

Reservoir Characteristics and Controlling Factors of the Fan Delta Front: A Case Study of the Lower Permian Wuerhe Formation in the Wuxia Area

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Abstract

This study focuses on the Lower Permian Wuerhe Formation in the Wuxia area of the Junggar Basin, analyzing the sedimentary characteristics, diagenetic processes, and their controlling factors on the reservoir quality of the fan delta front. Through core observation, well log analysis, and seismic attribute inversion, the main sedimentary facies types were identified, including subaqueous distributary channel facies, mouth bar facies, interdistributary bay facies, and sheet sand facies. Their spatial distribution and vertical evolution were thoroughly characterized. The study found that the subaqueous distributary channel facies is the primary development zone of high-quality reservoirs, featuring high porosity and permeability. Diagenetic processes significantly impact reservoir properties, with dissolution enhancing porosity and permeability, while compaction and cementation reduce reservoir quality. By analyzing the interaction between sedimentation and diagenesis, this study identifies key factors controlling reservoir development and proposes corresponding hydrocarbon exploration strategies. This research provides theoretical support for the exploration and development of hydrocarbon resources in the Junggar Basin and offers directions for future in-depth studies.

Keywords

Fan Delta Front; Reservoir Characteristics; Sedimentary Facies; Sediment Supply.

1. INTRODUCTION

The fan delta is a significant tectono-sedimentary unit in both modern and ancient depositional environments, extensively developed along continental margins and in lacustrine basins [1]. The fan delta depositional system is not only a crucial subject in sedimentary geology research but also a key area of focus in hydrocarbon reservoir studies [2]. The Junggar Basin, located in northwestern China, is a large Mesozoic sedimentary basin, where multiple fan delta systems have developed, particularly during the Permian period [3]. The interplay of tectonic activity and sedimentary processes in the basin has led to the formation of fan delta reservoirs with complex structures and diverse lithologies [4].

The Wuxia area, situated on the northwestern margin of the Junggar Basin, is adjacent to the western slope of the Mahu Depression (Figure 1). The Lower Wuerhe Formation (P2w) in this region represents an important depositional stage of the Late Permian, characterized by a typical fan delta front sedimentary system within the Wuxia Fault Zone [5]. With the evolution of regional tectonics and depositional environments, the reservoir characteristics and controlling factors in the study area exhibit complex spatial variations. A detailed study of these

reservoirs is of great significance for the exploration and development of hydrocarbon resources in the Junggar Basin [6].

To comprehensively analyze the depositional characteristics and controlling factors of the fan delta front reservoirs in the Lower Permian Wuerhe Formation in the Wuxia area, this study employed various geological research methods and techniques [7]. These include core observation and analysis, well logging data interpretation, seismic attribute inversion, and diagenetic process analysis [8]. By systematically examining and analyzing the core samples from 18 wells in the study area, combined with petrographic identification, the study aims to determine the lithology, grain size distribution, and sedimentary structures of the reservoirs, as well as to explore the different factors controlling reservoir development [9].

Through the integrated application of these methods, this study seeks to elucidate the development patterns and controlling factors of the fan delta front reservoirs in the Wuxia area from multiple perspectives, providing theoretical support for the exploration and development of hydrocarbon resources in the Junggar Basin [10].

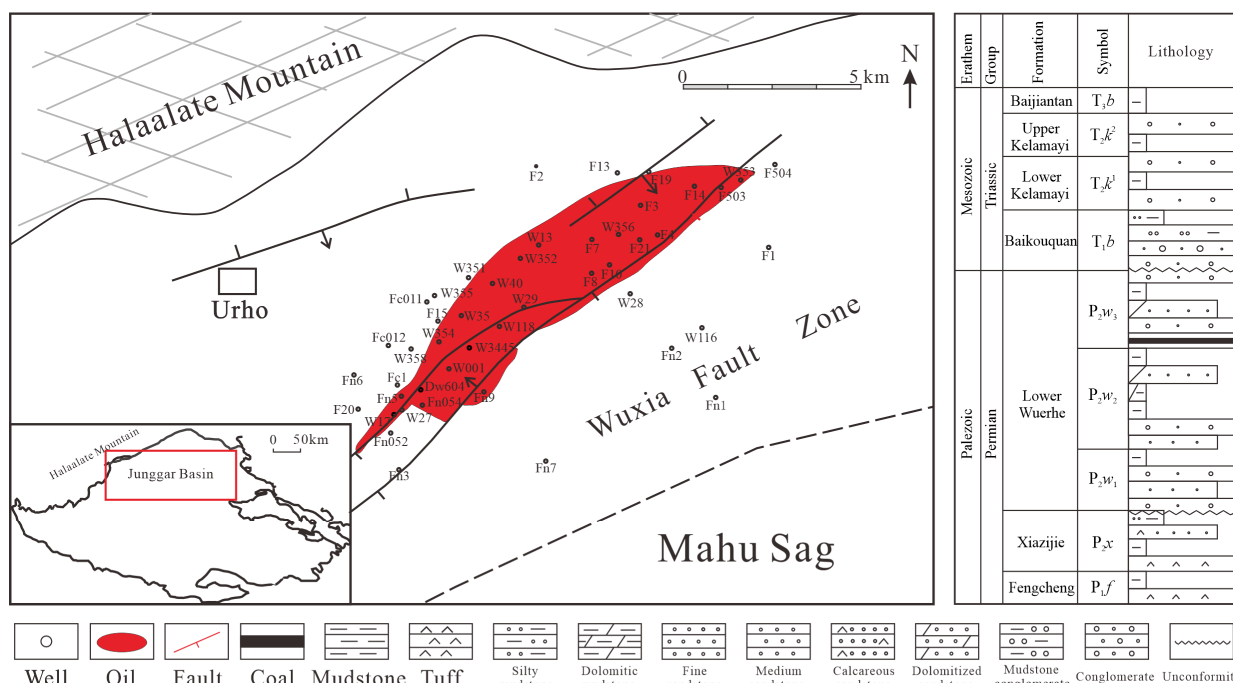


Figure 1. Structural Location of the Wuxia Fault Zone in the Junggar Basin and Stratigraphic Column

2. GEOLOGICAL BACKGROUND

The Junggar Basin is located in northwestern China, surrounded by the Tianshan Mountains, Altai Mountains, and the Tarim Basin. The basin is geologically complex and is a significant hydrocarbon resource area in China. The structural evolution of the basin has been mainly influenced by the Hercynian, Indosinian, and Yanshanian orogenies, which have shaped the overall structure of the basin and led to multiple stages of sedimentation.

During the Permian period, the southern part of the Wuxia Fault Zone experienced intense uplift and erosion, providing a substantial sediment supply that eventually led to the development of the fan delta depositional system. The tectonic setting of the Wuxia Fault Zone provided the structural framework for the formation of the fan delta front sedimentary system [11]. The tectonic activities not only influenced the direction and rate of sediment supply but also determined the spatial distribution of the depositional system.

The sediments in the Mahu Depression are primarily sourced from the northern and western mountainous regions, which, due to tectonic uplift during the Permian, generated substantial clastic material. These sediments were transported and deposited within the Mahu Depression through river and fan delta systems, forming a thick sequence of sedimentary layers with significant thickness variations [12]. The sediments of the Lower Wuerhe Formation were deposited under this depositional environment, with sediment transport and deposition primarily controlled by the northwest to southeast hydrodynamic forces.

The Lower Wuerhe Formation (P_{2w}) is an important stratigraphic unit of the Late Permian in the Junggar Basin, widely distributed along the northwestern margin of the basin. Based on lithology and sedimentary characteristics, the Lower Wuerhe Formation can be further subdivided into three main subunits: P_{2w1}, P_{2w2}, and P_{2w3}. These three subunits exhibit a progressive change in depositional environments and grain size from bottom to top, reflecting the evolutionary process of the depositional environment.

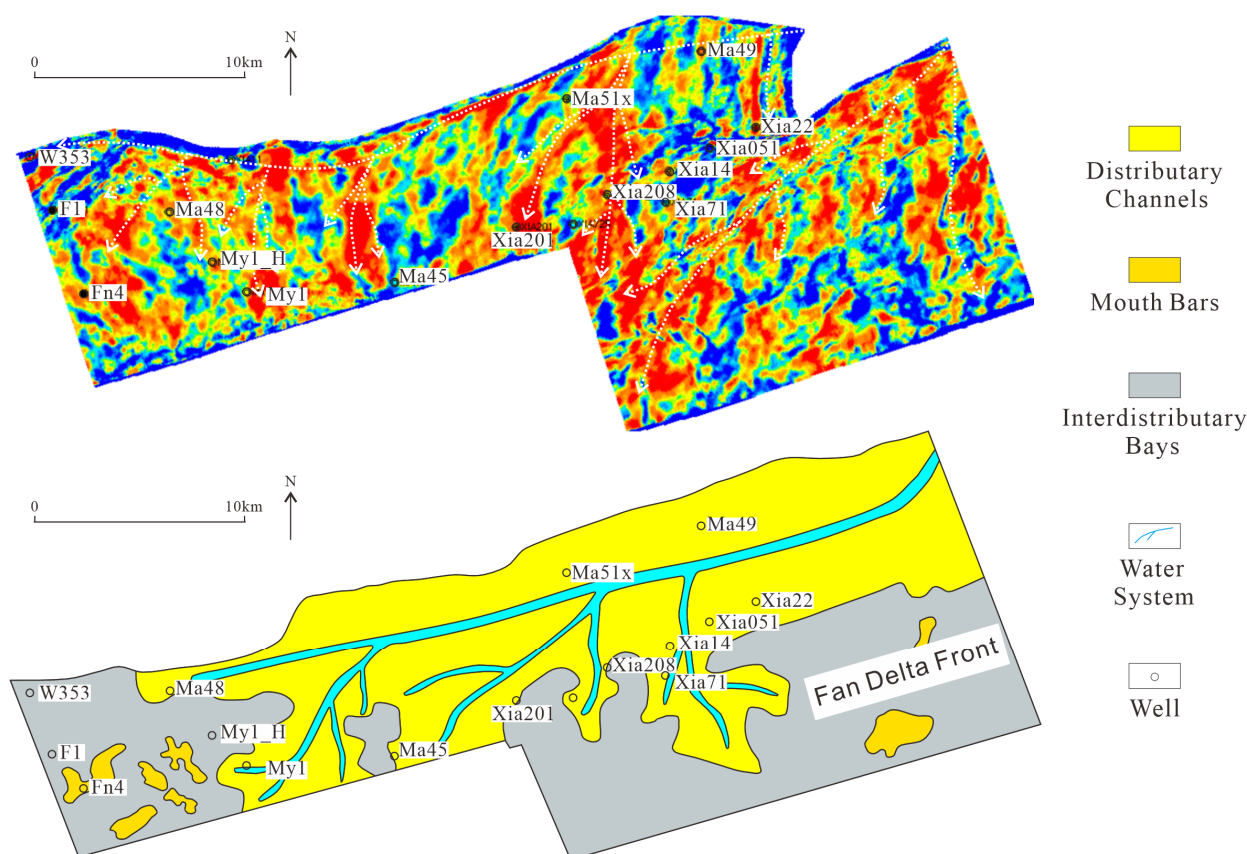


Figure 2. Subfacies of the Fan Delta Front of the Lower Wuerhe Formation in the Wuxia Area, Junggar Basin

3. SEDIMENTARY CHARACTERISTICS

Through a comprehensive analysis of cores, well logs, and seismic data from the Lower Wuerhe Formation in the Wuxia area, the following major sedimentary facies types have been identified:

Subaqueous Distributary Channel Facies: Lithological Characteristics: Mainly composed of medium to coarse-grained sandstones and conglomerates, commonly displaying cross-bedding, trough bedding, and planar bedding, indicating strong hydrodynamic conditions. Evident erosional bases with common filling structures, indicating repeated channel migration and infilling processes. Characterized by low gamma-ray (GR) values, high resistivity (RT), and high

acoustic time (AC) values, with log shapes typically bell-shaped or funnel-shaped. Mainly distributed in the central and northern parts of the study area, trending NW-SE, with thicknesses varying significantly, averaging 10-15 meters. Depositional Environment Interpretation: Represents the main sediment transport channel in the high-energy environment of the fan delta front, responsible for the primary sediment supply.

Mouth Bar Facie: Lithological Characteristics: Dominated by fine to medium-grained sandstones with minor muddy interlayers, commonly displaying horizontal and wavy bedding, indicating relatively stable depositional conditions. Well-developed bedding with grain sizes gradually fining upwards, reflecting the gradual decrease in hydrodynamic energy. Moderate to low GR values, moderate RT values, and high AC values, with log shapes typically box-shaped or bell-shaped. Mainly distributed downstream of the subaqueous distributary channels, forming fan-shaped expansions with relatively large areas, averaging 5-8 meters in thickness. Formed at the mouth of rivers entering the lake, where the decreasing hydrodynamic energy leads to rapid sediment accumulation, representing the main sandy bodies of the fan delta front.

Interdistributary Bay Facies: Lithological Characteristics: Mainly composed of siltstones and mudstones, with minor fine-grained sandstones, commonly displaying horizontal bedding and bioturbation structures: Parallel, continuous bedding with a high degree of bioturbation, reflecting a low-energy, relatively stable depositional environment. High GR values, low RT values, and low AC values, with log shapes typically finger-shaped or irregular. Distributed in low-lying areas between subaqueous distributary channels and mouth bars, with relatively small but widespread areas, typically 3-5 meters in thickness. Represents fine-grained deposits in low-energy environments of the fan delta front, often serving as areas of organic matter accumulation.

Sheet Sand Facies: Lithological Characteristics: Mainly composed of fine-grained sandstones and siltstones with gently sloping bedding, homogenous structures, and well-sorted and rounded grains. Continuous, thin bedding with wavy and horizontal bedding commonly observed. Moderate GR values, moderate RT values, and stable AC values, with log shapes typically flat. Widely distributed in the peripheral areas of the study area, forming extensive coverage with relatively uniform thicknesses, generally less than 3 meters. Formed in the distal, low-energy environment of the fan delta front, where sediments settle slowly from suspension.

4. RESERVOIR CHARACTERISTICS

4.1. Petrological Characteristics

Through detailed analysis of cores and thin sections, the petrological characteristics of the Lower Wuerhe Formation reservoirs have been identified as follows. Sandstones: Mainly composed of feldspathic sandstones and lithic arkoses, with feldspar content averaging 30-40%, lithic fragments about 20-30%, and quartz content about 30-40%. Conglomerates: Primarily clast-supported and matrix-supported types, with clasts mainly composed of granite, metamorphic rocks, and sedimentary rock fragments, ranging in size from 2 to 10 cm, with moderate sorting and rounding. Cement: Mainly calcareous, ferruginous, and siliceous cements, with varying degrees of cementation from weak to strong. In some areas, there is also argillaceous cementation. Secondary Minerals: Common clay minerals include chlorite, illite, and kaolinite, with some regions exhibiting secondary enlargement of calcite and quartz.

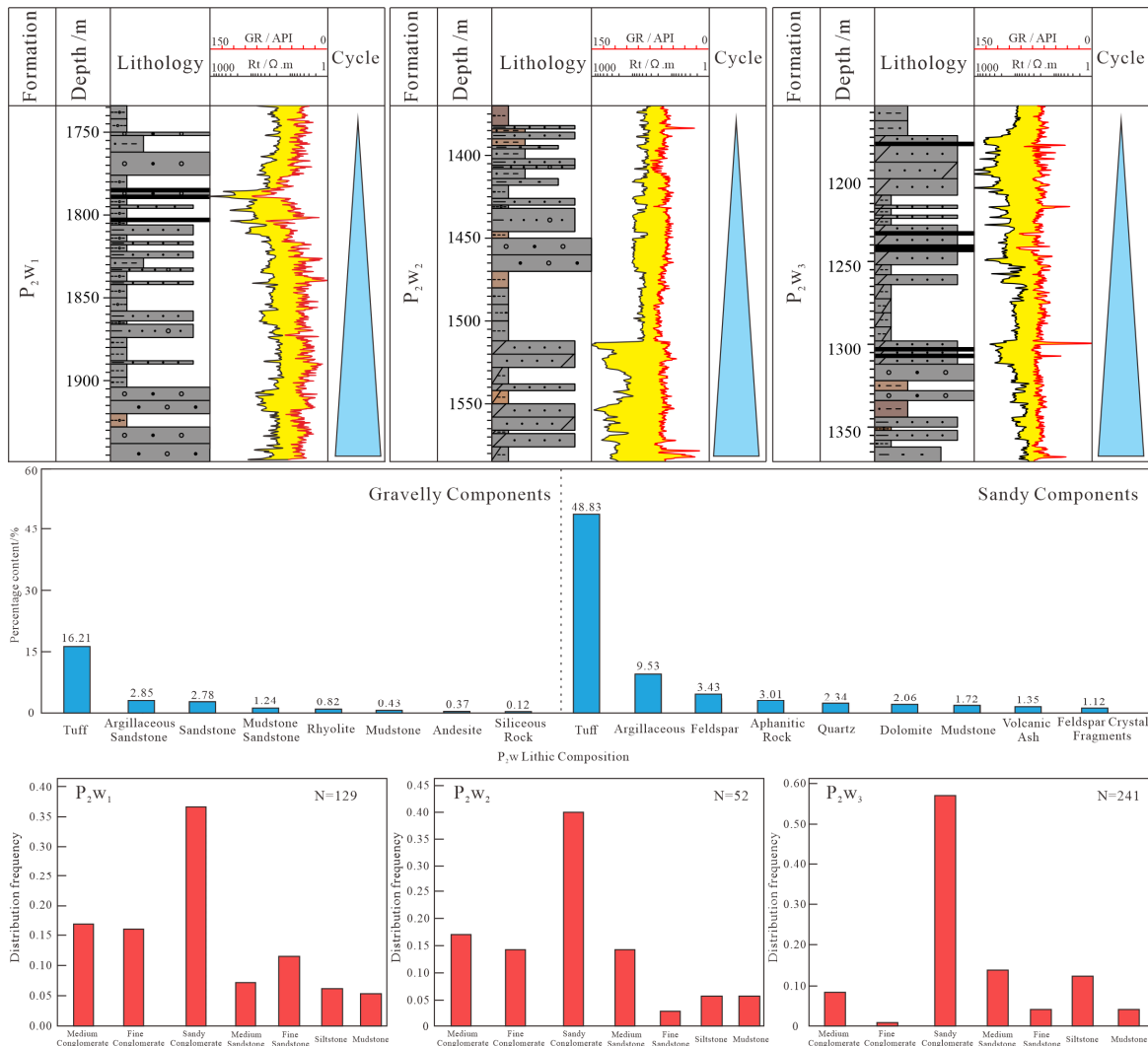


Figure 3. Reservoir Characteristics of the Lower Wuerhe Formation in the Wuxia Area, Junggar Basin

4.2. Structural Characteristics

Overall moderate sorting, with sandstones in the subaqueous distributary channel facies exhibiting better sorting, while conglomerates are less well-sorted. Sandstone grains range from sub-angular to sub-rounded, while conglomerate clasts exhibit poorer roundness, indicating relatively short transport distances.

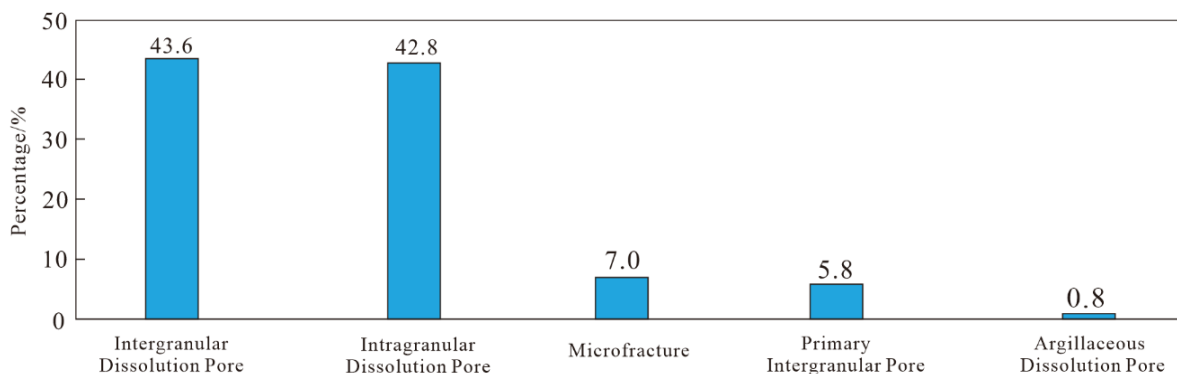


Figure 4. Distribution of Pore Types in the Lower Wuerhe Formation in the Wuxia Area, Junggar Basin

4.3. Pore Structure Characteristics

Using casting thin sections and scanning electron microscopy (SEM), the pore structure of the reservoirs has been studied in detail: Primary Pores: Mainly intergranular pores found in sandstones and conglomerates, with relatively regular shapes and good connectivity. Secondary Pores: Include intragranular dissolution pores, intergranular dissolution pores, and microfractures, with the development of secondary pores having a significant impact on reservoir properties.

Overall Porosity: Based on physical property testing, the porosity ranges from 10% to 25%, with an average porosity of about 18%. The highest porosity is found in the subaqueous distributary channel facies, averaging around 22%, followed by the mouth bar facies, while the interdistributary bay and sheet sand facies have lower porosity, averaging around 12%.

Overall Permeability: The permeability ranges from 50 mD to 1000 mD, with an average permeability of about 300 mD. Consistent with porosity distribution, the subaqueous distributary channel facies has the highest permeability, exceeding 500 mD, followed by the mouth bar facies with permeability ranging from 200-400 mD, and the other facies have lower permeability.

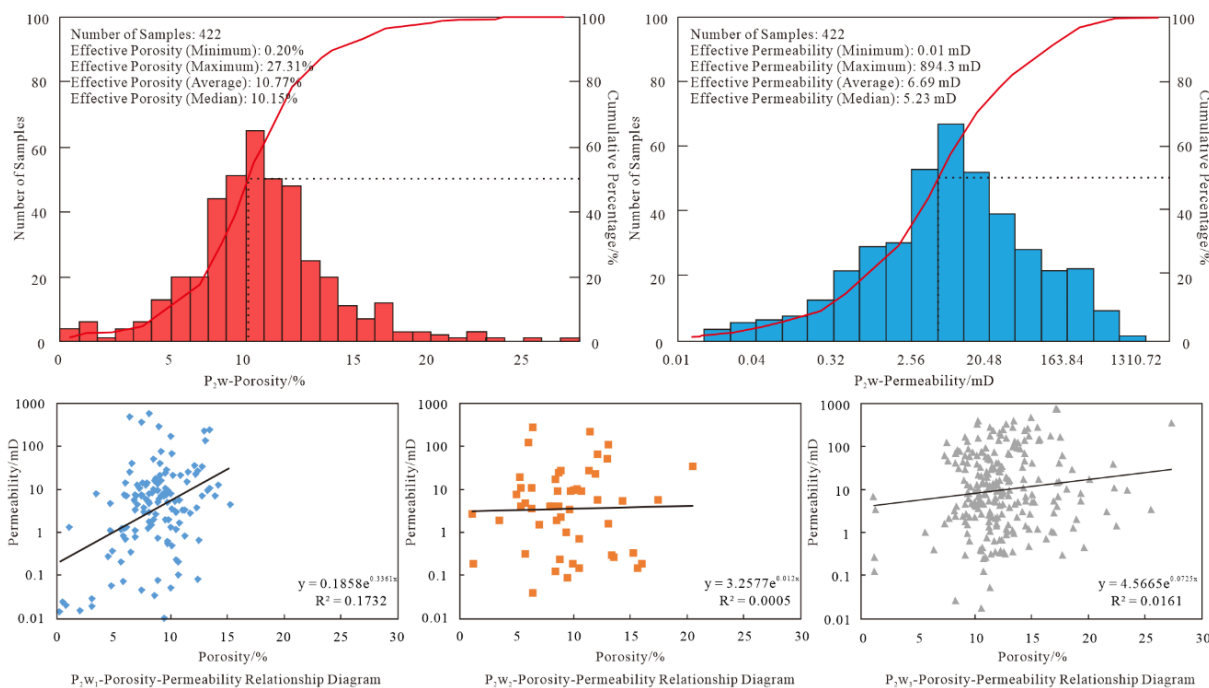


Figure 5. Porosity-Permeability Relationship of the Lower Wuerhe Formation in the Wuxia Area, Junggar Basin

5. CONTROLLING FACTORS ANALYSIS

5.1. Sedimentary Controlling Factors

Hydrodynamic conditions are key factors that determine sediment types, grain size distribution, and sedimentary facies development. In the fan delta front of the Wuxia area, hydrodynamic conditions directly influence the development of different sedimentary facies and their reservoir properties.

High-Energy Environment: In the subaqueous distributary channel facies, strong hydrodynamic conditions lead to coarse-grained sediment deposition, primarily composed of medium to coarse-grained sandstones and conglomerates, forming high-quality reservoirs.

Under high-energy conditions, sediments are rapidly transported and deposited through channels, resulting in high porosity and permeability reservoirs. Low-Energy Environment: The mouth bar and interdistributary bay facies form in relatively low-energy environments, with finer grain sizes, primarily consisting of fine-grained sandstones and mudstones. In low-energy conditions, sediments gradually accumulate, resulting in lower porosity and permeability. In particular, the interdistributary bay facies have higher clay content, further reducing reservoir quality.

5.2. Sediment Supply

The amount and variation of sediment supply are important factors influencing sediment characteristics. The sediment supply in the Wuxia area mainly originates from the uplifted region to the northwest, with different stages of sediment supply affecting sedimentary facies types and reservoir quality.

Abundant Sediment Supply: During the early deposition of the Lower Wuerhe Formation (P_2W_1), abundant sediment supply transported a large amount of coarse-grained material to the basin through subaqueous distributary channels, forming thick layers of conglomerates and sandstones that constitute high-quality reservoirs.

Decreased Sediment Supply: As sedimentation progressed, sediment supply gradually decreased, leading to finer-grained sediments, and the development of mouth bar and interdistributary bay facies. The reduction in sediment supply resulted in increased clay content, leading to decreased porosity and permeability in the reservoirs.

5.3. Sedimentation Rate

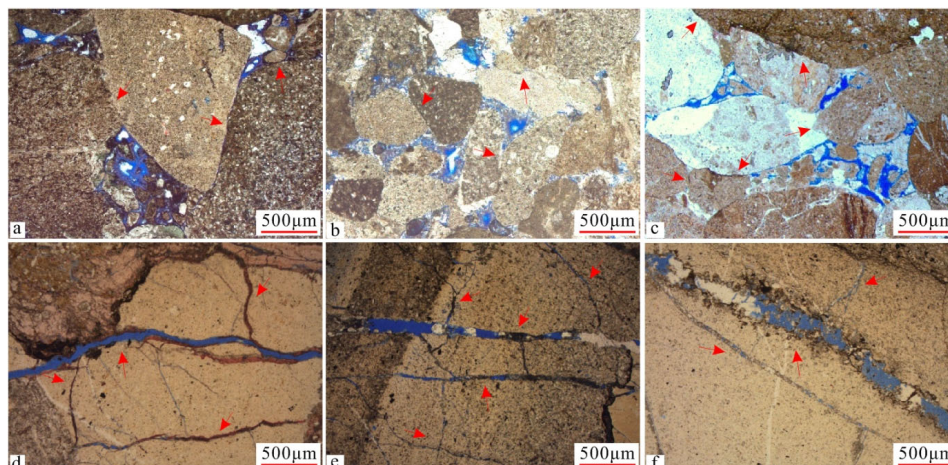
Sedimentation rate influences the degree of diagenetic processes and reservoir properties. Higher sedimentation rates result in less compaction and cementation during burial, preserving the original porosity of the reservoir.

High Sedimentation Rate: The subaqueous distributary channel and mouth bar facies have higher sedimentation rates, leading to rapid sediment accumulation, reducing the negative impacts of compaction and cementation, and preserving high porosity and permeability. **Low Sedimentation Rate:** The interdistributary bay and sheet sand facies have lower sedimentation rates, leading to more significant compaction during burial, resulting in reduced porosity and poor permeability.

5.4. Changes in Depositional Environment

Changes in the depositional environment, particularly the transition from progradation to retrogradation, significantly affect reservoir properties. The depositional environment of the Lower Wuerhe Formation in the Wuxia area experienced evident transgressive and regressive cycles, leading to alternating sedimentary facies. During the progradation stage, the depositional environment is dominated by high-energy subaqueous distributary channels and mouth bar facies, resulting in high-quality reservoirs. The rapid accumulation of sediments and channel migration form thick, high-quality reservoirs. During the retrogradation stage, the depositional environment gradually transitions to lower-energy interdistributary bay and sheet sand facies, resulting in decreased reservoir quality. Increased fine-grained sedimentation and clay content complicate pore structures and reduce permeability.

5.5. Diagenetic Controlling Factors



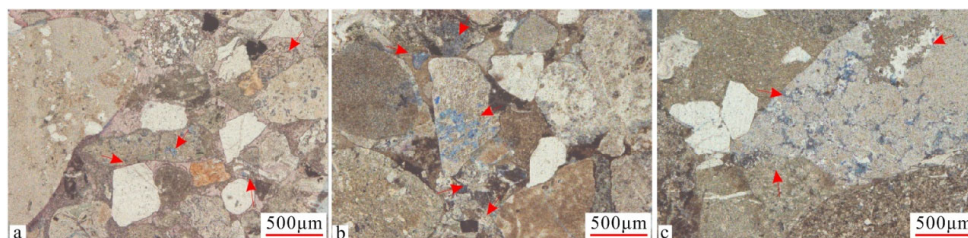
a: Line contact between grains, with developed residual intergranular pores, Well Fn1, 2758.58 m. b: Point and line contact between grains, with developed intergranular and intragranular dissolution pores, Well Fn1, 2537.01 m. c: Line-concave-convex contact between grains, with developed intergranular dissolution pores, Well Fn1, 2594.72 m. d: Microfractures developed between grains, showing fractured rigid particles, Well W41, 1694.22 m. e: Partially filled fractures developed between grains, showing fractured rigid particles, Well W41, 1716.14 m. f: Partially filled fractures developed between grains, showing fractured rigid particles, Well W41, 1715.64 m.

Figure 6. Microscopic Features of Compaction in the Conglomerate Reservoirs of the Lower Wuerhe Formation in the Wuxia Area, Junggar Basin

Compaction is one of the earliest diagenetic processes, significantly affecting pore structure in reservoirs. As sediments are buried, intergranular pores are compressed, leading to decreased porosity.

Degree of Compaction: The degree of compaction in the Lower Wuerhe Formation reservoirs increases with burial depth. The subaqueous distributary channel facies, with coarser grains, exhibit better resistance to compaction, preserving porosity, whereas the interdistributary bay facies, with higher clay content, experience stronger compaction, significantly reducing porosity.

Impact Analysis: Compaction primarily reduces primary porosity during early diagenesis, but at greater depths, it may also form microfractures, providing secondary migration pathways for hydrocarbons and improving reservoir permeability.

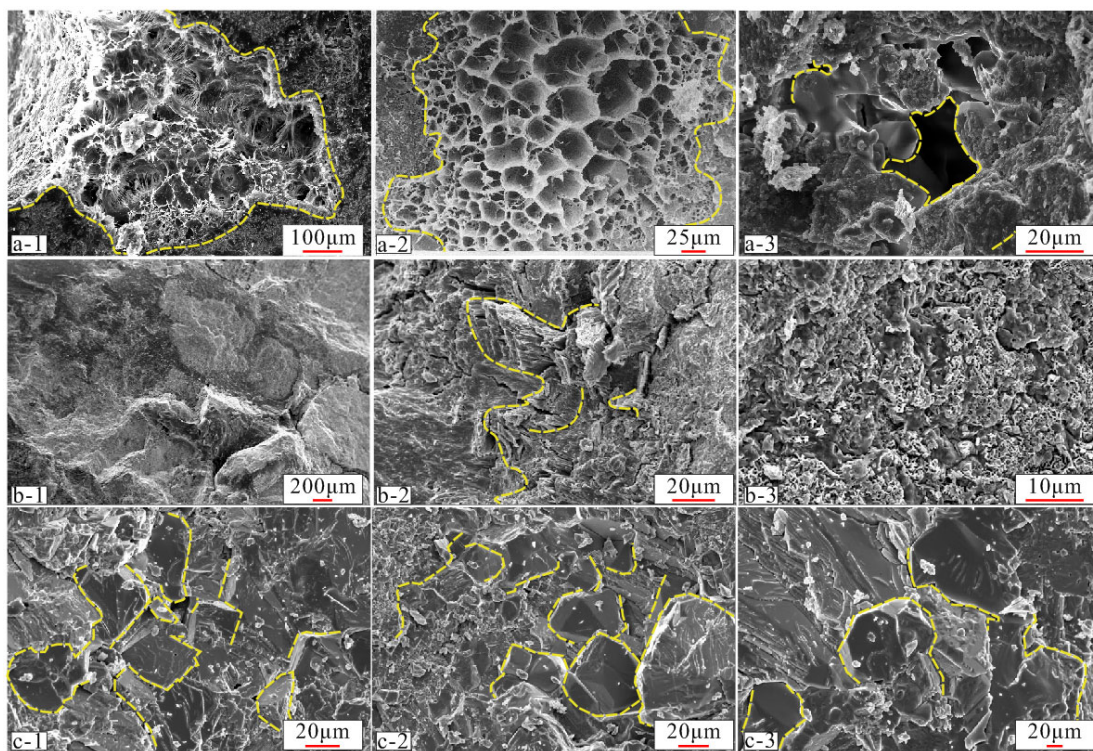


a: Matrix cementation between grains, with well-developed dissolution pores, Well Fn11, 2758.28 m. b: Point contact between grains, with developed intragranular dissolution pores, Well Fn11, 2764.80 m. c: Line contact between grains, with developed intragranular dissolution pores, Well Fn11, 2758.28 m.

Figure 7. Microscopic Features of Dissolution in the Reservoirs of the Lower Wuerhe Formation in the Wuxia Area, Junggar Basin

Dissolution is a key source of secondary porosity during diagenesis, typically occurring during the middle to late diagenetic stages due to organic acids or CO₂ in groundwater. In the Lower Wuerhe Formation reservoirs, dissolution primarily includes intragranular and intergranular dissolution. The dissolution of feldspar and lithic fragments forms significant secondary pores, greatly enhancing reservoir porosity and permeability. The occurrence of dissolution is influenced by rock type, pore fluid composition, and burial depth. Dissolution is well-developed in the subaqueous distributary channel and mouth bar facies, forming numerous secondary pores and significantly improving reservoir quality.

Cementation has a dual impact on reservoir pore structure during diagenesis. Moderate cementation can enhance reservoir stability, while excessive cementation can block pores, reducing reservoir permeability. Types of Cementation: The main types of cements in the Lower Wuerhe Formation reservoirs include calcareous, siliceous, and ferruginous cements. Calcareous cements are common in the mouth bar and interdistributary bay facies, while siliceous cements are more prevalent in the subaqueous distributary channel facies. The impact of cementation on reservoir properties varies significantly across different sedimentary facies. Moderate siliceous cementation in the subaqueous distributary channel facies helps maintain high permeability, while strong calcareous cementation in the mouth bar facies reduces permeability.



a-1: Fibrous illite, showing intercrystalline pores formed by feldspar alteration, Well Fn7, 2652.31 m. a-2: Honeycomb-like illite-smectite mixed-layer cement, Well Fn7, 2594.72 m. a-3: Granular quartz crystals, showing dissolution pores, Well Fn7, 2544.27 m. b-1: Irregular illite-smectite mixed-layer minerals on the grain surface, Well W351, 1824.30 m. b-2: Dissolution of analcime grains, Well W351, 1824.30 m. b-3: Vermicular kaolinite, Well W351, 1824.30 m. c-1 to c-3: Zeolite minerals filling intergranular spaces, with underdeveloped pores, Well W351, 2148.55 m.

Figure 8. Microscopic Features of Dissolution in the Reservoirs of the Lower Wuerhe Formation in the Wuxia Area, Junggar Basin

Pressure solution typically occurs during deep burial, negatively affecting porosity and permeability, but it may also form microfractures that enhance permeability.

In the Lower Wuerhe Formation reservoirs, pressure solution is often observed as grain-to-grain dissolution lines and stylolites, leading to further reduction in primary porosity. Although pressure solution generally reduces porosity, in some regions, microfractures formed by pressure solution can serve as pathways for hydrocarbon migration, enhancing reservoir permeability.

5.6. Comprehensive Impact Analysis

Sedimentation establishes the initial porosity and pore structure of the reservoirs, while diagenetic processes further modify reservoir porosity and permeability. In the Lower Wuerhe Formation, the spatial distribution of sedimentary facies controls the types and extents of diagenetic processes, ultimately leading to different reservoir types:

High-Quality Reservoirs: The subaqueous distributary channel facies, with favorable sedimentary conditions and moderate diagenetic modification, preserve high porosity and permeability.

Medium-Quality Reservoirs: The mouth bar facies, although deposited under good sedimentary conditions, experience stronger cementation, leading to reduced reservoir quality.

Low-Quality Reservoirs: The interdistributary bay and sheet sand facies, due to both sedimentary conditions and diagenetic processes, exhibit poor porosity and permeability.

Analyzing the impact of sedimentary and diagenetic controlling factors on reservoirs provides insights for hydrocarbon exploration: **Identification of Favorable Reservoirs:** Prioritize exploration in subaqueous distributary channel facies, which have high porosity and permeability, making them prime targets for hydrocarbon exploration. **Prediction of Diagenetic Processes:** In hydrocarbon exploration, it is essential to consider the impact of diagenetic processes on reservoir properties, particularly in deep reservoirs, where compaction and dissolution play significant roles. **Comprehensive Exploration Strategy:** Combine sedimentary facies analysis with diagenetic studies to develop more precise exploration strategies, improving the accuracy of reservoir prediction and optimizing well placement.

6. CONCLUSION

1. **Sedimentary Characteristics:** The fan delta front sedimentary system in the Lower Wuerhe Formation of the Wuxia area includes subaqueous distributary channel facies, mouth bar facies, interdistributary bay facies, and sheet sand facies. Among these, the subaqueous distributary channel facies is the primary reservoir type, characterized by high porosity and permeability. The reservoirs are mainly composed of primary intergranular pores and secondary dissolution pores. Diagenetic processes, especially dissolution, significantly enhance porosity and permeability, while compaction and cementation negatively impact reservoir quality.

2. **Identification of High-Quality Reservoirs:** Subaqueous distributary channel facies should be the primary target for exploration. Combined with diagenetic process analysis, reservoir prediction accuracy can be improved. It is recommended to integrate well logs, seismic inversion, and core analysis to construct detailed reservoir geological models, optimizing drilling design and development plans.

3. **Deepening Understanding of Sedimentary Patterns:** Future studies should expand to broader regional comparisons, focusing on the relationship between tectonic activity and sedimentary facies distribution.

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