Engineered Science
DOI: https://dx.doi.org/10.30919/es1832

Characteristics and Distribution Patterns of Mixed Reservoirs in the Upper Subsea of Liangjialou Sand Formation during Purification

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Abstract

The upper member of sha 4 in the study area belongs to beach bar deposits in underwater uplift, which is relatively far away from terrigenous clastic supply area and is mainly affected by lake waves and shore currents. The sediments have the characteristics of terrigenous clastic and carbonate mixed facies deposits, forming a special lithofacies system. The upper part of Es4 (Shahejie Formation 4th Member) in the study area is a shore-shallow lake subfacies deposit, developed with shore-shallow lake sand bar, shore-shallow lake sand beach and shore-shallow lake mud bay three microfacies, lithology is divided into sandstone and carbonate rock, both can form a single type of reservoir, but also can form a complex mixed reservoir. The shallow lake beach bar sedimentary reservoir body of the upper submember of Shahejie Formation can be divided into 6 lithofacies types, which are sandstone bar body, calcareous sandstone bar side edge, argillaceous beach sand, calcareous beach sand and mudstone bay. Through the analysis of oil and gas logging and comprehensive oil testing results of the target layer in the research area, it is believed that the favorable lithofacies are the main body of the sandstone dam and the lateral edge of the calcareous sandstone dam.

Keywords: The Shahejie formation; Mixed reservoir; Lithofacies; Favorable facies zone; Chun hua-Liang jia lou Area.

Received: 11 May 2025; Revised: 17 October 2025; Accepted: 21 October 2025.
Article type: Research article.

1. Introduction

Over the past few years, mixed siliciclastic–carbonate deposits have been documented from a growing number of continental lacustrine basins, prompting a fundamental shift in how the “mixed sedimentation” concept is perceived. No longer viewed as simple alternations of siliciclastics and carbonates, these systems are now understood as dynamic, multi-component, multi-process, and multi-scale couplings. Li *et al.*[1] describe mm-scale rhythmic alternations of bryozoan bioherms and siltstones within a Devonian intra-platform depression in Guangxi, underscoring the retentive effect of skeletal build-ups on carbonate production and demonstrating that significant mixing can occur even inside carbonate platforms. Liu *et al.*[2] and Wu *et al.*,[3] focusing on Lower Cambrian marine shales in the Tarim and Upper Yangtze regions respectively, offer marine analogues: the former propose a “siliciclastic-starved—calcite-mud cloud settling” model for an offshore ramp, whereas the latter invoke upwelling–salinity oscillations to explain alternations of calcareous and siliciclastic laminae—parallels for the flood–evaporation cycles now recognized in lacustrine settings. Moving into the continental realm, Chen *et al.*[4] delineate three hierarchical facies belts in the Paleogene of the Qaidam Basin—high-energy shoreline shoal, shallow-lacustrine mud, and semi-deep lacustrine lime mud—and identify early-dolomitized shoreline shoals as the most favorable reservoirs, thus translating mixed-sediment research into exploitable targets. Meng *et al.*[5] introduce a dual-parameter scheme for the Shahejie Formation in the Dongying Sag that combines three end-members (siliciclastic, carbonate, organic) with three textural classes (laminated, massive, bioturbated) and embed these in a three-factor developmental model (siliciclastic input, water chemistry, bioturbation), providing a template now widely adopted for lacustrine studies. Wang *et*

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al.[6] reconstruct paleosalinity and paleo-alkalinity from Sr/Ba, B/Ga, and C-O isotopes, arguing that water-column stratification coupled with salinity oscillation is the principal dial governing mixed-lithofacies stacking. Finally, Ye *et al.*[7] integrate computed tomography (CT)-derived 3D pore networks with evidence for event deposition and chemical precipitation to construct a four-factor coupling model (flood-driven turbidity currents, authigenic carbonate precipitation, and subsequent biogenic reworking), pushing genetic interpretation from facies scale to a seamless "process-to-pore" integration. Collectively, these studies illustrate the diverse expressions and dominant controls of mixed sedimentation across contrasting tectono-climatic settings, variable provenance–chemical regimes, and a spectrum of observational scales.

The study of "mixed sediments" has not only attracted the attention of experts in universities, but also gradually attracted the attention of production units such as oil fields. The concept of "mixed sedimentation" was first introduced by Mount in 1984;[8] subsequently, Chinese scholars have refined it along four axes—terminology, classification, reservoir evaluation, and research outlook. Wang Jinyou argued that Mount's original definition was too broad and proposed restricting the term "mixed rock" to those in which terrigenous clasts and carbonate particles were deposited contemporaneously within the same hydrodynamic unit, thereby distinguishing true mixing from simple interbedding.[9] Building on this, Zhang Xiong-hua presented a three-end-member (clastic–carbonate–chemical precipitate) and four-genetic-mechanism (mechanical mixing, biogenic induction, chemical cementation, diagenetic overprint) framework, providing a dual "composition–genesis" coordinate system for later studies.[10] Focusing on the Paleogene of the Xiaoliangshan–Shizigou area in the northwestern Qaidam Basin, Sima *et al.*[11] used conventional logs and thin-section statistics to divide the Shizigou Formation mixed rocks into three reservoir facies—clastic-dominated, carbonate-dominated, and dolomite-dominated—while Zhang *et al.*[12] combined mercury-injection and CT analyses to show that the dolomite–feldspar mixed framework of the lower Ganchaigou Formation can generate high-to-medium porosity/permeability sweet spots, illustrating that intra-basin heterogeneity of mixed reservoirs far exceeds that of purely clastic or purely carbonate ones. In a 2021 review, Li *et al.*[13] expanded the investigative scale from outcrop and core to seismic, logging, and geochemical data, proposing a new triple-coupling model—event-driven processes, chemical thresholds, and biological mediation—and highlighted the need to focus on nano- to micro-scale organic–inorganic interactions within fine-grained mixed rocks.

The sediments of the upper Es4 (Shahejie Formation 4th Member) member in Chunhua Liangjialou area are typical mixed rocks of the first stage, including mixed sediments of terrigenous clastic and carbonate components in the same formation and interbedded sediments of two lithologies. In addition, there are great differences in oil-gas potential and oil-gas productivity of different lithologic formations in the study area, so this study is aimed at the mixed reservoir in the mixed rock.[14,15] Because it is difficult to distinguish the control effect of terrigenous clastic and carbonate to reservoir only by sedimentary microfacies analysis, petrofacies analysis is introduced to study mixed reservoir. A lithofacies is generally regarded as the fundamental genetic unit characterized by uniform lithology and sedimentary structures that reflect specific hydrodynamic conditions.[16,17] So lithofacies analysis can better reflect the control of lithologic differences on reservoirs.

2. Experimental

Chunhua-Liangjialou area is located in the west of Chunhua Town, Boxing County, Zibo City, Shandong Province. The regional structure is located in the saddle part and Chunhua-Caoqiao fault nose belt of Boxing sag and Niuzhuang sag on the south slope of Dongying depression, adjacent to Xiaoying Oilfield in the west, Qiaozhuang Oilfield in the north, separated by Shicun fault and Boxing Oilfield in the south, and opposite to Le 'an Oilfield in the southeast.[18-20]

The sedimentary period of the upper Es4 member in Chunliang area is an underwater uplift, shallow lake sedimentary environment is developed, mudstone color is mainly greenish gray to light gray, siltstone is deposited under the action of lake wave and bank current, forming beach bar deposit, and due to insufficient supply of clastic materials, mixed layer deposits such as oolitic limestone, argillite limestone, calcareous siltstone, siltstone, argillaceous siltstone and mudstone are developed in this area. The upper beach bar deposit of Sha Si in the study area belongs to the beach bar at the underwater uplift. The uplift area is relatively far away from the terrigenous detritus supply area and is mostly affected by the comprehensive action of lake waves and shore currents. Oolitic limestone will be developed locally in the area with relatively less terrigenous detritus supply. Therefore, the study area has the characteristics of limestone and sandstone mixed facies deposition, forming a relatively special lithofacies system.[19,21-24]

2.1 Lithofacies characteristics of the upper submember of Shahejie formation

The reservoir of upper Es4 in the study area is influenced by specific sedimentary environment. Lithology can be divided into two types: sandstone and carbonate rock. Both of them can form a single type of reservoir and a complex mixed reservoir. The complexity and variability of reservoir types in plane and vertical constitute the unique characteristics of the reservoir in this area.

2.1.1 lithologic character

According to core observation and casting thin section analysis, quartz is the main component of sandstone, followed by feldspar and cuttings, with contents of 48.2 %, 35.6 % and 16.2 % respectively. The ratio of quartz to feldspar + cuttings content is close to but slightly less than 1. According to the classification standard of sandstone composition maturity, the sandstone in the upper sub-member of Es4 belongs to middle-low maturity sandstone. Sandstone lithology is mainly feldspar siltstone, a small amount of feldspar fine sandstone and lithic siltstone (Fig. 1a). Feldspar siltstone is dominated by argillaceous feldspar siltstone, followed by calcareous feldspar siltstone and dolomite feldspar siltstone. The structure is medium dense to dense, and most of them form thin interbeds of sand and mud with mudstone.

The debris developed in this area are metamorphic rocks, extrusive rocks, limestone debris and calcite debris. The debris components are mainly metamorphic rocks, followed by magmatic rocks and sedimentary rock debris (Fig. 1b). Most of them are porous cementation, intergranular pores are relatively developed, the components of clastic interstitial materials are mainly argillaceous matrix, cements are calcite, and pyrite is occasionally seen, reflecting the characteristics of stable current sedimentation and wave elutriation.

According to the above analysis, the sandstone matrix content of the upper Es4 member in this area is greater than 5 %, the grain sorting is medium, and the roundness is relatively low. According to the classification standard of structural maturity, it belongs to the sandstone with medium structural maturity.

There are many types of carbonate rocks in the upper submember of Shahejie Formation 4 in this area, with complex structures. The types can be divided into three categories:

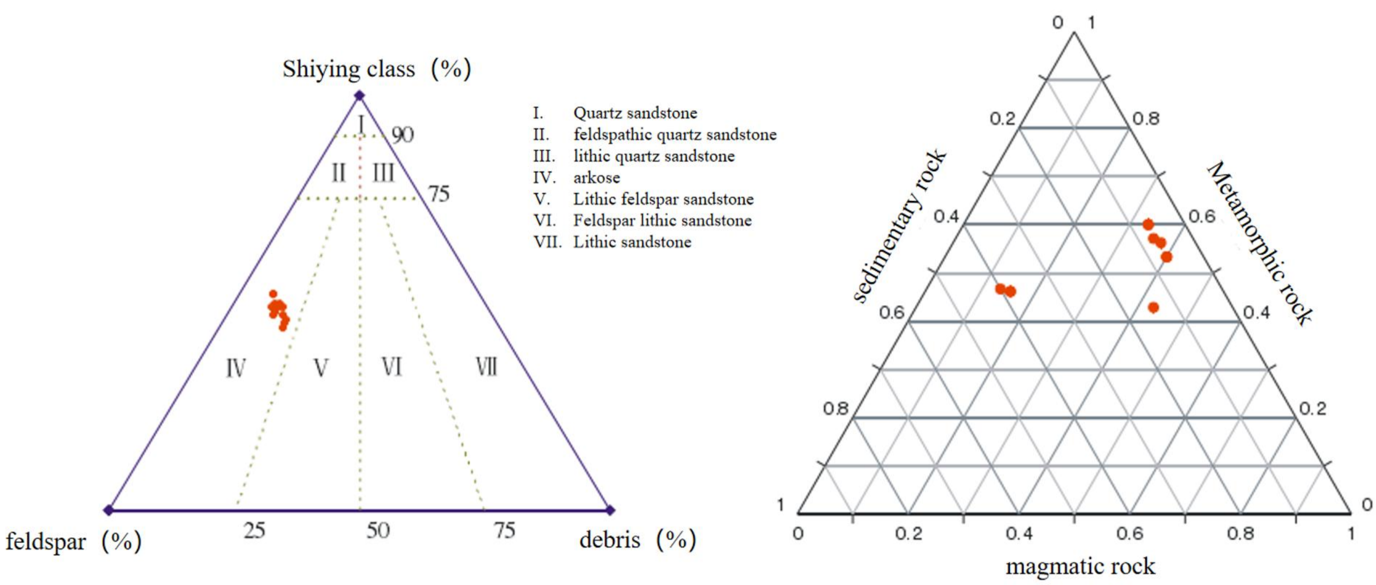
① Marl: including cryptocrystalline marl, silty marl, dolomite marl, *etc.*

② Limestone: including granular limestone, argillaceous aphanitic limestone, dolomite limestone, phylloid limestone, *etc.*

③ Dolomites: including sand chips, granular dolomite and cryptocrystalline dolomite, *etc.*

The carbonate rocks above are mainly fine grained and light gray and gray in color.

According to logging data and core observation, mudstone color is mainly gray and dark gray, occasionally green and grayish green, a few brown red, impure in quality, mostly fine and silty, and high in carbonate (lime or dolomite) content, compact and hard in structure, and shale interlayer can be seen locally. Seasonal horizontal laminations are more common in



(a) Particle content triangle (b) Cuttings content triangle

Fig. 1: Triangle diagram of rock composition.

mudstone, less massive, and interbedded with thin sandstone. Wave bedding composed of siltstone is common in thinner mudstone, and some mudstone contains calcareous bands, which is typical shallow lake deposition under weak oxidation to reduction environment.

2.1.2 Particle size characteristics

Grain-size cumulative probability curve of sandstone in upper Es4 in the study area shows typical multi-stage jumping "one hanging and one jumping" two-stage type, and the jumping order is more than 70 %, which reflects the grain size characteristics of beach bar as a whole.

The two-stage probability curve of the study area is mainly composed of jumping subpopulation and floating subpopulation, lacking rolling subpopulation, which can be divided into three cases:

The first one is shown in Fig. 2A. The intersection point of the jumping subpopulation and the suspended subpopulation is within the (2-3) Φ interval, and the hydrodynamic conditions are relatively weak. The content of jump fraction is relatively small, with slope of 40°~45° and volume fraction of 30 %~40 %, and the separation is poor; the total content of suspended fraction is relatively high, with slope of 10°~15° and volume fraction of 60 %~70 %, mostly beach sand deposits 5-6 m.

In the second case, as shown in Fig. 2B, the intersection point of jumping subpopulation and suspended subpopulation is in the interval of (3-4) Φ, and the hydrodynamic conditions

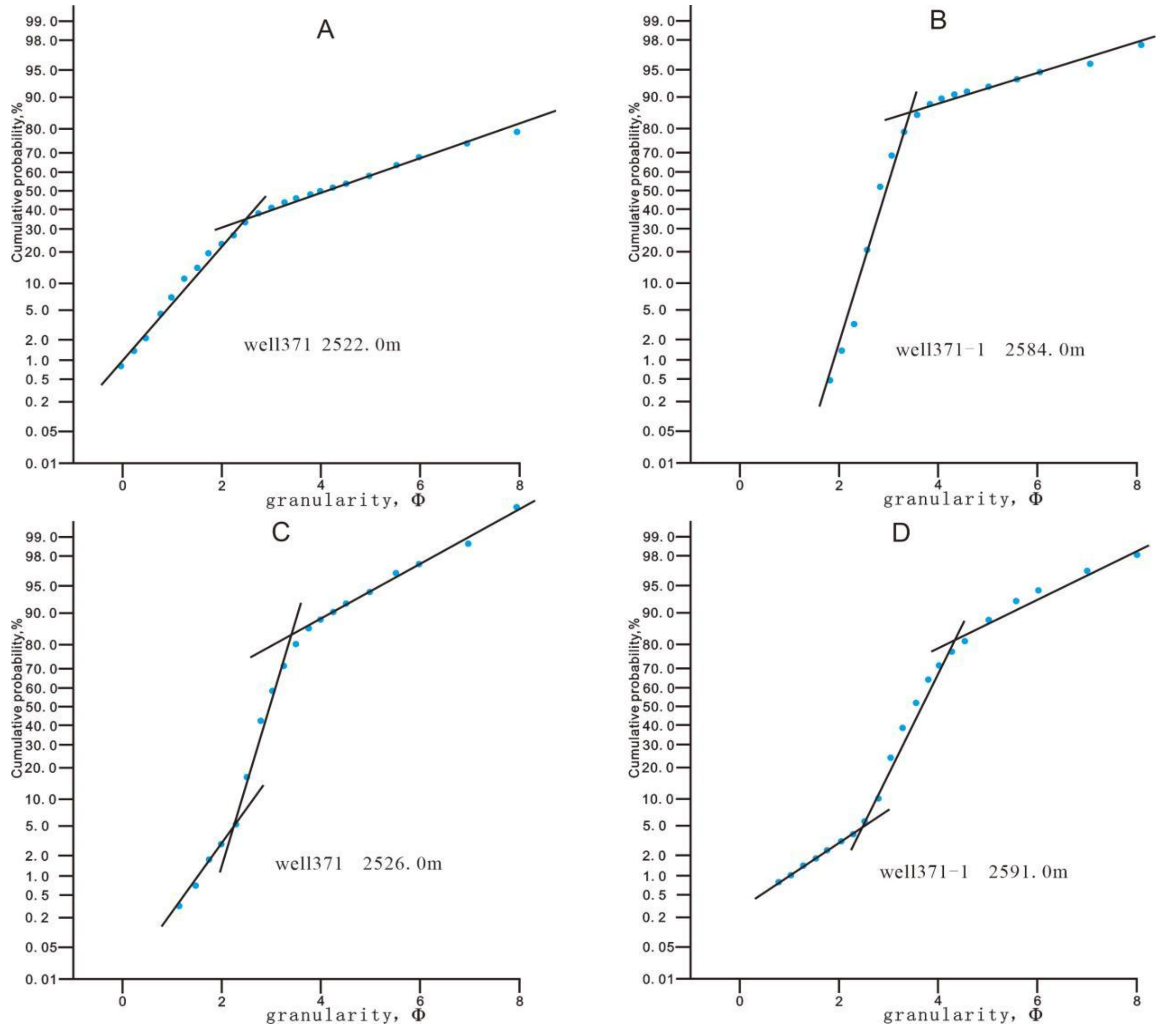


Fig. 2: Grain-size probability curve of upper part of Shahejie Formation in the study area (A is the probability distribution curve of rock particle size at 2522 meters in Well 371; B is the probability distribution curve of rock particle size at 2584 meters in well 371-1; C is the probability distribution curve of rock particle size at 2526 meters in well 371; D is the probability distribution curve of rock particle size at 2591 meters in well 371-1).

are relatively strong. The content of jump component is relatively high, the slope is 65°~70°, the volume fraction is 70 %~80 %, and the separation is good; the overall slope of suspension is 15°~20°, the volume fraction is 10 %~15 %, and most of them are dam sand deposits.

The third type, as shown in Figs. 2C and 2D, consists of two jump subpopulations and one suspension subpopulation. The double-jump feature reflects that waves have two hydrodynamic characteristics: scour and backflow. The intersection point of jump subpopulation and suspension subpopulation is in the interval (2-3) Φ, and the hydrodynamic condition is relatively strong. The content of jump component is relatively high, the slope is 60°~70°, the volume fraction is 80 %~85 %, and the sorting is moderate; the overall slope of suspension is 20°~25°, and the volume fraction is 15 %~20 %, which mostly reflects the sedimentary characteristics of dam sand.

2.1.3 Sedimentary structures and inclusions

By studying the primary structure of sediments, we can understand the intensity and direction of water flow, which is helpful to identify sedimentary system, judge sedimentary environment and divide sedimentary microfacies. According to the observation and description of 3 coring wells Liang 75-1, Liang 76 and Liang 752, horizontal bedding, cross bedding and wave bedding are mainly developed in the study area.

(1) Massive bedding: it is rare in the study area, mainly appearing in gray, greyish green and greyish black mud, shale, siltstone and fine sandstone (Figs. S1a and S1b). The materials in the layers are uniform, there is no difference in composition and structure, and there is no fine bedding structure. Massive bedding of sandstone often appears in the sediment of dam body.

(2) Horizontal bedding: it mainly occurs in fine-grained rocks, such as shale, mudstone, silty mudstone and calcareous mudstone. The laminae are parallel to the interfaces of strata. Horizontal bedding is formed under relatively weak hydrodynamic conditions, so it often occurs in low-energy environments such as beach sheets or shallow lake mud.

(3) Parallel bedding: mainly occurs in light gray and taupe siltstone, and is formed in rapid current and high-energy environment. Such bedding often occurs in dam body (Fig. S1c).

(4) Cross bedding: the study area is relatively developed, mainly developed in gray and light gray siltstone, dominated by wave sand striated cross bedding and tabular cross bedding, and soft sediment deformation structure appears locally (Fig. S1d), reflecting frequent lake wave activity in the study area.

2.2 Characteristics of sedimentary microfacies in the upper submember of Shahejie formation

On the basis of previous studies on sedimentary environment, through core observation, comprehensive study on lithological and electrical characteristics, it is considered that the upper member of Es4 in the study area is a shore-shallow lake subfacies deposit, and there are three microfacies: shore-shallow lake sand bar, shore-shallow lake sand beach and shore-shallow lake mud bay.

2.2.1 Shore-shallow lake sand bar microfacies

Sand bar of shore-shallow lake is the main part of reservoir developed in shore-shallow lake sedimentary environment, which is mostly distributed in strip, and its trend is related to wind direction, palaeocurrent (shore current) direction and structural trend during sedimentation. Most of them are nearly parallel to lake shore or oblique at small angle, and a few of them are oblique at large angle. Lithology of shallow lake sand bar in upper Es4 member of study area is mainly gray-green siltstone, siltstone, a small amount of argillaceous siltstone, with thin layer of light gray, gray-green mudstone and silty mudstone.

There are few layers of sand layers in vertical direction of sand bar microfacies, but the thickness of single sand layer is relatively large, generally greater than 2m, sand mud is relatively large, sand mud is covered, the rhythm is mostly reverse rhythm or compound rhythm of reverse first and then positive, and sedimentary structures such as parallel bedding, wave bedding and wave sand ripple bedding are mostly developed. Due to the strong hydrodynamic force of sand bar sedimentary environment, sand bar sandstone contains no or a small amount of carbon debris, and biological burrows are few. The particle size probability curve is generally composed of jump + suspension two sub-populations, there are also rolling + jump + suspension three stages, but the rolling component content is small, mostly distributed in 1 %~4 %. The microfacies of sand bar can be subdivided into two parts: main body and side edge.

Dam main body: the dam main body is the main part of the shore-shallow lake sand dam, with the strongest sedimentary hydrodynamic force and the coarsest grain size of sediments, which is the highest distribution area of composition and structural maturity. Most of them are thick coarse siltstone and siltstone, with few mudstone interlayers. The thickness of single sand body is generally 2~3m, and anti-rhythm or compound rhythm is the main one. The particle size probability diagram shows that the jumping sub-class is generally developed, the slope is large, and the sorting is good, while the suspended sub-class is generally underdeveloped, the slope is small, and the sorting is poor. Sedimentary structures are mainly parallel bedding, wave cross bedding, sand bedding and wave bedding. SP curves are combinations of (dentate) box shape, mid-high amplitude bell shape, mid-high amplitude funnel shape, oval shape or high wide width finger shape, with high values of microelectrodes and obvious amplitude difference (Fig. 3a). It is usually potato-like or short strip distribution in plane.

Dam side edge: the dam side edge is the side edge of the shore-shallow lake sand dam, located around the dam main body. The water body energy is medium, mainly composed of fine siltstone, argillaceous siltstone and silty mudstone, often containing argillaceous, gray and dolomite. The thin mudstone interlayer is relatively more than the microfacies of the dam main body. The grain size of microfacies in the main body of the dam is relatively fine, the thickness of single sand body is generally 1.5~2.5m, and the anti-rhythm is dominant. Carbon chips and plant rhizomes are relatively developed, and sedimentary structures mainly develop horizontal bedding, wavy bedding and lenticular bedding. SP curves were funnel, bell or finger shaped with middle amplitude, and most of them had reversion. The distribution of them is strip shape in plane.

2.2.2 Shore-shallow lake beach microfacies

The shore-shallow lake sandbank microfacies was formed in the flat shore-shallow lake subfacies belt at the lake bottom and is the main sedimentary part of the shallow lake subfacies. The hydrodynamic condition of the sandbank microfacies development area is weaker than that of the sandbar microfacies development area, so it can be divided into sandstone beach and limestone beach according to the carbonate rock content and its formation reason.

Sandstone beach: Sandstone beach is developed in shallow water area, but it is always under water. Wave and lake current are obvious. Sandstone beach sand body is fine grained than bar sand due to lake water oscillation. The beach sand in the study area mainly consists of light gray siltstone, argillaceous siltstone, silty mudstone and a small amount of mudstone, with a small amount of carbonate rocks with thickness less than 0.5m, such as marl, argillaceous dolomite and argillaceous limestone. In the vertical direction, sandstone and mudstone are generally interbedded frequently. Single sand body has the characteristics of thin sand body thickness, multiple layers and development of thin mudstone interlayer. The thickness of sand body is generally less than 2m, and the rhythm is mostly anti-rhythm but sometimes the rhythm is not obvious (Fig. 3b). Development level, wavy, wavy cross bedding and other bedding. The particle size probability curve consists of two jump segments + one suspension subpopulation, or one jump segment + one suspension subpopulation. The two jump segments reflect the characteristics of wave scouring and backflow.

Ash rock beach: ash rock beach is mainly formed on the terrace of shallow lake subfacies zone with relatively flat terrain. The terrace is uneven and partially uplifted, but the fluctuation is not large. During the sedimentary period of the upper part of the fourth member of Shahejie Formation in the study area, the lake surface was wide, the surrounding terrain of the lake was gentle, and it was far away from the source, resulting in the lack of terrestrial debris. In addition, the climate was dry, the water body was shallow and clear, forming a brackish water environment with high salinity, forming a shallow lake beach dominated by limestone, which was defined as limestone beach. The main rock types are limestone, dolomite limestone and marl, and oolitic limestone is developed in some sections, sometimes interbedded with fine-grained sandstone (Fig. 3c). Spontaneous potential (SP) curves are straight and linear, R4 curves are thin high peak fingers, and they are distributed like flowers or sheets on the plane.

2.2.3 Shallow lake mud bay microfacies

The shallow lake mud bay microfacies is developed in the deep water area in the shore-shallow lake subfacies environment. The hydrodynamic force in this area is very weak. In the vertical section, light gray mudstone and deep black shale are mainly interbedded, with thin marl and siltstone mudstone. Mudstones are mostly flat, some of which contain calcareous bands, and sand bodies are not developed. SP curves are not smooth straight lines or some of them are micro-tooth curves, GR curves are obviously higher, micro-electrode curves are basically coincident. On the plane, the distribution range is small, mostly in the shape of flowers or belts. Generally, there are no oil storage conditions or the oil storage properties are extremely poor (Fig. 3d).

3. Results and discussion

Reservoir lithofacies refers to rocks or rock assemblages formed in certain sedimentary environment, which is the main component of sedimentary facies. Lithofacies is the most basic unit of sedimentary facies sequence and the first element to analyze the formation process of sediments. Based on the characteristics of sedimentary microfacies and lithofacies, the classification and distribution of reservoir lithofacies in the study area are studied.

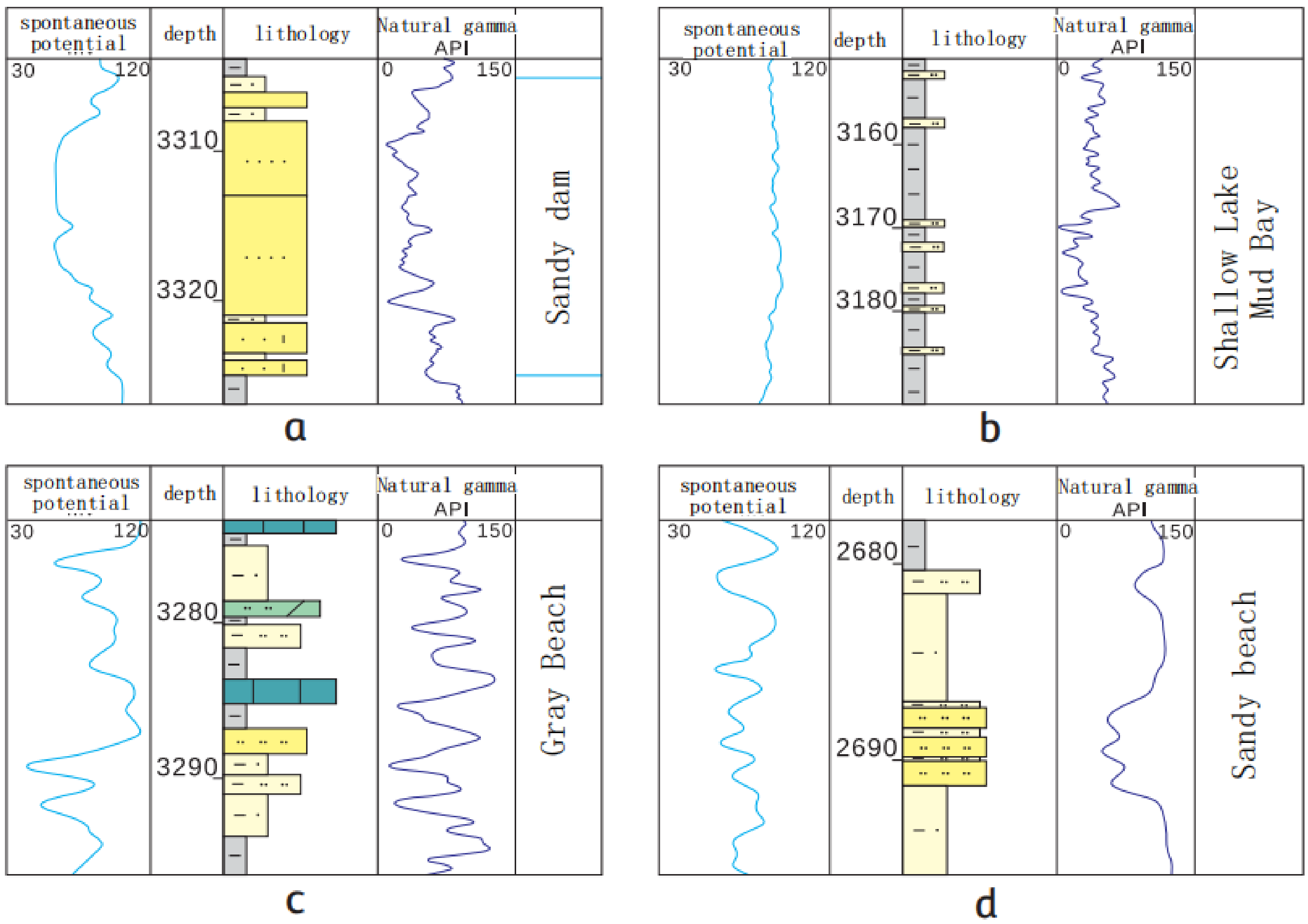


Fig. 3: Lithology and logging response characteristics of each microfacies of shore-shallow lake subfacies in the upper part of Es4. a represents the Main lithology and logging response characteristics of the dam; b represents the Lithology and logging response characteristics of sandstone beach; c represents the Lithology and logging response characteristics of limestone beach; d represents the Lithology and logging response characteristics of shallow lake mud bay.

3.1 Reservoir lithofacies type

Reservoir distribution is closely related to sedimentary microfacies type. Different sedimentary microfacies have different formation conditions and lithology. Reservoir is classified according to microfacies type and lithology description of coring well. (Table 1).

The six lithofacies assemblages are sandstone dam body, calcareous sandstone dam side edge, argillaceous sandstone dam side edge, argillaceous beach sand, argillaceous beach sand and mudstone bay. Siltstone bar mainly occurs in sand bar deposits, calcareous sandstone and argillaceous sandstone lateral margins are distributed in bar lateral margin deposits, argillaceous shoal sand and argillaceous shoal sand are widely distributed and concentrated in coastal shallow lake shoal, and mudstone interbay mainly occurs in mudstone deposits, belonging to intershoal deposits.

Table 1: Classification of lithofacies types of upper Es4 in the study area.

Microfacies type		Lithofacies type	
Beach shallow lake sand dam	Main body of the dam	Main body of sandstone dam	
	Dam side edge	Side edge of gray sandstone dam	Side edge of mudstone sandstone dam
Shallow lake beach	Sandstone beach	Muddy sandstone beach	
	Gray Beach	Mudstone beach	
Shallow Lake Mud Bay		Mudstone Bay	

3.2 Distribution law of reservoir lithofacies

According to the core well division and classification principles, fine division has been carried out for single wells collected in the study area, and lithofacies plane distribution map of 4 main sand groups has been compiled (Fig. 4).

Sandstone dam body is mainly developed in upper 1 sand formation of Shahejie Formation, which is distributed in Chun 80, Liang 9-5, Chun 23 and Liang 76 well areas in the central and western regions. The common feature is that single sand body with more than 10m length is developed in single well in this sand formation, and oil bearing property is relatively good. For example, the reservoir thickness corresponding to the sand dam of Liang752 well and Chun 5 well is about 5-8m, which still has good oil-bearing property. The distribution area of lime sandstone dam side edge is relatively small, such as Chun 107 well block and Liang 112 well block. Marl beach is only developed in local area, and it is developed in Chun 374 well area in southeast. The mud formation in the eastern part of the study area becomes larger, and intermudstone bays are mainly developed.

Two sandstone dam bodies are developed in the north and south of Sha 4 upper 2 sand formation, of which the sandstone dam body covers a large area in Liang 752-Liang 106 well area in the north and a small area in Chun 9 well in the south. Limestone dam flanks are developed in Chun 63-1 well block in the south and Liang 103 well block in the north. Sandstones are not developed in the north and south sides of the eastern part of the study area, mudstone-bearing beach is developed in

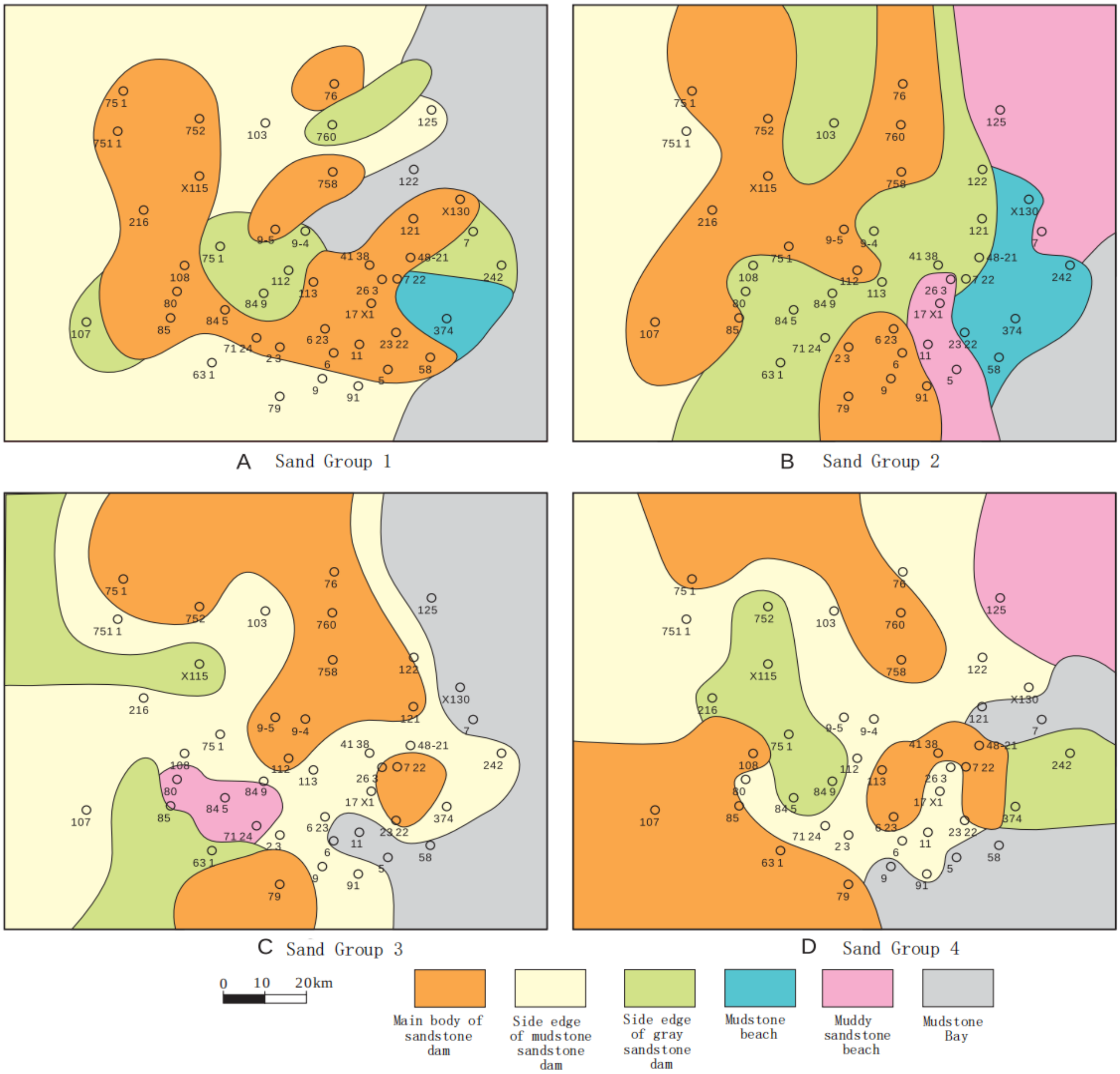


Fig. 4: Lithofacies plane distribution map of sand formations in upper part of Shahejie Formation in the study area.

the north, mudstone bay is developed in the south, limestone is more developed in Chun 374 well area in the middle, and marl beach is distributed. In the western part of the study area, there are whole argillaceous sandstone dam flanks.

Shaly sandstone dam lateral margin dominated by argillaceous siltstone is developed in the middle of upper 3 sand formation of sha 4, and argillaceous sandstone beach is developed in tong 84 well area with higher argillaceous content. Sandstone dam body with large thickness is developed in Liang752 well block, Liang758 well block, Chun 79 well block and Chun 26 well block in the north of the study area, lime sand dam side edge is developed in the north and south sides of the west, and large mudstone bay is mainly developed in the east.

Sand Formation S4 develops small-scale sandstone dam main body in the southwest Chun 107 well area, the north Chun 75-1 well area and the central Liang 113 well area, develops muddy sandstone beach in the east north wing, develops mudstone bay and contains a small amount of calcareous sandstone dam side edge in the south wing, and the other well areas in the whole region basically are muddy sandstone dam side edge.

3.3 Facies analysis of favorable reservoir

According to oil and gas logging display and oil test results of comprehensive oil test wells in the study area, reservoirs in the study area are divided into oil layer, oil-water layer, water layer and dry layer. It is found through acoustic wave and resistivity intersection diagram of different types of reservoirs (Fig. 5) that the resistance of oil layer in the lower sub-member of pure Es4 in the study area is generally higher than 4 Ω, corresponding acoustic wave range is 240-300 μs/m, and the resistance of oil-water layer is 2.5-4 Ω. Therefore, we think that the lower limit standard of oil layer is resistance 4 Ω. Acoustic time difference 240-300 μs/m.

According to the above electrical property standards, the oil-gas potential of the entire study area was studied through logging interpretation. It was found that except for the target layer of Well Chun 58, which did not develop oil layers, the rest of the wells developed oil layers with thicknesses ranging from 0.5m to 29.3m. Well Liang 9-5 has the largest thickness, mainly because the well develops large-scale sandstone dam body and the thickness of single sand body is large. And Liang 75 well block in the north and Chun 6 well block in the south contain more oil. It is considered that the main reason for forming this rule is that the side edge of limestone dam is mainly developed in this area. According to the production data of this area, the daily oil of single well in the main body of sandstone dam is 15.2 tons/day at the initial stage, and the accumulated oil of single well reaches 15,000 tons; the daily oil of single well in the side edge of limestone dam is 9.5 tons/day at the initial stage, and the accumulated oil of single well reaches 11,000 tons; the daily oil of single well in muddy beach sand and muddy beach sand is less than 5 tons/day, and the accumulated oil of single well does not exceed 5,000 tons. According to lithology, microfacies type and lithofacies, the reservoir is classified into two lithofacies: sandstone dam main body and lime sandstone dam lateral source. Therefore, it is considered that the favorable lithofacies are the main body of sandstone dam and the lateral edge of lime sandstone dam.

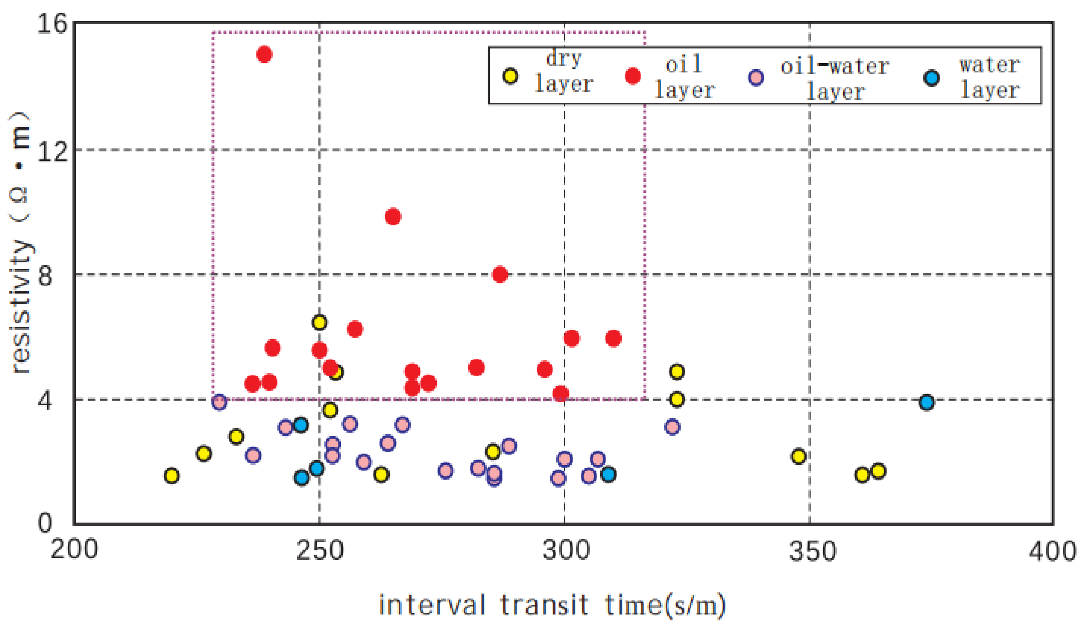


Fig. 5: Electrical property chart of upper Es4 reservoir in study area.

4. Conclusion

The upper part of Es4 in the study area belongs to shore-shallow lake subfacies deposit, and there are three microfacies: shore-shallow lake sand bar, shore-shallow lake sand beach and shore-shallow lake mud bay. Sand bar microfacies can be divided into two parts: main body and side edge of the dam. Shore-shallow lake sand beach can be divided into sandstone beach and limestone beach according to its carbonate content and its formation reason.

The lithology of the upper Es4 member in the study area can be divided into two types: sandstone and carbonate, which can form either a single type of reservoir or a complex mixed reservoir. The lithology of sandstone in the target layer is mainly feldspar siltstone, a small amount of feldspar fine sandstone and lithic siltstone, belonging to middle-low maturity sandstone, and the grain size cumulative probability curve has two or three sections.

The shallow lake beach bar sedimentary reservoir bodies of the upper Es4 member in the study area can be divided into 6 lithofacies types, namely sandstone bar body, calcareous sandstone bar lateral margin, argillaceous sand bar lateral margin, argillaceous beach sand, argillaceous beach sand and mudstone interbay. According to the data of oil and gas logging and oil test and production test of target formation in the study area, it is considered that the favorable lithofacies are the main body of sandstone dam and the lateral edge of lime sandstone dam.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Applicable.

CRediT Statement

Jianping Guo: Writing – review & editing, Supervision, Resources, Project administration, Investigation, Funding acquisition. **Lingwen Meng**: Writing – Original draft, Methodology, Investigation, Formal analysis, Data curation.

References

[1] Y. Li, D. Han, C. Wang, G. Li, X. Xu, W. Ma, X. Li, C. Lv, B. Lv, W. Zhang, Discovery of Devonian bryozoa from Longjiang, Guangxi and its geological significance, *Modern Geology*, 2020, **34**, 745-756, doi: 10.3969/j.issn.1000-8527.2020.04.011.

[2] W. Liu, Y. Li, Z. Gao, T. Fan, T. Zhang, M. Kuang, Lithofacies characteristics and sedimentary model of Lower Cambrian shale in northeastern margin of Tarim Basin, *Modern Geology*, 2023, **37**, 1155-1168, doi: 10.3969/j.issn.1000-8527.2023.05.012.

[3] Y. Wu, T. Fan, H. Ding, Lithofacies types and sedimentary models of Lower Cambrian marine shales in the Upper Yangtze region, *Modern Geology*, 2017, **31**, 1222-1232, doi: 10.3969/j.issn.1000-8527.2017.06.010.

[4] Y. Chen, H. Yi, L. Chen, X, Wu, W. Tang, R. Wang, Y. Yun, C. Zhang, Analysis of astronomical cycles and evolution of ancient lake levels in the Niubao Formation of the Paleogene on the Qinghai Tibet Plateau: A case study of Well Ni 1 in the Nima Basin, *Sediments and Tethys Geology*, 2023, **43**, 555-564. doi: 10.19826/j.cnki. 1009-3850.2021.09003

[5] Q. Meng, F. Hu, Z. Liu, P. Sun, R. Liu, Lithofacies types and genesis of fine-grained sedimentary rocks in terrestrial depressions and lake basins: a case study of the Late Cretaceous Qingshankou Formation in the Songliao Basin, *Journal of Jilin University (Earth Science Edition)*, 2024, **54**, 20-37, doi: 10.13278/j.cnki. jjusese. 20220314.

[6] Q. Wang, F. Hao,H. Zou, Y. Xue, C. Niu, Several Thoughts on the Source and Exploration Prospects of Deep Natural Gas in Rich Oil Basins: A Case Study of Bohai Central Area in Bohai Sea, *Journal of Yangtze University (Natural Science Edition)*, 2023, **20**, 47-54, doi: 10.3969/j.issn.1673-1409.2023.05.004.

[7] M. Ye, X. Jie, C. Xu, X. Du, Z. Song, X. Du, Discussion on the Classification and Naming System of Mixed Rocks and Its Implications for Reservoir Evaluation: A Case Study of Mixed Rocks in the Bohai Sea, *Geological Review*, 2018, **64**, 1118-1131, doi: 10.16509/j.georeview.2018.05.006.

[8] J. F. Mount, Mixing of siliciclastic and carbonate sediments in shallow shelf environments, *Geology*, 1984, **12**, 432, doi: 10.1130/0091-7613(1984)12432:mosacs>2.0.co;2.

[9] J. Wang, L. Zhang, S. Zhang, H. Lin, Sedimentary characteristics and genesis analysis of lacustrine mixed rocks in the Sha2 section of the Zhanhua depression in the Jiyang depression: a case study of the Luojia Shaojia area, *Geological Review*, 2013, **59**, 1085-1096, doi: 10.16509/j. georeview, 2013.06.019.

[10] X. Zhang, Classification and genesis of mixed rocks, *Geological Science and Technology Information*, 2000, **19**, 31-34.

[11] L. Sima, Y. Yang, F. Wu, J. Yao, W. Zhao, Reservoir evaluation of mixed rocks of Shizigou Formation in Xiaoliangshan area, northwestern Qaidam Basin, *Modern Geology*, 2014, **1**, 173-180, doi: 10.3969/j.issn.1000-8527.2014.01.018.

[12] S. Zhang, X. Zhang, T. Zhang, P. Wang, X. Nan, Y. Gou, Reservoir characteristics and influencing factors of mixed rocks in Lower Ganchaigou Formation of Paleogene in Shizigou area, western Qaidam Basin, *Modern Geology*, 2017, **31**, 1059-1068,

doi: 10.3969/j.issn.1000-8527.2017.05.017.
[13] Q. Li, Z. Bao, Y. Xiao, J. Chen, Z. Li, Z. Wang, M. Liu, Z. Li, X. Xu, F. Cao, Research advances and prospect of mixed deposition, *Acta Sedimentologica Sinica*, 2021, **39**, 153-167, doi: 10.14027/j.issn.1000-0550.2020.140.
[14] A. D. Miall, Architectural-element analysis: a new method of facies analysis applied to fluvial deposits, *Earth-Science Reviews*, 1985, **22**, 261-308, doi: 10.1016/0012-8252(85)90001-7.
[15] N. Zou, J. Shi, D. Zhang, C. Ma, S. Zhang, X. Lu, Sedimentary model of fan delta of Baikouquan Formation in Mabei area, northwest margin of the Junggar Basin. *Journal of Sedimentology*, 2015, **33**, 607-615, doi: 10.14027/j.cnki.cjxb.2015.03.019.
[16] A. D. Miall, Architectural elements and bounding surfaces in fluvial deposits: anatomy of the Kayenta formation (Lower Jurassic), Southwest Colorado, *Sedimentary Geology*, 1988, **55**, 233-262, doi: 10.1016/0037-0738(88)90133-9.
[17] G. Postma, Architectural Elements Formed Within Channels, *The Geology of Fluvial Deposits, Sedimentary Facies, Basin Analysis, and Petroleum Geology*, Springer Berlin, Heidelberg, 1997, **110**, 149-150, ISBN: 978-3-540-59186-3.
[18] Y. Jia, Y. Cao, C. Lin, J. Wang, Formation mechanism and distribution characteristics of high-quality reservoirs in the Sha4 upper sub section of the Boxing Depression in Dongying Depression, *Journal of Jilin University (Earth Science Edition)*, 2018, **48**, 652-664, doi: 10.13278/j.cnki. jjusese. 20160368.
[19] M. Lv, Research on Sedimentary Facies and Sand Body Distribution of Sha-4 Member in Shubei Gaosheng Area, Western Depression of Liaohe River, *China University of Petroleum (Beijing)*, 2021, doi: 10.27643/d.cnki.gsybu.2011.001644.
[20] Y. Li, F. Wang, Research on sedimentary characteristics and prediction of favorable areas in the Sha2-Sha-4 section of the southern slope of Boxing Depression, *Energy and Environmental Protection*, 2021, **43**, 96-103, doi: 10.19389/j.cnki. 1003-0506.2021.2.017.
[21] Y. Wang, C. Lin, H. Li, Y. Sun, H. He, Q. Wang, Z. Zhang, M. Ji, Characteristics of carbonate microfacies and sedimentary environment of Lower Carboniferous in Marsel exploration area of Kazakhstan, *Modern Geology*, 2018, **32**, 511-526, doi: 10.3969/j.issn.1000-8527.2018.03.008.
[22] Y. Wang, C. Dong, C. Lin, Y. Wang, Q. Hou, Types and characteristics of slope break belt in the gentle slope and its controlling effect on the deposition: Taking the deposition of lacustrine carbonates in Es^{4s} formation in the Dongying sag as an example, *Journal of China University of Mining & Technology*, 2021, **50**, 329-341, doi: 10.13247/j.cnki.jcumt.001249.
[23] L. Q. Zhao, Petrological characteristics and sedimentary model of carbonate rocks in gentle slope zone of salinization lake basin, *Journal of Xi'an Petroleum University (Natural Science Edition)*, 2022, **37**, 10-16, doi: 10.3969/j.issn.2096-3246.2022.04.002.
[24] M. Ni, X. Zhu, W. He, S. Yang, Y. Zou, Y. Zhang, Sedimentary environment and model analysis of Fengcheng Formation in Mahu Sag, Junggar Basin, *Modern Geology*, 2023, **37**, 1194-1207, doi: 10.3969/j.issn.1000-8527.2023.05.019.