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Sedimentary Analysis of the Cretaceous Yingcheng Formation–Denglouku Formation in Shuangcheng Area, Northern Songliao Basin

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Abstract. Shallow oil and gas resources in the northeastern region have been preliminarily explored. However, with sustained economic growth driving increasing energy demands, deep oil and gas exploration has gradually become a new focal point. The Denglouku oil reservoir in the Shuangcheng South area of the Songliao Basin is a recently discovered significant deep formation, yet systematic fundamental geological research in this region remains lacking. This study focuses on the third member of the Cretaceous Yingcheng Formation and the two members of the Denglouku Formation in the Shuangcheng area of the northern Songliao Basin. Through single-well facies identification, cross-well profile analysis, and other comprehensive research methods, a five-level sequence stratigraphic framework was established. Three major sedimentary systems were identified: shallow-water delta, braided river, and fan delta, with further subdivisions into subfacies and microfacies. The study clarifies sandstone distribution patterns and the sedimentary facies-reservoir response relationship, providing a geological basis for oil and gas exploration and development. Favorable hydrocarbon accumulation factors are summarized, and exploration recommendations are proposed.

Keywords: Sedimentary facies, sequence stratigraphy, Shuangcheng area, lithofacies paleogeography

1. Introduction

As a crucial energy production base for oil and natural gas in China, the northeastern region has undergone half a century of exploration and development, leading to the preliminary confirmation of shallow oil and gas resources. However, with the growing energy demands driven by economic development, deep oil and gas exploration has become a new pathway for sustaining and increasing production in this region. Located in northeastern China, the Songliao Basin is rich in oil and gas resources and holds an extremely important position among China's continental petroliferous basins. In recent years, energy authorities at various levels have conducted targeted exploration and research on deep formations in several major sag zones of the northeastern region, leading to the discovery of hundreds of millions of tons of oil and gas reserves in the eastern Songliao Basin. However, the Denglouku oil reservoir in the Shuangcheng South area of the northern Songliao Basin is a newly

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discovered formation currently in the rolling evaluation and development stage. Systematic studies on its sedimentary background, depositional environment, provenance direction, and stratigraphic correlation standards have yet to be conducted, making it urgent to carry out relevant research to provide foundational support for deep exploration.

In the Shuangcheng area of northern Songliao, an oil-bearing assemblage has been discovered, with the Yingcheng Formation serving as the source rock and the Denglouku Formation sandstones acting as the primary reservoir, marking a breakthrough in petroleum exploration [1]. Currently, there remains insufficient understanding regarding the fluvial-shallow water delta sedimentary facies, sedimentary characteristics of channel sand bodies, and their distribution patterns in the Fuyu oil layer of the study area [2]. High-resolution sequence stratigraphy serves as a critical approach for clarifying the development patterns of reservoir sand bodies and identifying favorable reservoirs. Previously, only a limited number of scholars have researched the Yingcheng Formation source rocks and the Yingcheng-Denglouku formations. For instance, Sun Lidong et al. utilized TOC testing, rock pyrolysis, and other analytical methods to demonstrate that the Yingcheng Formation in the Shuangcheng area develops high-quality organic-rich source rocks, while also predicting the thickness and distribution of these source rocks through 3D seismic data interpretation [3]. Liu Chao et al. reconstructed the depositional environment of source rocks through core observation and trace element analysis, and further evaluated their hydrocarbon generation and expulsion potential using basin modeling techniques [4]; Zeng Huasen et al. conducted biomarker studies and confirmed genetic relationships between crude oils in the Shuangcheng area and the source rocks of the Yingcheng Formation[1].

This study focuses on the Shuangcheng area in the northern Songliao Basin as the research region, with the Cretaceous Yingcheng-Denglouku formations as the target strata. Building upon previous research, this paper systematically investigates the provenance direction, sequence framework, and planar distribution of sedimentary microfacies in the study area by integrating geological, well logging, core data, and laboratory analyses. The findings provide a robust geological foundation for future cost-effective exploration and development, summarize favorable factors for petroleum accumulation, and offer recommendations for subsequent exploration activities.

2. Geological overview

This study focuses on the Shuangcheng Sag, a well-explored area with abundant drilling and analytical test data where exploration breakthroughs have been achieved. By the end of the Yingcheng Formation deposition, the area entered a fault-depression transition period, leading to extensive sedimentation of the Yingcheng-4 Member, Denglouku Formation, and Quantou Formation (Figure 1a). In the Shuangcheng area, the dark mudstones of the Yingcheng-4 Member represent high-quality source rocks. The overlying Denglouku Formation, widely developed as a reservoir interval, has recently become a key exploration target [5].

The Yingcheng Formation essentially covers the entire study area, primarily consisting of the First Member (Y1) and Fourth Member (Y4) from bottom to top. The Y1 Member is predominantly composed of volcanic rocks with complex lithology, mainly acidic eruptive rocks interbedded with variable-thickness layers of sandy conglomerate, mudstone, and black coal seams. The formation thickness typically ranges from 100m to 300m.In the Shuangcheng area, the Y4 Member exhibits thickness variations from 60m to 220m in the southern trough, reaching its maximum thickness (270m) at the subsidence center of the southern trough in Shuangcheng Sag. The thickness decreases rapidly eastward, showing an overall distribution pattern with maximum thickness along the axis of

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the southern trough in Shuangcheng Sag, thinning towards both sides. The lithologic assemblage consists of dark mudstone intercalated with sandy conglomerate. The trough mainly develops shore-shallow lacustrine facies, while fan delta facies dominates the marginal zones.[6]

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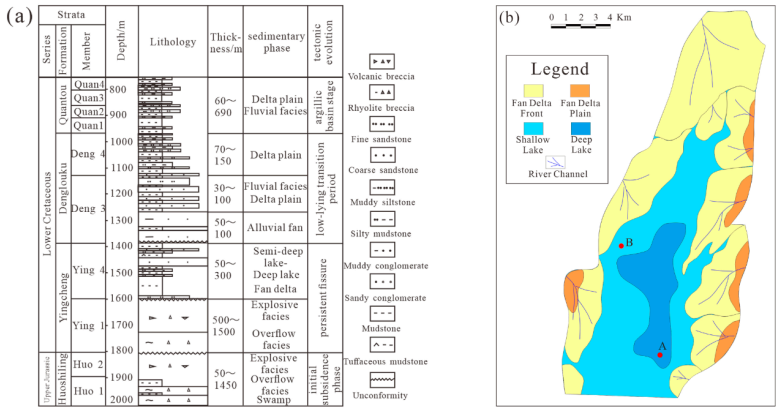

Figure 1: (a) Lithologic column of the study area; (b) Provenance directions and sedimentary facies map of the study area

3. Research methodology

The present study was conducted through systematic analysis of data from 18 wells in the study area, incorporating multiple analytical approaches. For each well, detailed sedimentary facies analysis was performed along with stratigraphic division and correlation, with particular attention to identifying key marker beds. The inter-well correlation played a crucial role in establishing a unified regional stratigraphic framework through comprehensive analysis of multiple well logging datasets. This approach effectively revealed lateral variations in formation thickness, lithology and sedimentary facies, while providing critical insights into reservoir distribution characteristics and heterogeneity patterns.

Following core facies analysis and depositional environment interpretation, detailed sedimentary microfacies and subfacies classification was conducted for individual wells, which was subsequently integrated through inter-well facies analysis to accurately identify depositional environments across the study area. Based on the sedimentary environment interpretation of all 18 wells, sandbody thickness maps and sand-to-shale ratio maps were generated for five target intervals to characterize the spatial distribution patterns of sandbodies. Additionally, sedimentary microfacies distribution maps were created to analyze the spatial characteristics of sedimentary facies. The reservoir

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potential was evaluated through integrated analysis of porosity and permeability data across all five target intervals.

A technical note regarding ResForm software application: Well location data input requires six-digit integer format, achieved by adding "420" before x-coordinates and "42" before y-coordinates. While this transformation enables successful data input, users should be aware it may introduce positional deviations in the output.

4. Data analysis

4.1. Sedimentary microfacies and sandbody distribution

Lithofacies provide critical evidence for determining sediment provenance, depositional dynamics, and paleoenvironmental reconstruction through their lithological characteristics and sedimentary structures/textures. They also form the basis for classifying sedimentary microfacies. As a more refined classification than sedimentary facies, microfacies represents assemblages of sedimentary rock bodies formed under localized depositional environments within a given sedimentary system. These assemblages reflect subtle variations in topography, water depth, and hydrodynamic conditions during different depositional stages. Consequently, microfacies analysis serves as a fundamental reference for interpreting sedimentary facies and reconstructing depositional environments[8].

The study area primarily develops sedimentary microfacies, including underwater distributary channels, interdistributary bays, channel bars, and others. These microfacies combine to form subfacies such as delta plains, fluvial channels, deep lacustrine, and semi-deep lacustrine environments, belonging to braided river, shallow-water delta, and lacustrine depositional systems. Each microfacies exhibits distinct lithological association characteristics (Study on High-Resolution Sequence Stratigraphic Division, Correlation and Genetic Controls of Cretaceous-Paleogene in Bayannaoer Sag)[9,10] .

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4.1.1. Single-well facies analysis

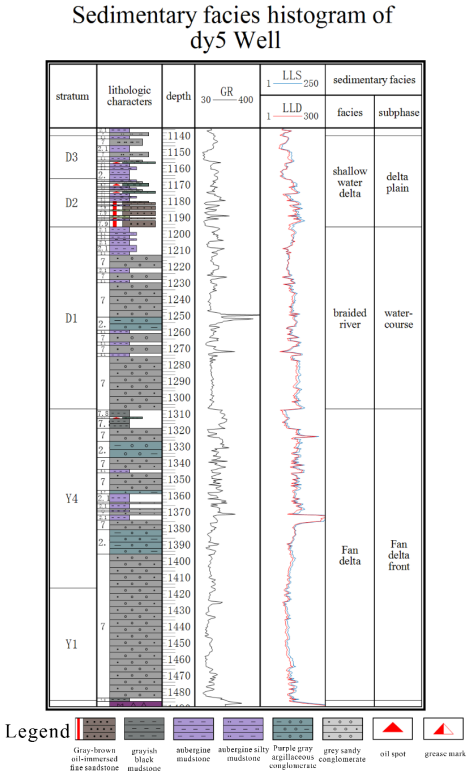

Figure 2: Lithologic column of well DY5

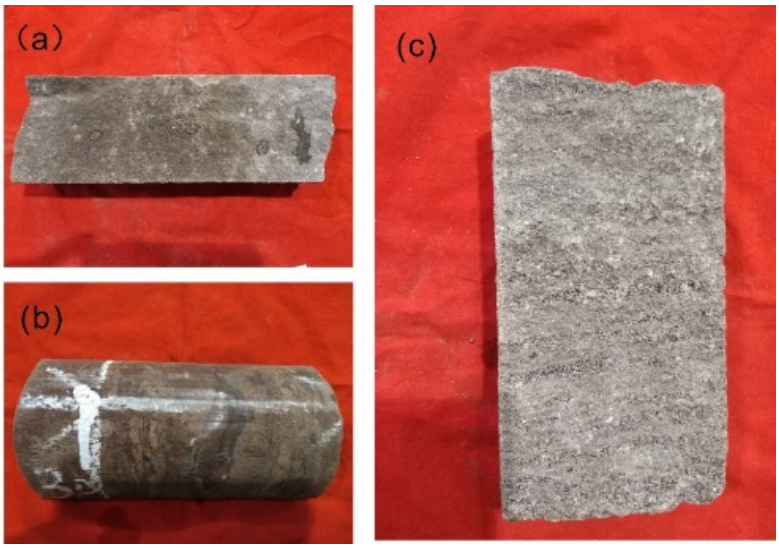

Figure 3: Core samples from well DY5: (a) Oil staining at 1190.8 m depth; (b) Parallel bedding in the upper section and trough cross-bedding in the lower section at 1193.5 m depth;(c) Bioturbation and wormholes at 1197.9 m depth

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Figure 2 presents a comprehensive analysis of Well DY5. Located in the central part of the study area, this cored well primarily develops the Denglouku and Yingcheng Formations, with oil staining observed between 1170-1195 m (Figure 2).

The upper section of the Denglouku Formation is dominated by grayish-brown oil-stained fine sandstones (Figure 3a), transitioning upward into interbedded purplish-red mudstones and gray argillaceous siltstones with cross-bedding and parallel bedding structures (Figure 3b). This interval mainly develops interdistributary, distributary channel, and natural levee microfacies, collectively forming the delta plain subfacies of a shallow-water delta system.

The lower Denglouku Formation consists principally of gray sandy conglomerates, grading upward into purplish-red silty mudstones exhibiting bioturbation and wormhole structures (Figure 3c). Channel bar and channel lag microfacies dominate this section, with floodplain microfacies appearing in the uppermost layers, together constituting the channel subfacies of a braided river system.

The YingchengFormation is characterized by gray sandy conglomerates, developing underwater distributary channels, interdistributary areas, and mouth bars. These components form the delta front subfacies of a fan delta depositional system.

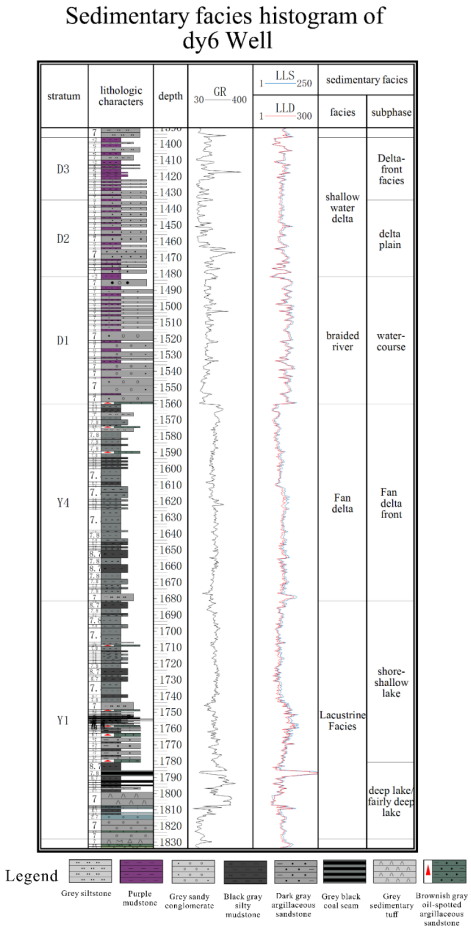

Figure 4: Lithologic column of Well DY6

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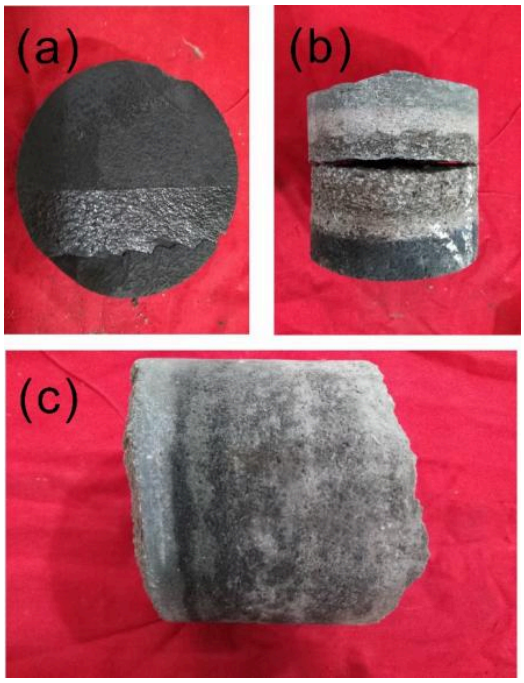

Figure 5: Core characteristics from Well DY5 (a) Grayish-black mudstone with oil films at 1751.58 m depth;(b) Grayish-black mudstone with organic pores at 1754.12–1754.29 m and 1755.08 m depths;(c) Gray oil-stained siltstone at 1755.27 m depth

Figure 4 and Figure 5 presents a comprehensive analysis of Well DY6. Located on the northeastern side of the study area, Well DY6 is a cored well. As shown in Figure 5, the well primarily develops the Denglouku Formation and the Yingcheng Formation.

The Denglouku Formation consists mainly of interbedded gray fine-grained sandstones and dark purple mudstones. The upper section is predominantly composed of subaqueous distributary channels, forming the delta front subfacies of a shallow-water delta. The middle section mainly features distributary channels and mouth bars, constituting the delta plain subfacies of a shallow-water delta. The lower section is characterized by channel bars and channel lag microfacies, forming the channel subfacies of a braided river.

In the upper part of the Yingcheng Formation, the lithology is primarily gray-black mudstone (Figure 5a), with sheet sands and subaqueous distributary channels, forming the fan delta front subfacies of a fan delta. The upper part also includes mud flats and beach bars, representing the shore-shallow lake subfacies of a lacustrine environment. The lower part of the Yingcheng Formation consists of turbidites and mud flats, forming the deep to semi-deep lake subfacies of a lacustrine environment. Organic pores are observed in the dark gray mudstone at 1755.08 m (Figure 5b), and oil-stained gray siltstone is present at 1755.27 m (Figure 5c).

4.1.2. Correlation of well sections

Based on single-well facies analysis, a correlation of well sections was conducted. As shown in Figure 6, the A-A' section of Wells DY18-DY13-DY14-DY6 in the study area represents a proximal-to-distal profile along the sediment source direction, trending approximately EW. The strata exhibit a "thinner in the west, thicker in the east" characteristic, with the thickest deposition reaching about 1828 m in Well DY7 in the eastern part, while Well DY12 has a relatively thinner deposition of about 1272 m.

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In the near-EW-oriented A-A' section, Well DY81, located near the sediment source area, predominantly developed a delta plain depositional environment of a shallow-water delta during the deposition of the second and third members of the Denglouku Formation. In the early stage of the first member of the Denglouku Formation, a approximately 30 m thick gray sandy conglomerate was deposited, mainly representing a channel bar depositional environment of a braided river. This indicates that from the early depositional stage of the first member to the second and third members of the Denglouku Formation, the sandbody depositional environment transitioned from a delta plain of a shallow-water delta to a channel, reflecting a shift in the regional water environment from shallow to deep.

The upper section of Well DY6 still exhibits delta plain and channel subfacies, but the Yingcheng Formation abruptly transitions to shore-shallow lake and deep to semi-deep lake subfacies, indicating a dramatic change in the depositional environment. The overall grain size of the sandbody coarsens upward, suggesting a gradual strengthening of hydrodynamic conditions in the study area. The sandbodies also exhibit good lateral connectivity.

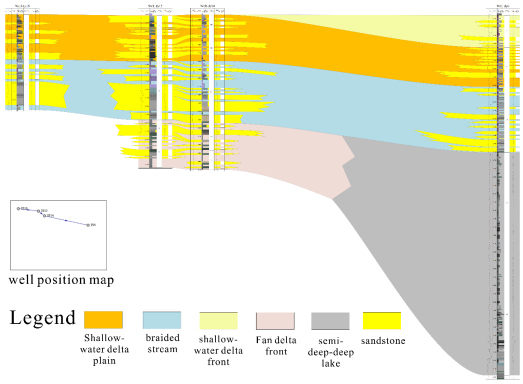

Figure 6: Shows the A-A' correlation profile along the paleo-transport direction (proximal-to-distal trend)

To further investigate the lateral distribution patterns of the depositional systems in the northern Shuangcheng area, a NE-SW trending B-B' well-tie cross-section (Figure 7) was constructed using Wells DY10-DY11-DY2-DY4-DY13.

This profile reveals that during the Yingcheng-Denglouku depositional period, the study area developed a sedimentary system transitioning from shallow-water delta to braided river and finally to delta front from north to south. The B-B' section is located on the northwestern side of the study area and cuts across the sediment transport direction.

The analysis demonstrates that braided channels in both shallow-water delta plain and fan delta plain settings represent the most favorable facies zones for sandbody development.

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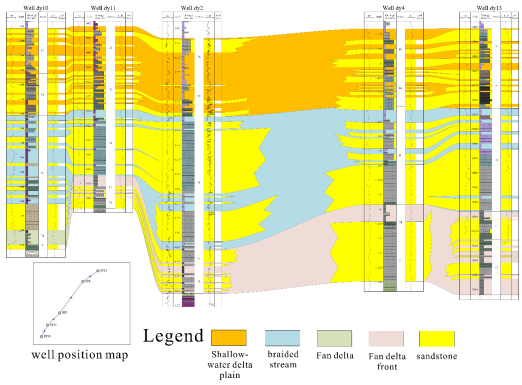

Figure 7: Displays the B-B' correlation profile transverse to the paleo-transport direction (across the sediment source trend)

4.2. Sandbody thickness distribution and planar facies architecture

4.2.1. Sandbody thickness and sand-to-mud ratio maps

An in-depth analysis of sandbody thickness and sand-to-mud ratio maps systematically reveals the spatial distribution characteristics of sandbodies. In the Denglouku Formation Member 3, sandbody thickness in shallow-water delta plain channels can reach up to 40 m with sand-to-mud ratios exceeding 0.5, displaying a distinctive anastomosing (net-like) distribution pattern where sandbodies are predominantly concentrated in the plain area while gradually thinning toward the delta front. The distribution in Member 2 shows similar characteristics, with sandbodies mainly developed in shallow-water delta plain channels, reaching maximum thicknesses of 80 m and sand-to-mud ratios greater than 0.7, exhibiting a well-connected belt-like distribution with excellent continuity (Figure 8).

Member 1 of the Denglouku Formation demonstrates moderate sandbody thickness with relatively uniform sand-to-mud ratios, presenting a sheet-like distribution that reflects the migratory nature of distributary channels in a braided river delta front environment. In the Yingcheng Formation, braided channel sandbodies in the fan delta plain also exhibit high sand-to-mud ratios (>0.7). However, similar to the Denglouku Formation, these sandbodies show significant thickness reduction toward the lacustrine basin direction, demonstrating strong heterogeneity in their distribution patterns.

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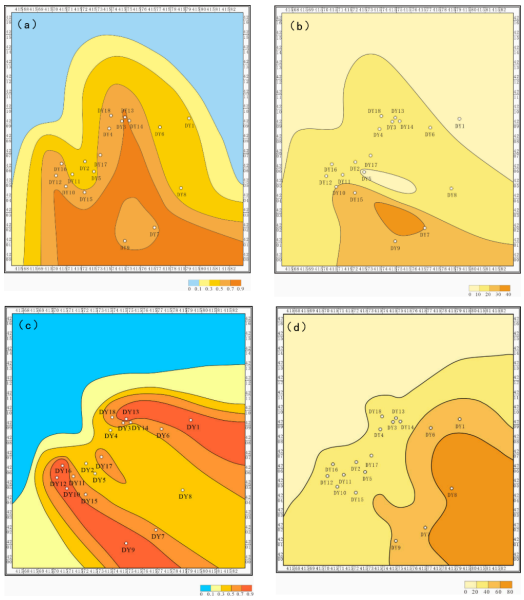

Figure 8: (a) Sand-to-mud ratio map of D3 (Denglouku Formation Member 3);(b) Sand thickness map of D3;(c) Sand-to-mud ratio map of D2 (Denglouku Formation Member 2);(d) Sand thickness map of D2

4.2.2. Planar distribution characteristics of sedimentary microfacies

Analysis of sedimentary microfacies distribution maps reveals distinct depositional environments and their spatial variations. The Denglouku Formation Members 3 and 2 are dominated by shallow-water delta plain deposits, characterized by extensively interconnected channels forming complex anastomosing networks, indicative of abundant sediment supply and strong hydrodynamic conditions. In contrast, Member 1 of the Denglouku Formation represents a braided river delta front environment, with relatively uniform sandbody distribution reflecting moderate hydrodynamic energy(Figure 9).

The Yingcheng Formation exhibits typical fan delta deposition, developing braided channels along with a fan delta plain and front facies. The dendritic channel patterns progressively extend basinward, demonstrating significant provenance control on sedimentation. Distally, these deposits transition into shore-shallow lake to semi-deep lake facies within the lacustrine basin. The spatial organization of these microfacies highlights: (1) increasing channel network complexity from Member 1 to Member 3, (2) pronounced provenance influence in the Yingcheng Formation, and (3) well-defined proximal-to-distal facies transitions that record variations in hydrodynamic energy across the depositional system. These patterns provide critical insights into the paleogeographic evolution and sedimentary processes of the study area.

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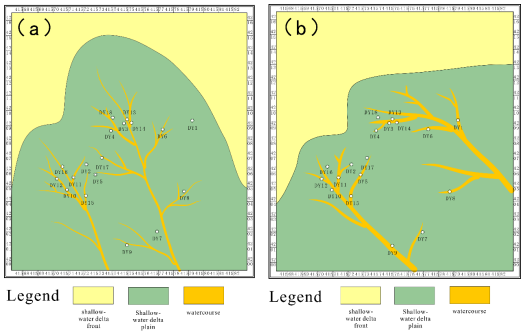

Figure 9: (a) Sedimentary facies map of D3 (Denglouku Formation Member 3);(b) Sedimentary facies map of D2 (Denglouku Formation Member 2)

4.3. Comprehensive analysis of reservoir porosity

The reservoir properties exhibit significant stratigraphic variations, with the Denglouku Formation Members 3 and 2 demonstrating optimal reservoir characteristics, showing medium-to-high porosity and permeability with excellent pore-throat connectivity, making them the most favorable intervals for hydrocarbon accumulation and flow. In contrast, Member 1 of the Denglouku Formation presents moderate reservoir quality, dominated by medium porosity and permeability, indicating acceptable but less ideal storage and flow capacity.

The Yingcheng Formation displays notably poorer reservoir performance, characterized by low porosity and permeability values that significantly restrict fluid storage and migration, resulting in substantial development challenges. These porosity-permeability trends reveal a clear quality deterioration from the Denglouku to Yingcheng formations, directly influencing their hydrocarbon potential and recovery feasibility. The analysis underscores the critical importance of pore structure characteristics in determining reservoir productivity, particularly highlighting the superior fluid flow properties of D3/D2 units compared to the tight nature of Yingcheng reservoirs that may require specialized stimulation techniques for economic production(Figure 10 and Figure 11)..

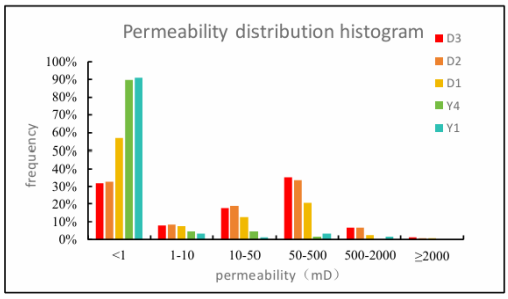

Figure 10: Permeability distribution histogram

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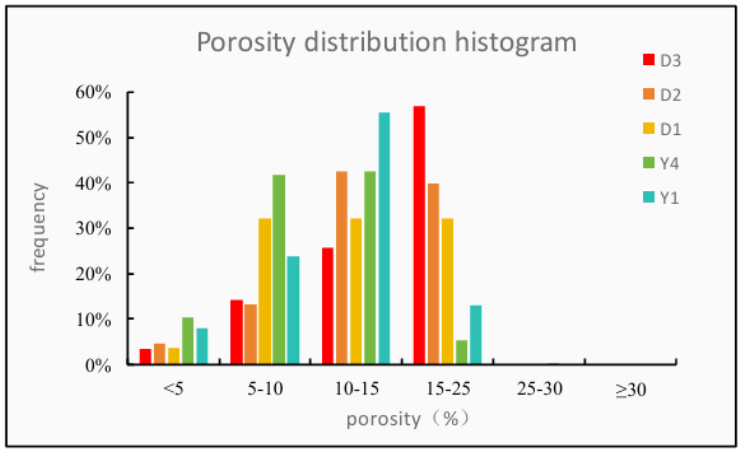

Figure 11: Porosity distribution histogram

The porosity distribution displays a dominant medium-to-high range, with peak values reaching 23.9%, confirming excellent storage capacity. Permeability distribution shows greater dispersion, yet 42.86% of samples fall within medium-to-high permeability ranges. A positive correlation is observed where permeability systematically increases with rising porosity, indicating well-connected pore networks (Figure 12, Figure 13 and Figure 14).

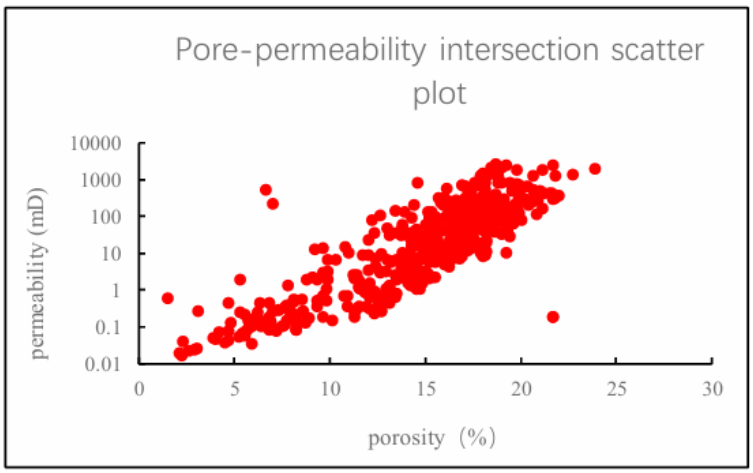

Figure 12: Pore-permeability intersection scatter plot

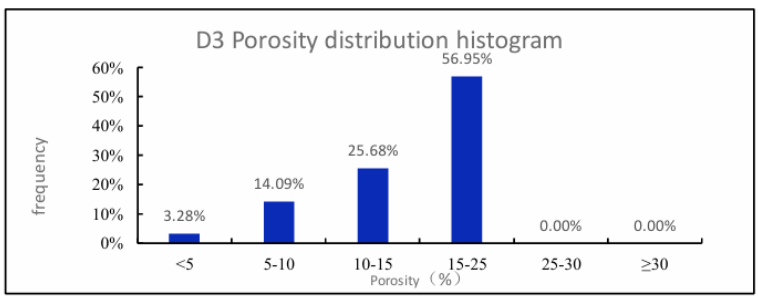

Figure 13: D3 Porosity distribution histogram

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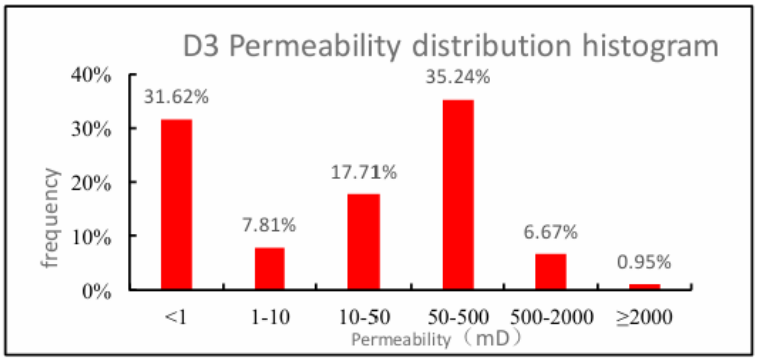

Figure 14: D3 Permeability distribution histogram

5. Conclusions

Through comprehensive analyses including single-well facies identification, interwell correlation, sandbody thickness distribution, planar microfacies mapping, and reservoir porosity evaluation of the Cretaceous Yingcheng-Denglouku formations in the Shuangcheng area of northern Songliao Basin, this study provides robust geological foundations for cost-effective exploration and development. Key findings on hydrocarbon accumulation favorable factors and recommendations for future exploration are summarized as follows:

A five-order sequence stratigraphic framework was established for the Denglouku Formation (three members) and Yingcheng Formation (two members), serving as an isochronous reference for facies analysis. Three major depositional systems were identified - shallow-water delta, braided river, and fan delta - showing vertical cyclicity of "shallow-water delta plain → braided river channel → fan delta front", reflecting lake-level fluctuations from shallow to deep with multi-phase sediment supply variations.The Denglouku Member 2 contains the thickest sandbodies (up to 80m) with sand-to-mud ratio >70%, showing ribbon-shaped distribution in shallow-water delta plain channels. Denglouku Member 3 develops 40m-thick sandbodies with >50% sand-to-mud ratio in anastomosing networks - both being premium reservoir intervals. In contrast, Yingcheng Formation sandbodies are only 3-5m thick with <40% sand-to-mud ratio, mainly in fan delta plain braided channels and thinning rapidly basinward.

Sandbody development is strictly facies-controlled, with shallow-water delta plain channels and braided river bars being the most sand-rich zones, while fan delta front sandbodies are thin and scattered due to weakened hydrodynamics.

This study has certain limitations that should be acknowledged. During well data processing, necessary adjustments made for software compatibility may have introduced positional deviations from actual well locations. The absence of seismic facies analysis in this research means structural interpretations of the area could potentially contain inaccuracies. Additionally, the hand-drawn illustrations in Chapter III may not precisely reflect subsurface realities.

The present study has confirmed the hydrocarbon potential of the Shuangcheng area in the northern Songliao Basin. Consequently, it is imperative to intensify research on the Yingcheng Formation source rocks at the basin scale, focusing specifically on their depositional environment, hydrocarbon-generation characteristics, resource potential, and hydrocarbon generation evolution.

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