

Article

Classification and Analysis of Dominant Lithofacies of the Fengcheng Formation Shale Oil Reservoirs in the Mahu Sag, Junggar Basin, NW China

An Xie ¹, Heyuan Wu ^{2,3,*}, Yong Tang ¹, Wenjun He ¹, Jingzhou Zhao ^{2,3}, Weitao Wu ^{2,3}, Jun Li ^{2,3} , Yubin Bai ^{2,3}  and Liang Yue ⁴ 

¹ Xinjiang Research Institute of Huairou Laboratory, Urumqi 830000, China; xiean@xjri.hrl.ac.cn (A.X.)

² School of Earth Sciences and Engineering, Xi'an Shiyou University, Xi'an 710065, China

³ Shannxi Key Laboratory of Petroleum Accumulation Geology, Xi'an Shiyou University, Xi'an 710065, China

⁴ School of Transportation Engineering, Jiangsu Vocational Institute of Architectural Technology, Xuzhou 221116, China; qzyueliang@163.com

* Correspondence: why@xsyu.edu.cn; Tel.: +86-15009906540

Abstract: The exploration of the Fengcheng Formation has revealed the characteristic orderly coexistence of conventional reservoirs, tight reservoirs, and shale reservoirs, constituting a full spectrum of reservoir types, and is important for unconventional oil and gas exploration and development. Affected by frequent volcanic tectonic movement, hot and dry paleoclimate, and the close provenance supply distance, unique saline–alkaline lacustrine deposits formed during the depositional period of the Fengcheng Formation. The lithologies of the Fengcheng Formation are highly diverse, with endogenous rocks, volcanic rocks, terrigenous debris, and mixed rocks overlapping and forming vertical reservoir changes ranging from meters to centimeters. Owing to the complexity of rock types and scarcity of rock samples, the evaluation of reservoirs in mixed-rock has progressed slowly. Hence, we aimed to evaluate the characteristics of Fengcheng Formation shale oil reservoirs. Centimeter-level core characteristics were analyzed based on the lithological change and structural characteristics. To investigate the lithofacies of the Fengcheng Formation in the Mahu Sag and factors affecting reservoir development, high-frequency sedimentary structures were analyzed using sub-bio-buffering electron microscopy, energy spectrum testing, and fluorescence analysis. The results showed that the shale oil reservoirs in the study area can be divided into four categories: glutenite, volcanic rock, mixed rock, and endogenous rock. The reservoir capacity has improved and can be divided into eight subcategories. Mixed-rock reservoirs can be further divided into four subcategories based on differences in structure and composition. Differences in the bedding and dolomite content are the main factors controlling the differences in the physical properties of this type of reservoir. This study provides a reference for the classification and characteristic study of shale oil reservoirs in saline–alkali lake basins.

Keywords: shale oil; lithofacies; reservoir type; Fengcheng Formation; mixed-rock



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1. Introduction

In recent years, there has been a notable enhancement in conventional oil and gas exploration theories and extraction techniques. Globally, countries have shifted their focus toward unconventional oil and gas resources [1]. China, in particular, has experienced a rapid development trend in this competitive realm [2–4]. Noteworthy oil and gas enrichment areas include the Junggar, Bohai Bay, Ordos, and Songliao Basins [5–9]. China's

advancements in unconventional oil and gas exploration have served as a guiding force globally [7,10–19]. Taking the Junggar Basin as an illustrative example, the annual output from the established national continental shale oil demonstration area has surpassed 600,000 t. The Permian Lucaogou Formation in the Jimusar Sag significantly contributes to the regional unconventional oil and gas sector, and the Mahu Sag, situated within the same basin, also plays a substantial role. Notably, the Permian Fengcheng Formation emerges as a crucial target for regional unconventional oil and gas exploration. The Fengcheng Formation in the Mahu Sag of the Junggar Basin has revealed multiple commercially viable hydrocarbon reservoirs. An in-depth investigation into the development patterns and hydrocarbon generation evolution of alkaline lacustrine facies source rocks within this formation provides critical case studies for advancing the geological theory of hydrocarbon enrichment in continental petroliferous basins, thereby enriching and advancing the relevant theoretical frameworks.

The source rocks in this stratum exhibit significant characteristics, including substantial thickness, high organic matter content, robust hydrocarbon generation capacity, and efficient source rock conversion, garnering considerable attention [20–23]. However, the evaluation of reservoirs within this layer has been hindered by the intricate nature of rock types and the scarcity of rock samples [24,25]. This bottleneck impedes the efficient exploration and development of shale oil. In this study, we systematically describe the characteristics of the Fengcheng Formation shale oil reservoirs and identify their favorable types through centimeter-level core observation and microscopic analysis. We also determine the main factors controlling reservoir development, providing a reference for the classification and characterization of shale oil reservoirs in saline–alkaline lake basins.

2. Geological Background and Material

2.1. Geological Background

The Mahu Sag situated on the northwestern edge of the Junggar Basin, northwest China, serves as a basin subsidence center characterized by an extended influx of terrigenous clastic deposits. During the early deposition of the Fengcheng Formation, the regional climate experienced prolonged dry and hot conditions, coupled with continuous influence from nearby volcanic activities. This sedimentary period unfolded within a closed lake environment, marked by a structurally asymmetric dustpan-shaped foreland depression featuring a steep western and gentle eastern paleotectonic background [26]. The sedimentary strata exhibit notable thickness variations, being thicker in the west and thinner in the east (Figure 1), with significant differences in sedimentary thickness ranging from 800 m to 1800 m.

The structural evolution of the Mahu Sag is intricate, yet its overall preservation is good without large-scale tectonic disturbances. The Lower Permian Fengcheng Formation in the Mahu Sag contains the world's oldest alkaline lake source rocks. Formed in a semi-arid climate, these source rocks are characterized by high organic matter content and a strong hydrocarbon-generating ability. The Upper Triassic, thick mudstone acts as a regional cap rock, effectively preventing oil/gas escape and aiding its accumulation in the reservoir.

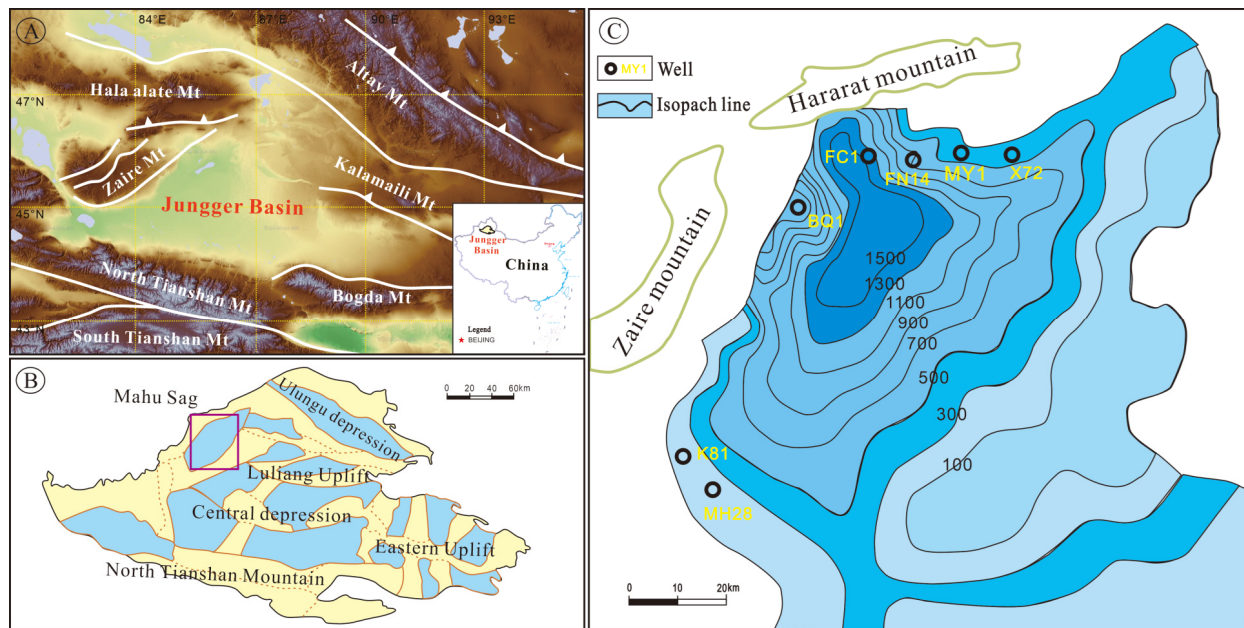


Figure 1. Location of the study area and isopach line of the Fengcheng Formation. (A): Location of Junggar Basin in China. (B): Location of Mahu Sag in the Junggar Basin. (C): Distribution thickness of the Fengcheng Formation in Mahu Sag and map of the well distribution.

The sedimentary sequence of the Fengcheng Formation (P_{2f}) undergoes a comprehensive baseline transition from lake intrusion to high-level and lake retreat (Figure 2). This sequence is further categorized into three distinct sections—first (P_{2f1}), second (P_{2f2}), and third (P_{2f3})—each delineating the evolution of the sedimentary environment from delta front to semi-deep, deep, and shallow lake settings [27,28]. Due to the sedimentary environment, there are significant differences in the lithology and lithofacies distribution of each layer [29]. Based on salinization degree results during the sedimentary period [30–32], the Fengcheng Formation is stratified into five lithological combinations from bottom to top (Figure 2). The first combination encompasses freshwater or low-salinity sedimentary sections with volcanic rocks, predominantly comprising fine conglomerates, sandstones, siltstones, or muddy siltstones. The second combination is a salinized sedimentary section, primarily composed of mudstone enriched in dolomite layers, with occasional dolomite and layers or lenses of dolomitic and muddy sandstone. The third combination is an alkaline, sedimentary section, mainly consisting of mudstone mixed with dolomite, gypsum, and datolite, interbedded with limited dolomitic-sandy mudstone, dolomitic-muddy sandstone layers, or lenses. The fourth combination is a saline sedimentary combination, predominantly featuring mudstone enriched in dolomite layers, occasionally interspersed with dolomite–siltstone lenses or mudstone–siltstone lenses. The fifth combination is a freshwater or low-salinity sedimentary combination, mainly composed of siltstone and muddy siltstone interbedded with sandy mudstone layers. These lithological combinations signify rapid changes in the sedimentary environment, highlighting the complex composition and strong heterogeneity of the rocks within the Fengcheng Formation [4,33,34], significantly amplifying the challenge in studying reservoir characteristics. In addition, reservoir’s physical properties are directly related to single-well productivity, showing the characteristics of “lithofacies controlling reservoirs and physical properties controlling oil reservoirs” [28].

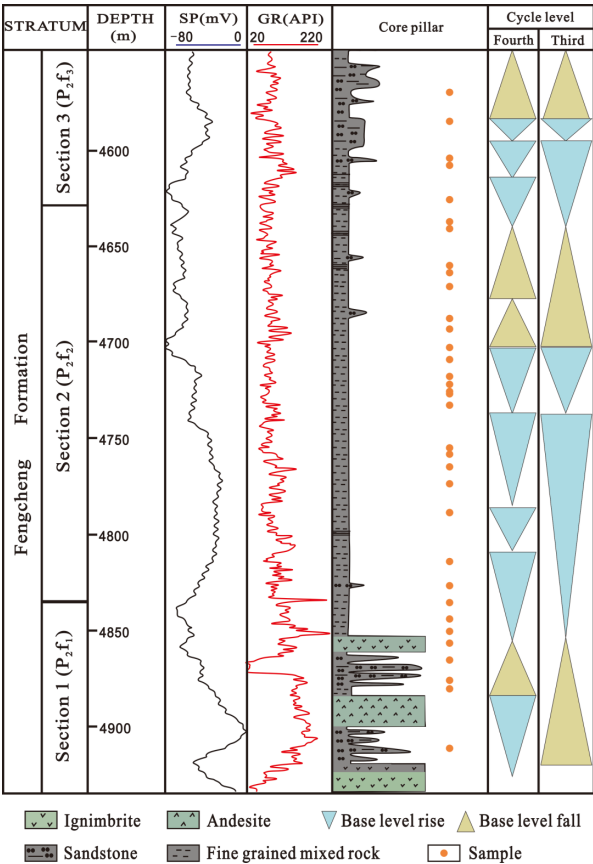


Figure 2. Composite column of the Fengcheng Formation.

2.2. Methods and Materials

2.2.1. Centimeter-Level Core Observation

The Fengcheng Formation exhibits a diverse array of rock types, including volcanic, clastic, multi-source mixed mudstone, and endogenous rocks, all extensively developed. Determining planar and vertical stacking patterns between these rock types and accurately identifying fine-grained sediments without component analysis pose considerable challenges. To address this, high-resolution centimeter-level lithology observations were conducted to discern the structure and lithology of the Fengcheng Formation in well MY1 within the Mahu Sag (Table 1). Through the correlation between sedimentation rate and sedimentary structure, strong associations were anticipated between layer thickness, lithology, and structure. The Fengcheng Formation was segmented at centimeter intervals based on sedimentary structures, mineral enrichment patterns, and grain size variations. These segments were then characterized, establishing correlations between layer thickness, structure, and lithology. This approach enabled the examination of shale oil reservoir characteristics from a structural perspective, providing insights for analyzing the complex lithology.

Table 1. Core observation parameters of Fengcheng Formation shale oil reservoir in Mahu Depression.

Rock Type	Clastic Rock					Volcanic Rock	Dolomite	Fine Grained Mixed Rock				
Lithology	Argillaceous Siltstone	Dolomitic Siltstone, Siltstone	Fine Muddy Sandstone, Fine Silty Sandstone, Fine Sandstone	Silty Sandstone with Muddy Gravel	Medium-Fine Calcium Sanstone	Medium Coarse Sandstone, Coarse Sandstone, Coarse Sandstone with Gravel, Sandy Conglomerate	Andesite and Fused Tuff	Limestone and Mudstone	Dolomitic Mudstone/ Shale	Dolomitic-Silty Mudstone/ Shale	Silty Mudstone/ Shale	Mudstone Containing Dolomite/Shale
Colour	Light gray white, silver gray, gray, light green gray						Light green gray, light gray brown	light gray	Black, black gray, dark gray, light gray			
Thickenss	Laminae, thin layer, middle layer, thick layer, extremely thick layer						Thick layer, extremely thick layer	Thin layer, laminated layer	Layer, thin layer, middle layer			
Structure	Parallel bedding, granular bedding, and lenticular bedding						Blocky, angular, and coiled	lenticular	Page bedding, lens like bedding, horizontal bedding			
Characteristic mineral	Pyrite						Turbidite and quartz	/	Flint, calcareous minerals, datolite, gypsum			
Enrichment forms of characteristic minerals	Nodular						Pore filling	/	Layered-similar layer, rooted or networked, snowflake or star shaped			
Development of cracks	Near vertical cracks, near horizontal cracks, suture lines						Near vertical cracks, near horizontal cracks, suture lines	/	Page seams, near horizontal cracks, suture lines			
Oiliness	Rich in oil, oil immersion, oil spots, and oil stains						Rich in oil, oil immersion, oil spots, and oil stains	/	Oil immersion, oil stains, oil stains			
Pore	Cracks, mineral dissolution pores						Cracks and pores	/	Mineral dissolution pores, intergranular pores, cracks			

2.2.2. Microscopic Analysis

Samples from various rock types and structures underwent comprehensive analyses, including rock composition analysis, pore permeability analysis, sub-ion polishing, fluorescence, thin section observations, and energy spectrum mineral identification. Given the complexity and variability of rock types, a total of 142 samples from a single well underwent whole-rock mineral analysis using X-ray diffractometer (Instrument model: D/MX-2400, Japan) to identify their composition and content. Complementary experiments, including nitrogen adsorption (10 samples) (instrument model: QUADRASORB evo, America), high-pressure mercury intrusion (1124 samples) (instrument model: PoreMaster 33, America), and nuclear magnetic resonance analysis (10 samples), were employed to conduct porosity and permeability tests on the samples. The tests provide information on pore throat size distribution, pore volume, and connectivity. The data help in understanding how fluids flow through the rock and the rock's potential as a hydrocarbon reservoir. This facilitated the comparison of physical properties among different reservoir types (instrument model: MesoMR23-60H-I, China). Utilizing cast thin-section analysis (84 samples) and sub-ion polishing electron microscopy analysis (19 samples) (instrument model: Leica TCS SP8, Germany), we scrutinized the pore structure characteristics of different reservoir types and summarized the attributes of reservoir space types. This analysis helps in understanding the spatial relationships between minerals and pores, and evaluating the rock's potential for hydrocarbon storage. A fluorescence microscope (35 samples) (instrument model: Leica TCS SP8, Germany) was employed to observe and consolidate the locations of oil and gas enrichment in different reservoir types. The test helps in understanding the distribution and potential productivity of hydrocarbons in various reservoir types. This comprehensive microscopic analysis forms the basis for the holistic evaluation of each reservoir type.

3. Results and Analyses

3.1. Layer Thickness and Structural Development Characteristics

Significant variations were identified in sedimentary structure, layer thickness, and enrichment patterns of characteristic minerals among different rock types in the Fengcheng Formation (Table 1, Figure 3).

The primary focus of early tight oil exploration, the sandy conglomerate reservoir, consists mainly of medium- to block-like layers distributed in P_{2f1} and P_{2f3} of the Fengcheng Formation (Figure 2), exhibiting a broad range of layer thicknesses from thin to extremely thick.

Sandstone reservoirs are predominantly found in P_{2f1} and P_{2f2} , with intermittent development of calcareous and dolomitic sandstones.

Siltstone reservoirs are randomly distributed in three sections of the Fengcheng Formation, characterized by two main lithofacies: dolomitic siltstone and dolomite-bearing mudstone–siltstone. Core observations reveal that the primary thickness range of sandy conglomerate reservoirs is 1–40 cm. In the lower part of P_{2f1} , the sandy conglomerate can reach a maximum thickness range of 2–3 m, appearing as a medium-thick layer, while the majority of layers are thin, layered, or lens-shaped.

Volcanic reservoirs concentrate in P_{2f1} , where basaltic andesite and fused tuff form thick blocks or breccia (Figure 2). These reservoirs display rich pore structures, frequent vertical fractures, abundant oil invasion, and oil spots.

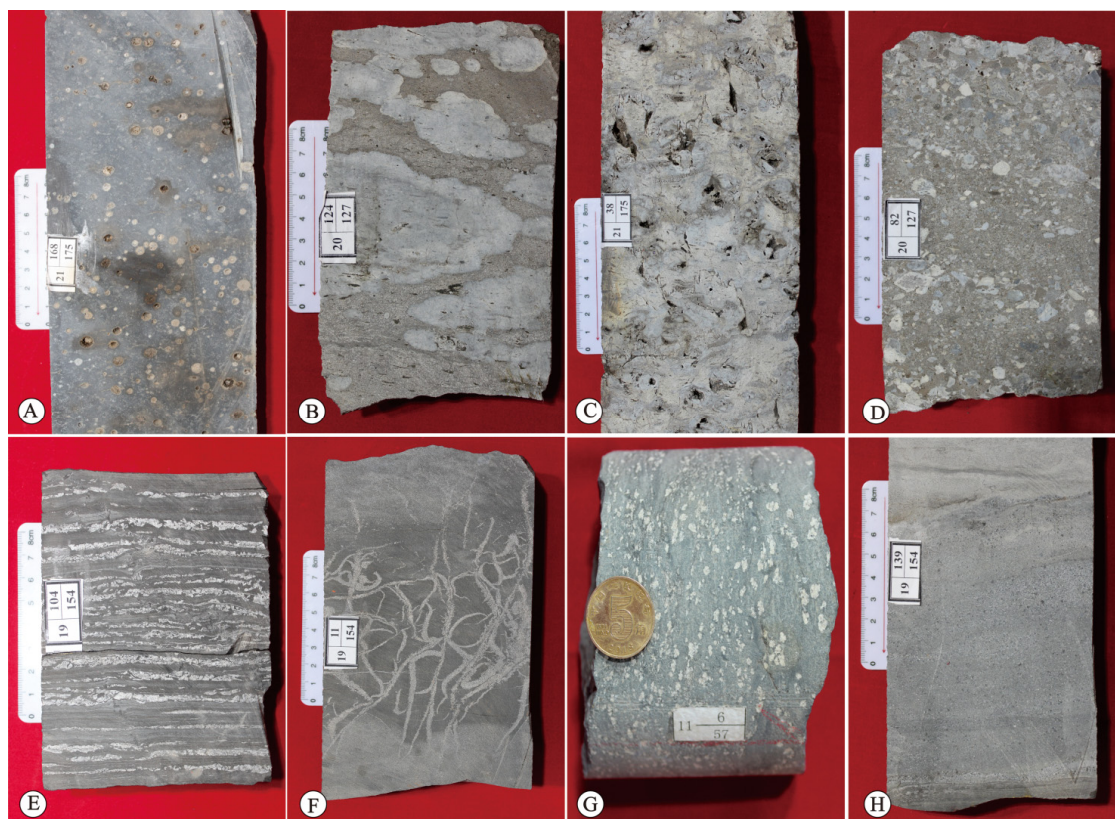


Figure 3. Main lithology and structural characteristics of the Fengcheng Formation. (A–F): Well MY1, (A): Andesite. (B): Tuff; (C): Molten tuff. (D): Sandy fine conglomerate. (E): Layered fine-grained mixed rock. (F): Rooted fine-grained mixed rock. (G): Snowflake fine-grained mixed rock from well FN14. (H): Starry fine-grained mixed rock from well MY1.

Endogenous rock reservoirs, primarily evaporite rocks composed of sodalite, sodium carbonate (natural alkali), soda ash, and silicon boron sodium silicate rocks, mainly develop

in fine-grained mixed rocks in layered or similar layers, with small amounts of dolomite, mudstone dolomite, tuffaceous dolomite, calcareous dolomite, and limestone in thin layers. Although endogenous minerals are relatively developed, widespread layered endogenous rocks have not yet been discovered in the Fengcheng Formation, and mixed deposition is the primary factor contributing to the complex composition of fine-grained rocks in this formation.

Mud-grade fine-grained mixed rocks are extensively developed in the three subsegments of the Fengcheng Formation (Figure 2). The total thickness of mud-grade fine-grained mixed rock in well MY1 is 262.3 m, primarily concentrated in the second (P_{2f2}) and third (P_{2f3}) sections of the Fengcheng Formation, with a relatively small proportion in P_{2f1} . Due to the relatively deep-water bodies in the sedimentary environment, shallow to semi-deep lake environments are mainly dominated by relatively weak static water. The sedimentary structure is simple and lens-like, with widely developed horizontal beddings. The rock composition is dominated by fine-grained mud and endogenous minerals, including flint, calcite, dolomite, silicate calcium carbonate, and gypsum. These minerals exhibit different enrichment styles, dividing the matrix mudstone into thin layers ranging from centimeter to decimeter scales, leading to diverse rock structural characteristics. High-resolution core observations indicate that endogenous mineral enrichment in the Fengcheng Formation primarily manifests in three styles: tree root or network-like, layered or similarly layered, and snowflake- or star-shaped (Figure 3).

3.2. Rock Composition

Volcanic reservoirs within the Fengcheng Formation are readily distinguishable from other reservoir types due to their distinctive structures. Sandstone reservoirs predominantly consist of coarse-grained terrestrial detrital quartz and feldspar, with a minor amount of calcareous cementation. Consequently, the primary focus of the study shifts towards mud-grade fine-grained mixed rocks through compositional analysis. Utilizing the concept of generalized mixed rock [35–37], X-ray diffraction analysis of the entire mud-grade fine-grained sediment within the Fengcheng Formation reveals varying degrees of development in dolomitic and calcareous components, ranging from 15% to 50% (Figure 4). A few lens-like interlayers exhibit dolomitic characteristics. The composition of mudstone in the Fengcheng Formation significantly varies across different strata, with P_{2f1} being rich in felsic minerals, P_{2f3} exhibiting a relatively high clay content, and the second section Fengcheng Formation (P_{2f2}) insignificantly differing in terms of clay mineral, felsic mineral, and dolomitic/calcareous compositions.

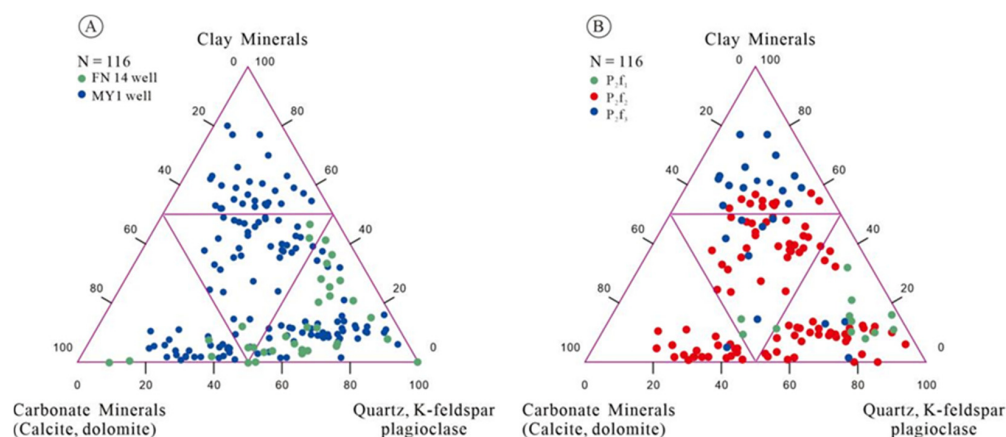


Figure 4. Ternary plot of the fine-grained mixed-rock lithology in the Fengcheng Formation, Mahu Sag. (A): Ternary plot of the mixed-rock. The samples are from wells MY 1 and FN 14. (B): Ternary plot of three sections of the Fengcheng Formation. The samples are from well MY 1.

3.3. Porosity and Permeability

Sandstone and volcanic reservoirs emerge as the primary targets for early exploration, boasting advantages in thickness and superior overall properties compared to fine-grained mixed rocks. The physical properties of sand and gravel reservoirs within the Fengcheng Formation exhibit considerable variability across different regions of the Mahu Sag (Figure 5). On the western slope, the porosity distribution range of sandstone reservoirs spans 1–13%, with an average of 2.89%, and reservoir permeability primarily falls below 0.1 mD. The average porosities of sandstone reservoirs in wells MY1, Xiazijie, K81, and FN14 are 6.9%, 6.2%, 7.2%, and 5.4%, respectively. While the average effective porosity of volcanic rock reservoirs can reach 7.3%, their permeability is lower than that of sandstone reservoirs and mainly depends on structural fractures to connect various isolated storage spaces.

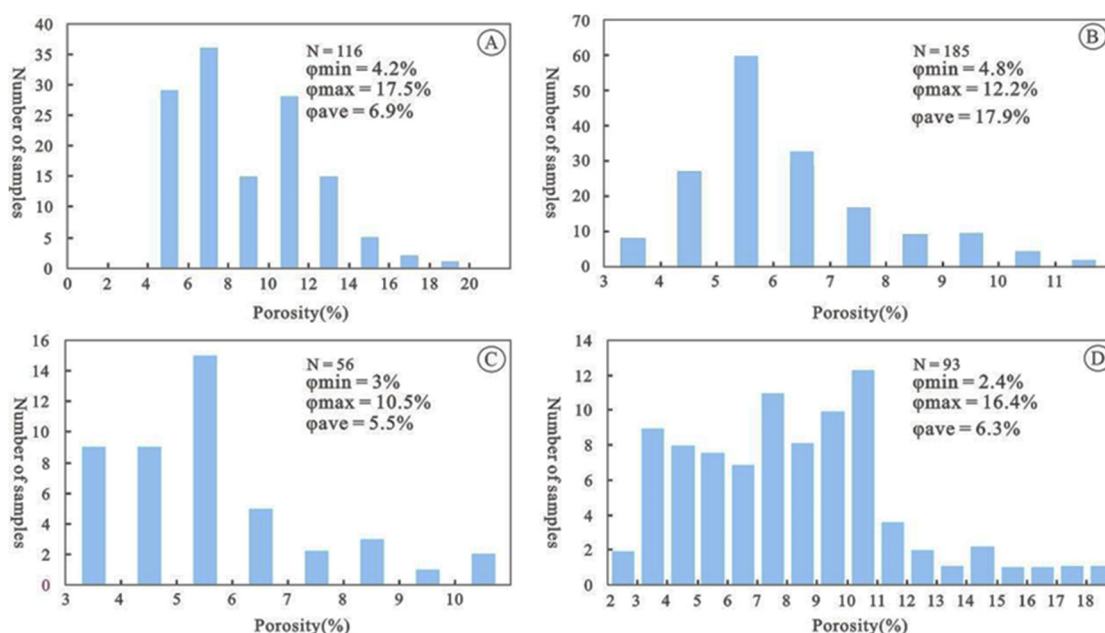


Figure 5. Comparison of the porosity of detrital reservoirs in the Fengcheng Formation, Mahu Depression. (A): Data for well MY1. (B): Data for well K81. (C): Data from well FN14. (D): Data for well XZJ.

Analyzing high-pressure mercury injection data from different reservoir types reveals that the maximum mercury saturation in sandstone can reach 95% (Figure 6), with an average mercury saturation of approximately 80%. The mercury saturation characteristics of basalt resemble those of mixed mudstone, with a primary distribution range of 60–30%. Significant differences are evident in the mercury saturation characteristics of various structural types of mixed mudstone. Layered mixed mudstone exhibits higher mercury saturation, ranging from 60% to 50%, and significantly lower displacement pressure than tree roots, snowflakes, or star-shaped mixed mudstones.

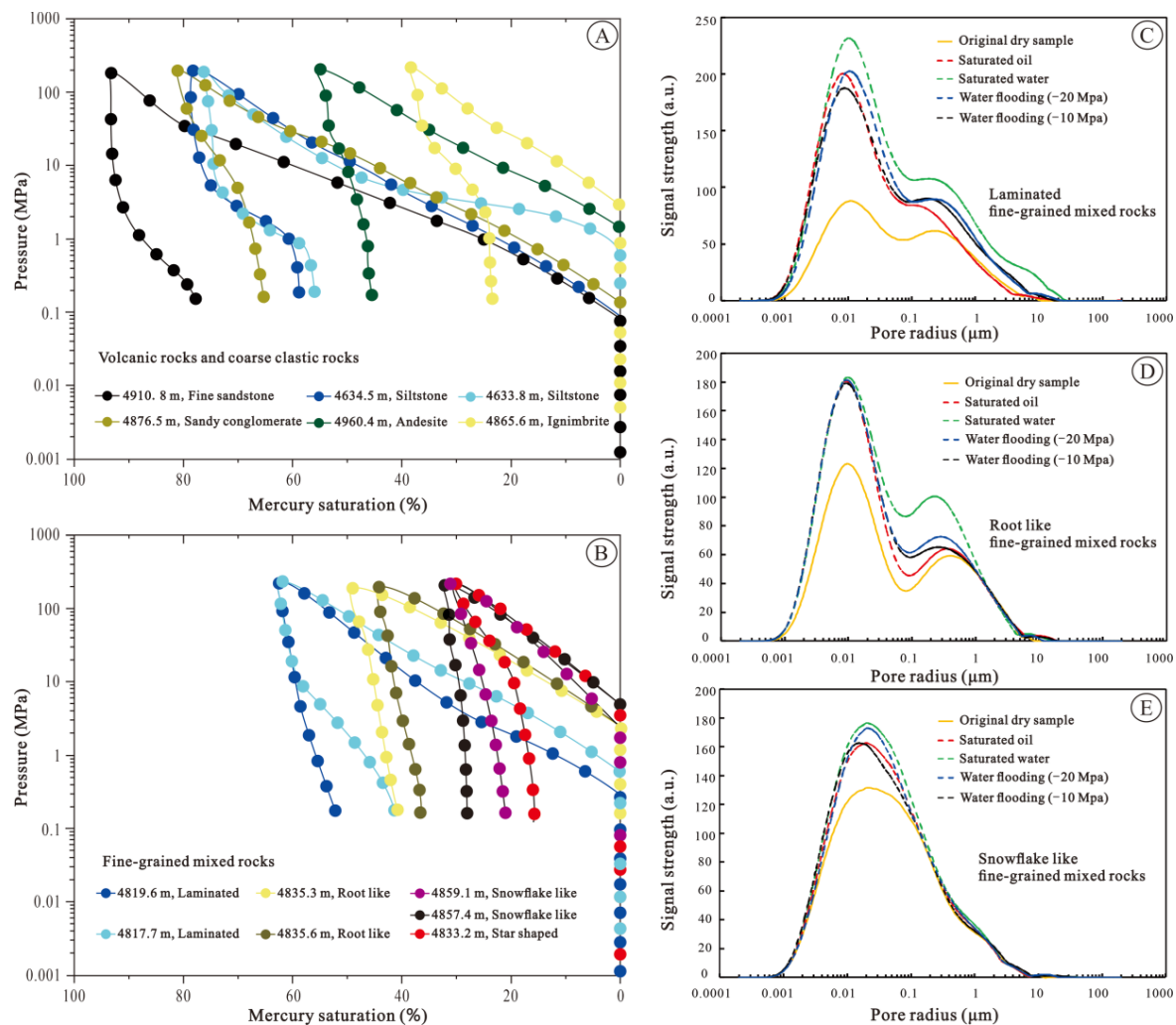


Figure 6. Comparison of high-pressure mercury injection and nuclear magnetic T2 spectra of different types of reservoirs in the Mahu Sag. All data are for samples from well MY1. (A): Mercury intrusion characteristics of volcanic and coarse clastic rocks. (B): Mercury intrusion characteristics of fine-grained mixed rock. (C–E): Characteristics of nuclear magnetic resonance T2 spectra of different types of fine-grained mixed rocks.

Considering the development status of the page structure, a porosity analysis was conducted on several types of fine-grained mixed rocks based on their endogenous mineral enrichment status (Figure 5). Fine-grained mixed rock with a well-developed structure demonstrates relatively concentrated porosity and large effective porosity, mainly falling within the range of 3–6%. Fine-grained mixed rock featuring a concentrated development of datolite layers exhibits an increased number of intergranular pores, with local porosity reaching 7–8%. The effective porosity is comparable to that of layered or similarly layered fine-grained mixed rocks but is relatively dispersed. The total porosity of a root-shaped mixed rock is significantly low. The effective porosity distribution range of snowflake- and star-shaped mixed mudstone is small, and the porosity is low. Snowflake-shaped mixed mudstone displays a high local total porosity, potentially linked to changes in dolomite content.

3.4. Storage Space Characteristics

In examining the reservoir space within volcanic rocks, sandstone, fine-grained mixed rock, and dolomite reservoirs, the study employs microscopic experimental methods, with primary pores and structural fractures in volcanic rocks being visible to the naked eye (Figure 7). The primary focus in sandstone, fine-grained mixed rock, and dolomite

reservoirs involves utilizing sub-ion polishing scanning electron microscopy and thin-section microscopy results.

- (1) The reservoir spaces in sandstone are predominantly represented by intergranular and secondary dissolution pores (Figure 7A–C). When primary intergranular pores are concentrated and developed, the overall clay mineral content is low, and debris particles mostly exhibit point-to-line contact. The remaining primary intergranular pores are either unfilled or filled, with a small amount of authigenic clay minerals. The close proximity of debris sources and the influence of volcanic activity in the source area contribute to a high feldspar mineral content. During later diagenetic evolution, organic acid dissolution generates abundant dissolution pores, forming a crucial foundation for high-quality reservoir formation.
- (2) Endogenous rock reservoirs: Endogenous rocks within the Fengcheng Formation, mainly evaporites, contain storage spaces consisting of intergranular pores within mudstone, dolomite, and limestone. The pores in dolomite crystals vary in size from micrometers to nanometers. Sodium carbonate, calcium limestone, and soda stone, formed in the sedimentary background of saline–alkali lakes, often exhibit lens-like and sporadic developmental characteristics. Due to their interlayered nature within fine-grained mixed rocks, obtaining thin-section samples is challenging. Hand specimens display coarse crystals with columnar aggregates and relatively large intergranular pores ranging from micrometers to millimeters.
- (3) Fine-grained mixed rock reservoirs: Characterized by the symbiotic relationship between terrestrial debris and endogenous minerals, exhibit storage space with combined characteristics of clastic and endogenous rocks. In contrast to sandstone and conglomerate reservoirs, the intergranular pore size in fine-grained mixed rocks is notably small, primarily manifesting as residual primary intergranular and intergranular dissolution pores. Primary intergranular pores are semi-filled with clay minerals, showcasing an average pore size distribution range of 10–100 μm , characterized by micrometer-sized pores with relatively high connectivity. Secondary dissolution pores (Figure 7D–I) result from the dissolution of endogenous authigenic dolomite and terrigenous detrital feldspar particles. These pores are distributed in an isolated manner, exhibiting poor connectivity. Dissolution pores of feldspar mainly exist in potassium feldspar particles, forming micro–nanoscale contiguous pores, and are also present in several sodium feldspar crystals. Organic matter pores (Figure 7J–L) are spindle- and bubble-shaped, planar isolated, and polygonal, with pore sizes mainly below 2 μm . Intergranular pores consist mainly of calcite and authigenic clay mineral intergranular pores (Figure 7M–O), displaying a dense development and spindle-like shape, with high connectivity in the pore plane. The distribution range is 2–5 μm . Microcracks manifest as edge and intragranular cracks in debris particles (Figure 7P–R). The crack extension exceeds 10 μm , and the seam width is less than 1 μm . The lower secondary mineral filling and a higher degree of opening in the cracks contribute to an increase in reservoir permeability.

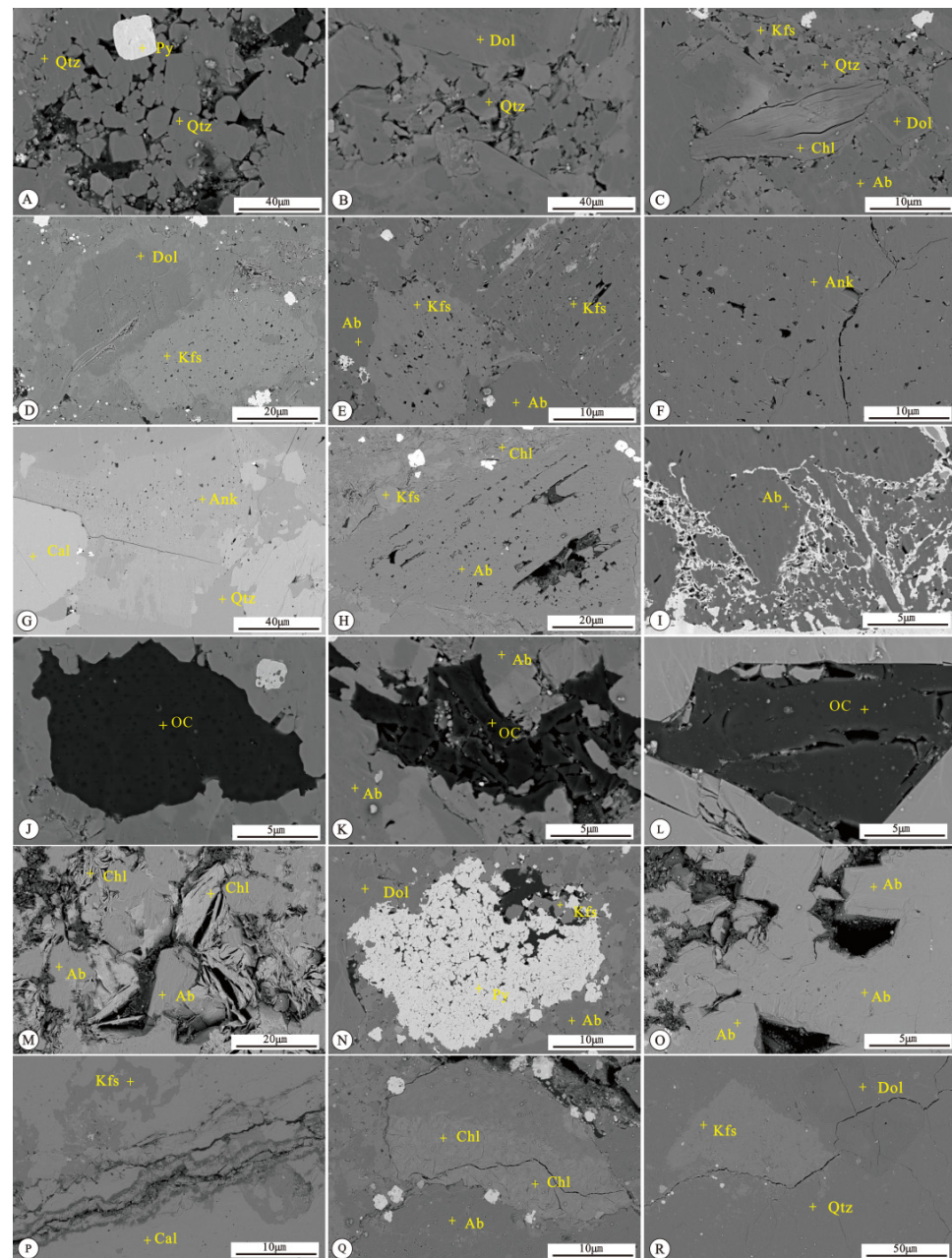


Figure 7. Main storage space types of shale oil reservoirs in the Fengcheng Formation of the Mahu Depression. All samples were obtained from well MY1. (A–C): Primary intergranular pores of debris particles. (D,E): Dissolution pores of potassium feldspar. (F,G): Dissolution pore of ankerite. (H,I): Dissolution pore of albite. (J–L): Pores of organic matter. (M): Intergranular pores of chlorite; (N): Intergranular pores of pyrite. (O): Intergranular pores of albite. (P–R): Microcracks in fine-grained mixed rock. Ab: Albite, Ank: Ankerite, Chl: Chlorite, Dol: Dolomite, Kfs: Feldspar, Qtz: Quartz, OC: Organic carbon.

4. Discussion

4.1. Classification of Reservoir Types

A comprehensive reservoir evaluation is imperative for large-scale regional development. The Fengcheng Formation shale oil reservoir is either self-generated or a near-source reservoir. Similarly to the evaluation of shale gas reservoirs, fundamental characteristics such as petrology and physical properties play a crucial role in determining the exploitable potential of shale oil reservoirs [38–40]. Argillaceous content and microstructural types are critical factors influencing the porosity and permeability of reservoir rocks. Analyzing

their capacity for fluid transmission (permeability) and storage (porosity) is essential data for subsequent hydrocarbon reservoir development, as these properties directly govern hydrocarbon migration, accumulation, and recoverability [41,42]. Combining component analysis with grain size, layer thickness, and structural development characteristics, the Fengcheng Formation reservoir in the Mahu Sag can be categorized into four major classes, eight subcategories, and 29 lithology types (Table 2).

Table 2. Classification of shale oil reservoir types in the Fengcheng Formation of Mahu Sag.

Reservoir Type	Rock Type		Layer Thickness Characteristics	Lithology	Developmental Position
	Major Categories	Subcategories			
Type I	Sand conglomerate reservoir	Conglomerate	Super-thick layer (>1.0 m)	Fine conglomerate, fine Sandy conglomerate	P ₂ f ₁
			Thick layer (0.3–1.0 m)		
			Medium layer (0.1–0.3 m)		
			Thin layer (<0.1 m)		
		Sandstone	Super-thick layer (>1.0 m)	Coarse pebbled sandstone, medium-coarse sandstone, fine sandstone, medium-fine calcareous/dolomitic sandstone, fine argillaceous silty sandstone, fine silty sandstone	P ₂ f ₃ P ₂ f ₂ P ₂ f ₁
			Thick layer (0.3–1.0 m)		
			Medium layer (0.1–0.3 m)		
			Thin layer (<0.1 m)		
		Siltstone	Thick layer (0.3–1.0 m)	Calcareous argillaceous siltstone, dolomitic siltstone	P ₂ f ₃ P ₂ f ₂ P ₂ f ₁
			Medium layer (0.1–0.3 m)		
			Thin layer (<0.1 m)		
Type II	Volcanic reservoir	Andesite	Super-thick layer (>1.0 m)	Basaltic andesite	P ₂ f ₁
		Tuff	Super-thick layer (>1.0 m)	Fused tuff	
Type III	Fine graine mixed reservoir	shale	Laminated structure	Calcareous mud/shale, dolomitic mud/shale, silty mud/shale, clay mud/shale	P ₂ f ₃ P ₂ f ₂
			Layered or similar layered		
		Mudstone	Layered or similar layered		P ₂ f ₃ P ₂ f ₂ P ₂ f ₁
			Network or tree root shaped		
			Snowflake shape or Star point shape		
Type IV	Endogenous reservoir	Evaporite	Thin layer (<0.1 m)	Argillaceous/calcareous dolomite, carbonite, sand clastic dolomite, soda rock	P ₂ f ₃ P ₂ f ₂
		Dolomite			

The four major categories are Class I (gravel reservoirs), Class II (volcanic reservoirs), Class III (mixed rock reservoirs; Table 3), and Class IV (endogenous rock reservoirs). Due to the complex mineral composition and small particle size of mixed rocks, the classification of lithological types in the Fengcheng Formation shale oil reservoir is based on practical on-site principles, with structural and layer thickness development characteristics as the primary references. A comprehensive evaluation of Fengcheng Formation shale oil was conducted based on three factors: reservoir properties, thickness, and storage space type. The storage conditions of Fengcheng Formation shale oil reservoirs, including gravel, volcanic rock, fine-grained mixed rock, and endogenous rock, have gradually deteriorated.

Table 3. Properties of mixed rock reservoirs.

Reservoir Type	Structural Features	Average Effective Porosity (%)	Average Free Fluid Pore (%)	Average Total Porosity (%)	Average Brittleness	Number of Samples
III-1	Laminated structure	3.89	1.76	6.38	4.61	154
III-2	Layered or similar layered	3.03	1.37	4.91	5.16	525
	Enrichment of datolite layers	3.27	1.33	5.89	4.31	164
III-3	Network or tree root shaped	2.92	1.28	5.33	4.54	59
III-4	Star shaped	2.31	1.15	5.34	4.34	61
	Snowflake shaped	2.63	0.95	5.52	4.16	245

The Fengcheng Formation exhibits significant vertical heterogeneity in reservoir lithology with markedly varied distribution proportions. In the Third Section of the Fengcheng Formation (P_{2f3}), sandy conglomerate reservoirs and volcanic reservoirs dominate the lithology, accounting for over 95% of the cumulative thickness within this interval. Fine-grained mixed sedimentary rocks are sparsely intercalated, representing less than 5% of the total thickness. In contrast, the First and Second Sections of the Fengcheng Formation (P_{2f1} and P_{2f2}) are predominantly composed of fine-grained mixed sedimentary rocks, which constitute more than 95% of the cumulative thickness. Volcanic reservoirs are absent in these intervals, while sandstone reservoirs occur locally as thin interbeds. Endogenic rock reservoirs (e.g., micritic carbonates) are sporadically present as thin laminae within the fine-grained mixed sedimentary rocks. Consequently, fine-grained mixed sedimentary rocks are the dominant and advantageous reservoir lithology in the Fengcheng Formation, serving as the primary host for hydrocarbon accumulation. Furthermore, Fine-grained mixed rocks have become an important exploration target due to their large thickness, wide range, self-generation, and self-storage characteristics.

4.2. Characteristics of Mixed Rock Reservoirs

The mineral composition of mixed shale exhibits slight variation, whereas mixed mudstone displays marked variations, presenting complex structural and lithological characteristics. Fine-grained mixed-rock reservoirs can be further divided into mixed shale and mixed mudstone reservoirs based on bedding development. Considering manifestations of datolite, calcite, and dolomite minerals, mixed mudstone can be categorized into laminated or similarly laminated mixed mudstone, tree root or network mixed mudstone, and snowflake- or star-shaped mixed mudstone.

Type III-1 mixed-rock reservoirs are rich in lamellation with straight and fine fissures. The developed section of lamellation exhibits relatively high porosity and permeability, with an average total porosity of 6.39% and significant permeability changes. In Type III-2 mixed-rock reservoirs, mineral layers are well developed and interbedded with clay and organic layers (Figure 8(A1–A4)), mainly composed of feldspar, dolomite, or datolite, forming layered or similar layers. Fluorescence reveals oily characteristics in mineral layers (Figure 8(B1–B4)), and the storage space consists of intergranular pores. Type III-3 mixed-rock reservoirs with low organic content and unclear mineral layers (Figure 8(C1–C4)), dolomite, or datolite are present in an irregular network or tree root shape. Areas in which dolomite minerals are enriched in the network or have tree-root shapes fluoresce, whereas datolite minerals do not show notable fluorescence characteristics. Type III-4 mixed-rock reservoirs show point-like development of dolomite and silica boracite minerals scattered in the matrix mudstone, forming a snowflake- or star-like pattern. Organic matter layers

are slightly developed, and the edges of dolomite particles and some organic matter layers exhibit fluorescence.

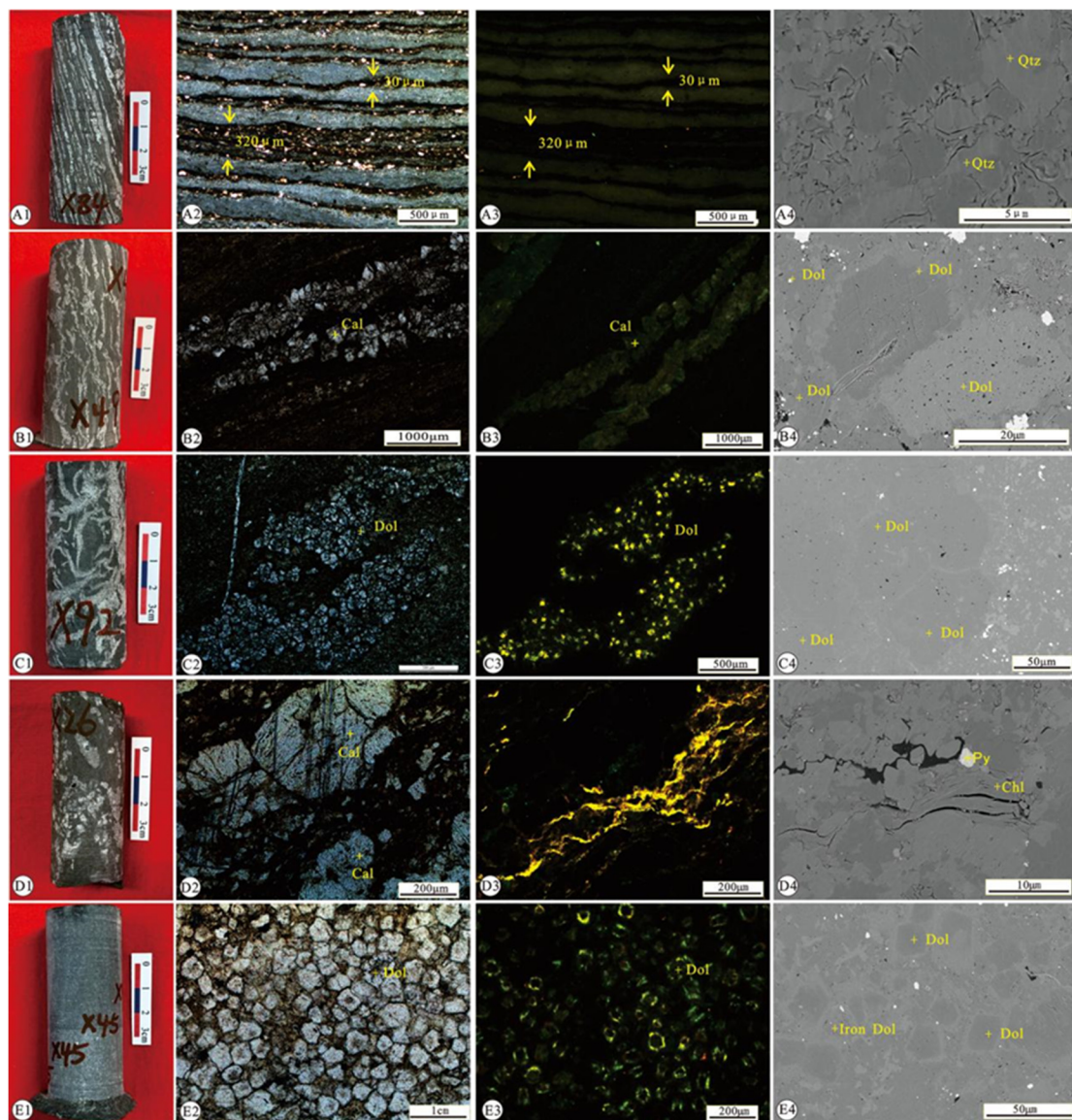


Figure 8. Comparison of macroscopic and microscopic characteristics of different types of fine-grained mixed rocks in the Fengcheng Formation, Mahu Sag. The five sets of photos in the figure were obtained from five rock samples from well MY1. Each set of photos from left to right represents core, polarized light, fluorescence, and plasma mass spectrometry scanning images. (A1–A4): Thin layered dolomitic mudstone. (B1–B4): Stratified dolomitic mudstone. (C1–C4): Root-shaped dolomitic mudstone. (D1–D4): Snowflake-shaped calcareous mudstone. (E1–E4): Starry dolomitic mudstone.

The microscopic characteristics analysis of fine-grained mixed rock indicates that the classification scheme of fine-grained mixed rock reservoir types based on mineral enrichment status is feasible but also has limitations. The reservoir-type classification, established for enhanced oil and gas exploration, should be combined with logging curves based on conventional research. This allows for comparing and summarizing the characteristics of different lithological reservoir types for a wide range of applications. However, the lithological composition of shale oil reservoirs is complex, especially in fine-grained mixed-rock reservoirs where clastic and endogenous chemical sedimentation interact. Analyzing the corresponding characteristics of logging curves solely by combining sedimentary struc-

tures and lithological composition changes is challenging. Therefore, further research is necessary for more comprehensive applications.

4.3. Mechanism of Hydrocarbon Occurrence

The mineral composition of reservoir rocks directly impacts their pore structure, fluid interaction, and diagenetic processes, thus governing reservoir properties [43]. Quartz, the most stable mineral in clastic rocks, resists weathering and preserves primary pores via rigid support and anti-compaction. However, during diagenesis, siliceous cementation can reduce or eliminate intergranular pores. In the Fengcheng Formation shale oil reservoir, free oil first increases and then decreases with higher quartz content (Figure 9A). Alkali feldspar, soluble in acidic conditions, forms kaolinite, creating secondary pores, but converts to illite in alkaline conditions, plugging pores. In the Fengcheng Formation, no functional relationship exists between feldspar content and free oil (Figure 9B). Carbonate minerals form high-permeability secondary pores through dissolution, yet cementation and diagenetic environment sensitivity limit their homogeneity [44]. In the Fengcheng Formation mixed rock, free oil first rises and then drops with more carbonate minerals (Figure 9C). Argillaceous minerals, due to adsorption and plastic deformation, worsen rock storage performance as their content increases (Figure 9D).

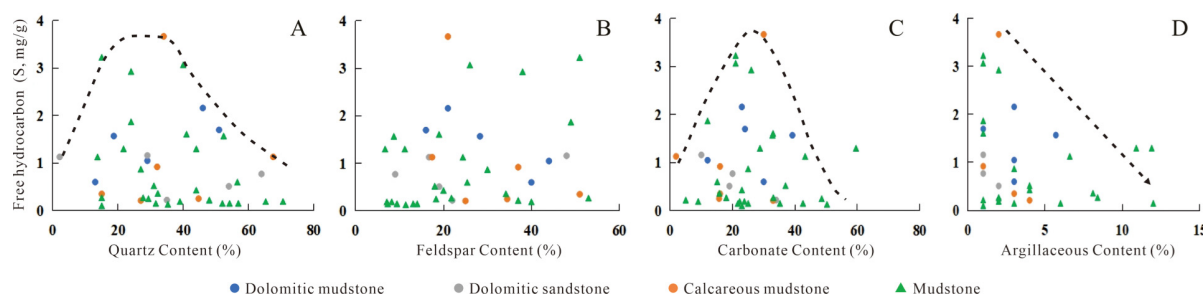


Figure 9. Relationship between mineral content and extracted free hydrocarbons in the Fengcheng Formation of Well MY1. (A): Quartz content. (B): Feldspar content. (C): Carbonate content. (D): Argillaceous content.

The reservoir rocks of the Fengcheng Formation were formed in a complex continental sedimentary environment, influenced by paleoclimate, paleogeography, and rapid sedimentary system changes. This complex background causes significant spatial changes in the lithology, thickness, and physical properties of the reservoir rocks, increasing exploration and development uncertainty. Compared to marine sedimentary shale oil reservoirs, the Fengcheng Formation's sedimentary environment is less stable, with frequent lithology changes and poor reservoir continuity and stability. The Eagle Ford Formation is mainly marine siliceous shale, featuring organic matter pores (10–100 nm) and intergranular pores (between siliceous grains), with isolated pores. Its development relies on natural fracture networks and requires dense cutting with small cluster spacing [45]. The Bakken Formation is a shallow marine reservoir, dominated by nanoscale organic matter pores (<50 nm), depending on natural fracture networks, and needs nanoscale imbibition technology to boost recovery [46,47]. The Fengcheng Formation's pore structure surpasses other domestic continental shales, yet its maturity and abundance of organic matter are lower than those of foreign marine shales. Shale oil development here depends on hydraulic fracturing. Consider that in its alkaline lake sediment context, volcanic material involved diagenesis, and dual medium storage layer with pores and fractures. Large-scale volume fracturing improves microstructure connectivity and increases movable resource volume.

5. Conclusions

Our findings reveal the following key points:

- (1) Shale oil reservoirs within the Fengcheng Formation in the Mahu Sag exhibit distinct types, including gravel, endogenous, fine-grained mixed rock, and volcanic rock. Among these, gravel reservoirs demonstrate the highest storage capacity, whereas endogenous rock exhibits the lowest. Fine-grained mixed rock and volcanic rock fall within the moderate range. Notably, fine-grained mixed-rock reservoirs emerge as favorable targets for subsequent exploration owing to their advantageous porosity, permeability, and structural characteristics. The reservoir space types within the Fengcheng Formation shale oil reservoir vary owing to differences in rock types. Volcanic reservoirs primarily consist of pores and microcracks, representing major storage spaces. Gravel reservoirs, on the other hand, exhibit widely developed secondary dissolution pores. Beyond the typical primary, intergranular, and secondary dissolution pores in conventional reservoirs, the presence of organic matter pores in fine-grained mixed-rock shale oil reservoirs becomes crucial, creating conditions conducive to the formation of high-quality reservoirs.
- (2) Fine-grained mixed-rock reservoirs can be categorized into two types: mixed shale and mixed mudstone. The porosity and permeability of mixed shale reservoirs surpass those of mixed mudstone reservoirs. Further subdivision of mixed mudstone includes layered or similarly layered, tree root or network, and snowflake- or star-shaped mixed mudstone, based on mineral development and performance characteristics. As observed, the physical properties of the reservoirs degrade gradually, leading to a continuous decline in storage capacity. The free oil content in the Fengcheng Formation shale oil reservoir is primarily controlled by mineralogical composition. As the quartz and carbonate mineral content increases, the free oil content initially rises but subsequently declines, whereas an increase in argillaceous mineral content corresponds to a reduction in the proportion of free oil.
- (3) The lithology of the Fengcheng Formation reservoir changes rapidly at the centimeter to decimeter scale. This strong heterogeneity increases the difficulty of identifying sweet spots and shale oil production. Multi-modal logging techniques (e.g., NMR + acoustic imaging) can enable precise formation identification, and the control accuracy of horizontal well trajectories needs to reach the sub-meter level.

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