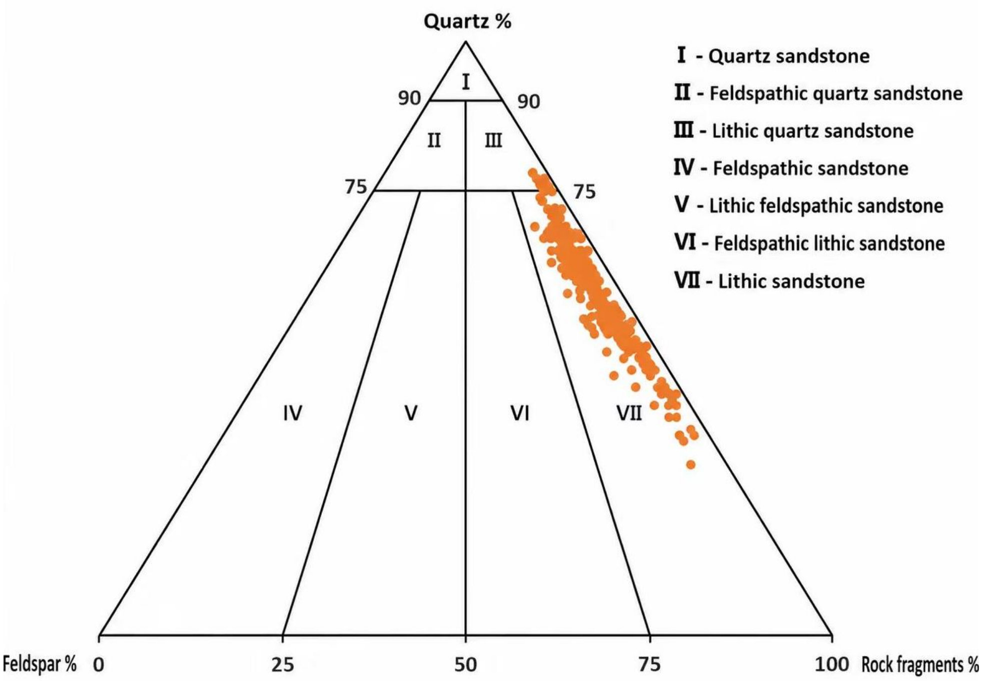


Figure 2. Reservoir rock-composition characteristics in the study area (original figure artwork retained from the source manuscript).

Table 1. Contents of different lithic-fragment types in the target intervals of the study area (%)

Interval	Sedimentary lithics			Metamorphic lithics			Igneous lithics	
	Siltstone	Claystone	Carbonate	Phyllite	Quartzite	Slate	Granite	Volcanic rock
Shihezi Fm.	1.88	2.56	0.12	3.22	19.29	5.98	1.20	1.66
Shanxi Fm.	1.04	7.64	0.33	3.16	13.52	6.56	0.33	2.11
Average	1.45	5.17	0.23	3.19	16.33	6.28	0.76	1.89

Petrographically, the reservoir grains are moderately to well sorted and relatively coarse, with pebbly coarse sandstone, coarse sandstone, and medium sandstone as the dominant textures. Framework grains and interstitial materials are mineralogically diverse. The average interstitial-material content is 15.49%, consisting mainly of matrix, kaolinite, chlorite, siliceous cement, and carbonate cement. Matrix, calcareous cement, and kaolinite are comparatively abundant (Table 2).

Table 2. Contents of different interstitial materials in the target intervals of the study area (%)

Interval	Matrix	Calcareous cement	Siliceous cement	Chlorite	Kaolinite	Total
Shihezi Fm.	6.04	3.40	1.60	0.52	3.75	15.31
Shanxi Fm.	5.51	4.60	2.11	0.92	2.56	15.70
Average	5.85	3.90	1.85	0.73	3.16	15.49

3.2 Reservoir Pore Types and Characteristics

Pore types in the target intervals are diverse and include intergranular dissolution pores, intragranular dissolution pores, dissolution-enlarged pores, intercrystalline micropores, residual intergranular pores, and microfractures (Figure 3). Secondary pores, especially intergranular and intragranular dissolution pores, are the dominant pore types, followed by residual primary intergranular pores, intercrystalline pores, and microfractures. In terms of contributions to total porosity, intergranular and intragranular dissolution pores make the largest contributions, whereas intercrystalline pores, residual primary intergranular pores, and microfractures contribute less (Figure 4).

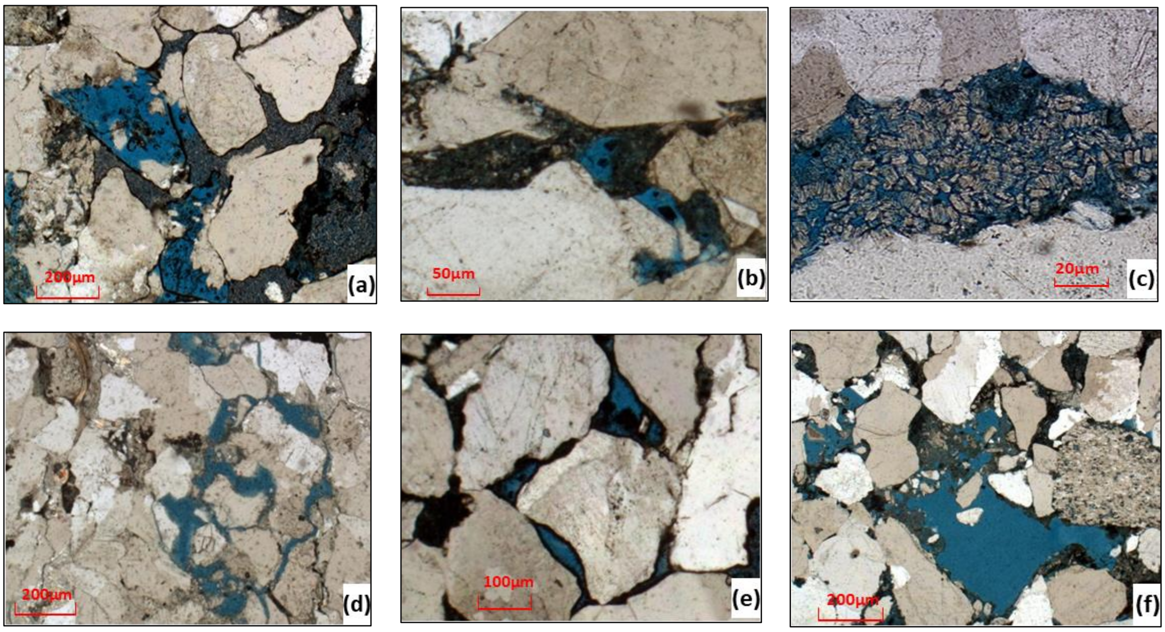


Figure 3. Types and characteristics of reservoir pore space in the target intervals. (a) Partial dissolution of detrital grains surrounded by clay coatings produces intragranular dissolution pores; the clay coating resists compaction, while altered kaolinite fills intergranular space and locally dissolves to form intergranular dissolution pores, Well T8-8, 3346.6 m. (b) Dissolution of intergranular matrix forms intergranular dissolution pores, Well T8-8, 3320.4 m. (c) Well-developed kaolinite intercrystalline micropores formed by feldspar alteration, Well T8-8, 3322.8 m. (d) Multiple structural microfractures with dissolution enlargement along the fractures, Well T8-8, 3317.4 m. (e) Clay coatings inhibit quartz overgrowths and preserve residual primary intergranular pores, Well T8-8, 3332.6 m. (f) Dissolution of both detrital grains and interstitial materials produces dissolution-enlarged pores, Well T8-8, 3328.1 m.

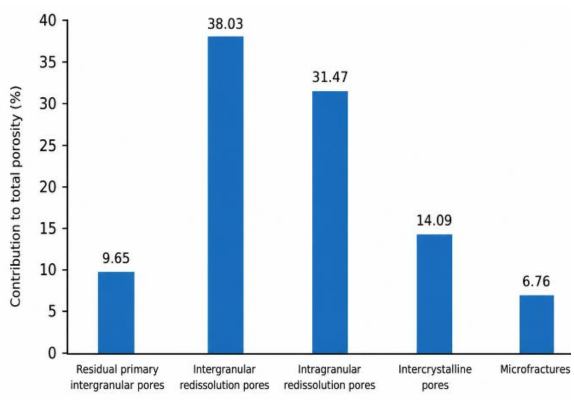


Figure 4. Contributions of different pore types to total porosity in the study area.

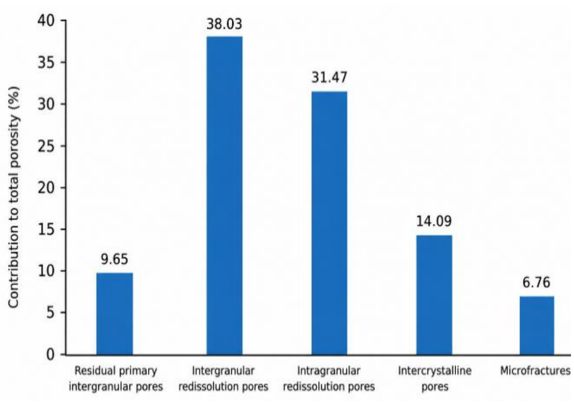


Figure 5. Porosity distribution among rocks of different grain-size classes.

4 Pore-Development Mechanisms and Major Controlling Factors

4.1 Preservation Mechanism of Primary Intergranular Pores

4.1.1 Influence of Rock Composition and Texture

A favorable rock composition and texture provide the material basis for preservation of primary pores. Rocks composed of different mineral assemblages differ substantially in compressive strength [9]. On this basis, mineral components can be broadly divided into rigid and ductile components. Rigid grains such as quartz, feldspar, quartzite lithic fragments, and igneous lithic fragments have relatively high compressive strength, resist compaction effectively, and favor preservation of primary pores. By contrast, ductile components such as phyllite and slate fragments, sedimentary lithic fragments, and matrix undergo strong plastic deformation during compaction and are unfavorable for primary-pore preservation. Thin-section statistics show a clear positive correlation between the content of rigid mineral components and porosity (Figure 6). Epoxy-impregnated thin sections further show that lithic-fragment type is critical to pore development: reservoirs with abundant quartzite fragments are generally more porous, whereas reservoirs rich in other ductile lithic fragments are commonly poorly porous. Reservoir properties also vary markedly with texture, and coarser-grained rocks generally have better properties (Figure 5). Thus, coarse-grained sandstones enriched in rigid mineral components represent relatively favorable reservoir lithofacies.

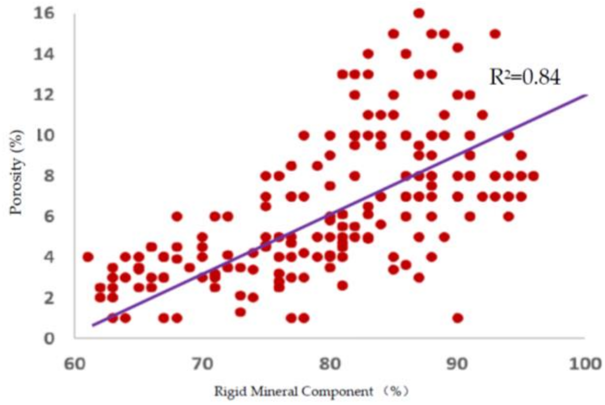


Figure 6. Relationship between rigid-mineral-component content and reservoir porosity ($R^2 = 0.84$; original plot retained from the source manuscript).

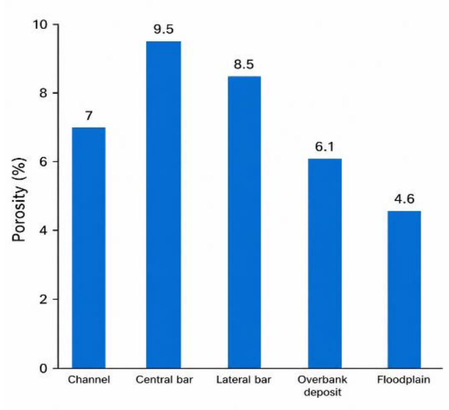


Figure 7. Reservoir porosity characteristics of different depositional microfacies.

4.1.2 Influence of Interstitial-Material Content

A moderate amount of interstitial material is important for preserving primary pores. Chlorite coatings occur in some reservoir intervals and are mainly developed as grain-rimming coatings. Under the petrographic microscope, the chlorite clay minerals around grain margins appear fibrous (Figure 8a), whereas SEM observations show a platy morphology. Because such chlorite coatings also occur at grain contacts, they are interpreted to have formed early. The coatings are inferred to have originated mainly from alteration of tuffaceous matrix. Chlorite and other clay coatings can effectively inhibit quartz overgrowths and thereby preserve primary pores [10–11]. Epoxy-impregnated thin sections show that where chlorite coatings are present in pore spaces, quartz overgrowths are weak and grains mainly exhibit point-to-line contacts (Figures 3e and 8a). In the absence of chlorite and similar interstitial materials, quartz overgrowths are intense, grains commonly display concavo-convex contacts, and pores are poorly developed (Figure 8b). Clay coatings can also resist compaction to some extent, helping preserve both primary and secondary pores (Figure 3a). In some intervals, pore space was initially filled by interstitial material formed through tuffaceous alteration. During burial, this material effectively resisted compaction; at a later stage, dissolution of unstable components in the matrix "released" previously filled intergranular spaces, effectively preserving intergranular pores through the burial history (Figures 3b and 8i).

4.1.3 Influence of the Depositional Hydrodynamic Environment

A favorable depositional hydrodynamic environment is a prerequisite for primary-pore preservation. Higher hydrodynamic energy produces coarser deposits, whereas lower energy produces finer deposits [12]. Hydrodynamic conditions affect not only grain size but also the types of rock components deposited. Phyllite and slate fragments are commonly platy, while sedimentary lithic fragments and matrix are relatively fine-grained; these ductile components are therefore more readily deposited under weak hydrodynamic conditions. Coarser and denser quartzite fragments, in contrast, are preferentially deposited under stronger hydrodynamic conditions. Strong hydrodynamic environments thus favor deposition of rigid mineral components, whereas weak hydrodynamic environments favor ductile components. Thin-section statistics indicate that central-bar, lateral-bar, and channel microfacies, which formed under stronger hydrodynamic conditions, have better reservoir properties, while overbank and floodplain microfacies have poorer properties (Figure 7). Therefore, high-energy depositional microfacies such as central bars provide favorable conditions for reservoir development.

4.2 Development Mechanisms of Secondary Pores

The Sulige Gas Field is a deeply buried tight sandstone gas accumulation developed in a coal-bearing stratigraphic setting. The reservoirs experienced complex diagenesis during burial, including multiple stages of dissolution affecting several minerals [13]. Secondary pores generated by superimposed multi-mineral dissolution and alteration are the most important pore type in the study area. Thin-section observations indicate that the principal secondary-pore types are intergranular dissolution pores, intragranular dissolution pores, intercrystalline (dissolution) pores, and microfractures. Their origins are discussed below according to the mineral or component affected by dissolution.

4.2.1 Feldspar Alteration and Dissolution

Microscopic observations show that feldspar grains are mainly altered to kaolinite, producing abundant intercrystalline pores or intercrystalline dissolution pores. A small amount of feldspar is dissolved to residual textures and develops intragranular dissolution pores. Feldspar dissolution commonly proceeds along cleavage planes and therefore shows a distinct directional character. Reactions between feldspar minerals and acidic fluids are given in the source manuscript as follows [14].

$$\text{K-feldspar: } 2KA1Si_3O_8 + 2H^+ + H_2O = 2K^+ + 4SiO_2 + Al_2Si_2O_5(OH)_4 \quad (1)$$

$$\text{Albite: } 2NaA1Si_3O_8 + 2H^+ + H_2O = 2Na^+ + 4SiO_2 + Al_2Si_2O_5(OH)_4 \quad (2)$$

$$\text{Anorthite: } CaA1Si_3O_8 + 2H^+ + H_2O = Ca^{2+} + 4SiO_2 + Al_2Si_2O_5(OH)_4 \quad (3)$$

Feldspar content is low in the study area and feldspar is predominantly altered to kaolinite. Consequently, the main pore-space contribution associated with feldspar is from intercrystalline pores in kaolinite (Figures 3c and 8c).

4.2.2 Dissolution of Quartz Minerals

Quartz-bearing components in the reservoirs include quartz grains, chert, and quartzite lithic fragments. Together, quartz minerals account for approximately 79% of the detrital mineral population. Epoxy-impregnated thin sections and SEM observations show that some quartz grains and quartzite fragments are dissolved along internal fractures into irregular shapes, causing partial loss of the original grains and, in some cases, residual textures. Other quartz grains are dissolved along their margins to form irregular embayed or serrated outlines, and some quartz overgrowth rims are also dissolved into irregular forms (Figures 8d–8g). Quartz dissolution is complex and has been widely investigated [15–17]. A common interpretation is that quartz dissolution is promoted under alkaline conditions: OH^- catalysis reduces the bond energy of Si–O–Si linkages, making them easier to break, while elevated formation temperature and the electrolyte "salt effect" of pore water further reduce the activation energy of quartz dissolution. The present study interprets quartz dissolution as closely associated with replacement by clay minerals in pore spaces. Clay-mineral surfaces have strong adsorption capacities and can concentrate large amounts of alkali-metal ions such as K^+ and Na^+. Potassium carbonate may be liberated at clay-mineral surfaces, forming localized strongly alkaline microenvironments that promote intense replacement and dissolution of quartz. Adsorbed electrolytes can additionally generate a salt effect and accelerate reaction rates. Through this process, quartz is progressively "corroded" and dissolved by clay minerals [18–19]. Secondary pores generated by dissolution of quartz minerals make the largest contribution to total pore space in the study area.

4.2.3 Dissolution of Different Lithic Fragments

Reservoir lithic fragments are compositionally complex and include metamorphic, igneous, and sedimentary rock fragments. Rigid lithic fragments with relatively high compressive strength can nevertheless be susceptible to dissolution. Quartzite fragments, for example, commonly contain cracks and develop residual textures after dissolution. Some igneous lithic fragments contain heterogeneously distributed soluble components; after dissolution they form honeycomb-like or spotted intragranular dissolution pores, and strongly dissolved fragments may also develop residual textures (Figure 8h).

4.2.4 Alteration and Dissolution of Matrix

Epoxy-impregnated thin sections show that some matrix in the study-area reservoirs is dissolved to form intergranular dissolution pores (Figures 3b, 8i, and 8j), while other matrix is altered to poorly euhedral, "dirty" kaolinite with intercrystalline micropores (Figures 3a and 8k). Secondary pores produced by matrix dissolution or alteration substantially improve reservoir porosity and permeability; relatively high-permeability intervals consistently contain intergranular dissolution pores formed by matrix dissolution. Further analysis indicates that the matrix commonly consists of micaceous minerals formed through tuffaceous alteration. Iron precipitates related to tuffaceous alteration are commonly observed within pore spaces (Figures 3e and 8i). Altered tuffaceous matrix contains unstable and readily soluble components that can dissolve under acidic conditions, releasing substantial intergranular pore space [20–21]. In addition, tuffaceous material may continue to alter to kaolinite during burial [21]. The resulting kaolinite crystals have poor euhedrality and relatively dirty surfaces; this alteration contributes abundant intercrystalline microporosity (Figures 3a and 8k).

4.3 Fluid-Flow Pathways for Mineral Dissolution

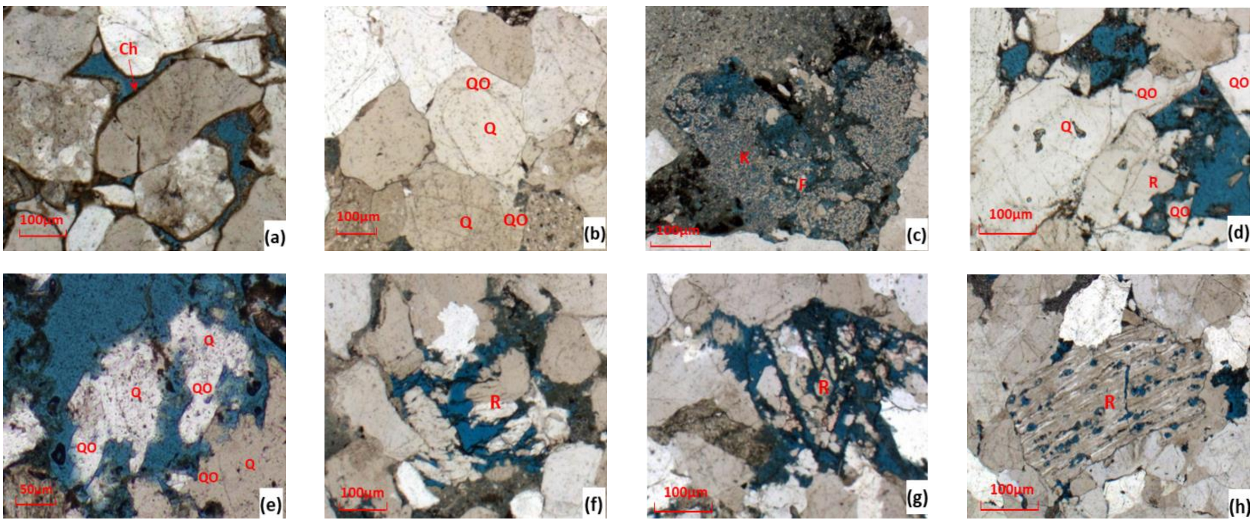
Soluble reservoir minerals can be dissolved only when they come into contact with externally introduced fluids; identifying fluid-flow pathways in the reservoir is therefore essential. Thin-section observations show that in strongly compacted or cemented zones, grains are tightly packed, dissolution is weak (Figure 8b), and pores are poorly developed. By contrast, reservoirs containing moderate amounts of matrix or well-developed microfractures commonly occur together with dissolution pores (Figures 3a, 3b, 3f, and 8f). These observations indicate that early structural microfractures, diagenetic shrinkage fractures, residual primary pores, and matrix micropores collectively form pore-fracture networks that provide flow pathways for mineral-dissolving fluids. Such pathways facilitate dissolution and the development of secondary pores. Their principal characteristics are as follows:

(1) Structural microfractures. Thin sections commonly show fracture enlargement by dissolution and development of intra- and intergranular dissolution pores along structural microfractures (Figure 3d).

(2) Diagenetic shrinkage fractures. These are abundant shrinkage fractures generated mainly by dehydration and shrinkage of the matrix. They commonly occur within the matrix or closely along the margins of detrital grains (Figure 8l).

(3) Residual primary pores. Primary pores are generally poorly preserved under intense compaction and cementation and occur mainly in coarse-grained sandstones containing a certain amount of interstitial material (Figures 3e and 8a).

(4) Matrix micropores. These are mainly intercrystalline micropores formed after matrix alteration to kaolinite (Figures 3a, 8f, and 8j).



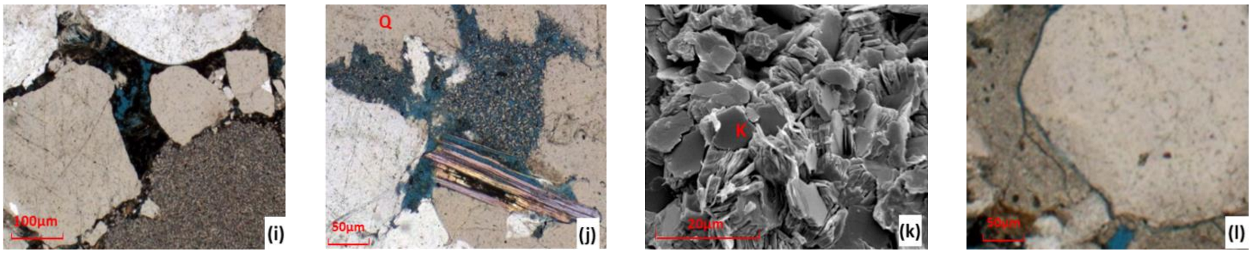


Figure 8. Pore-development mechanisms in the target reservoir intervals. (a) Grain-rimming chlorite film; weak quartz overgrowths and preserved residual primary pores, Well T8-8, 3346.7 m. (b) Strong quartz overgrowths, no intergranular interstitial material, concavo-convex grain contacts, and poor pore development, Well T8-8, 3354.7 m. (c) Feldspar altered to kaolinite, with intercrystalline pores and minor intragranular dissolution pores, Well T8-8, 3329.5 m. (d) Quartz grain with an overgrowth rim dissolved along fractures into an irregular shape; intergranular kaolinite is dissolved, producing intra- and intergranular dissolution pores, Well T8-8, 3321.4 m. (e) Quartz grain with an overgrowth dissolved to a residual texture, Well T8-8, 3323.5 m. (f) Quartzite fragment dissolved along internal fractures into an irregular residual texture, Well T8-8, 3353.2 m. (g) Quartzite fragment dissolved along two fracture sets into a residual texture, Well T8-8, 3354.6 m. (h) Heterogeneous dissolution of a lithic grain producing intragranular dissolution pores, Well T8-8, 3329.15 m. (i) Partial dissolution of intergranular matrix producing intergranular dissolution pores; feldspar is kaolinized and develops intercrystalline micropores, Well T8-8, 3323.9 m. (j) Dissolution of micaceous matrix and intergranular kaolinite, together with replacement of detrital grains, producing intergranular dissolution pores and intercrystalline pores, Well T8-8, 3323.1 m. (k) Poorly euhedral intergranular kaolinite formed mainly by tuffaceous alteration, Well T8-8, 3281.2 m. (l) Grain-rimming fractures developed along detrital-grain margins, interpreted as diagenetic shrinkage fractures generated by dehydration of intergranular matrix, Well T8-8, 3330 m. Mineral abbreviations: Q—quartz; F—feldspar; R—lithic fragment; Qo—quartz overgrowth; K—kaolinite; Ch—chlorite.

4 Conclusions

(1) Reservoir rocks in the study area are dominated by lithic sandstone. Lithic fragments and interstitial materials are compositionally complex, and rocks with different mineral assemblages exhibit markedly different diagenetic and pore-development characteristics. Reservoir pore types are diverse, with intergranular and intragranular dissolution pores making the greatest contribution to total porosity.

(2) Coarse-grained sandstones rich in rigid components such as quartz grains and quartzite fragments effectively resist compaction and favor both preservation of primary pores and development of secondary pores. Moderate amounts of interstitial material, including chlorite coatings and micaceous matrix, suppress quartz overgrowths and resist compaction, thereby playing an important role in preserving primary pores. The depositional hydrodynamic environment controls not only grain-size sorting but also, to some extent, the proportions of rigid and ductile mineral components, and therefore constitutes a prerequisite for favorable reservoir development.

(3) Superimposed dissolution and alteration of multiple minerals directly generate secondary pores. Extensive dissolution of quartz-rich minerals, including quartz grains and quartzite fragments, produces intra- and intergranular dissolution pores that make the largest contribution to reservoir pore space. Feldspar is scarce and is mainly altered to kaolinite,

producing intercrystalline micropores and minor intragranular dissolution pores and thus making a limited contribution to total pore space. In some intervals, micaceous matrix and kaolinite derived from tuffaceous alteration are present; intergranular dissolution pores formed by dissolution of these materials and intercrystalline pores in altered kaolinite significantly improve reservoir porosity and permeability.

(4) Structural microfractures, diagenetic shrinkage fractures, residual primary pores, and matrix micropores together form flow pathways for mineral-dissolving fluids, creating favorable conditions for dissolution of the various mineral components.

Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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