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Sedimentary Microfacies Types and Patterns of Chang 6 Member of Triassic Yanchang Formation in the Dalugou Area of Jing'an Oilfield in Ordos Basin, China

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Abstract: The sixth member of the Triassic Yanchang Formation (Chang 6 member) in the Dalugou area of the Jing'an Oilfield in the Ordos Basin is a typical ultra-low-permeability lithological reservoir. The Dalugou area has achieved some development progress in the past few years. With the development of the Chang 6 member in the Dalugou area, a better understanding of the sedimentary microfacies and depositional patterns is needed for precise oil development. The purpose of the study of the reservoir description is to understand the reservoir more accurately and provide a solid geological basis for the adjustment of the development strategy of the Chang 6 reservoir. The Chang 6 member of the Triassic Yanchang Formation in the Dalugou area of the Jing'an Oilfield belongs to the subfacies of the delta front, and the reservoir in the study area is mainly the underwater distributary channel deposition. There are two main depositional patterns in the study area: the dendritic sandstone depositional pattern and the lobate sandstone depositional pattern. The study on the sedimentary types and patterns of the Chang 6 member of the Triassic Yanchang Formation in the Dalugou Area of the Jing'an Oilfield can provide significant information for the evaluation of reservoir characterization. Furthermore, the heterogeneity of the Chang 6 reservoir under various depositional patterns has an important influence on oil enrichment.

Keywords: sedimentary microfacies; sedimentary patterns; Chang 6 member; Yanchang Formation; Ordos Basin

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1. Introduction

The Triassic Yanchang Formation in the Ordos Basin is rich in tight oil resources. The Chang 6 member of the Yanchang Formation is the main target for tight oil of the Ordos Basin. Adjacent to high-quality hydrocarbon source rocks, the Chang 6 member is a favorable oil layer for good reservoir conditions. The Chang 6 member has strong non-homogeneity, poor connectivity in plane, poor connectivity in the horizontal direction, and interlayer conflicts in the vertical direction. Previous studies have shown that changes in the sedimentary microfacies result in differences in the values of the reservoir non-homogeneity evaluation indicators [1–3] and cause vertical changes in the related non-homogeneity evaluation indicators [4–6]. Profoundly studying the sedimentary microfacies is significant for accurately predicting the distribution of the remaining oil and efficient mining production [7–14]. Interlayer conflicts are often prominent in the vertical direction. In the development process, the reservoir is poorly utilized due to the non-homogeneity in plane and between layers. The reservoir is poorly utilized due to planar and interlayer inhomogeneity.

However, it is difficult to explore the potential of conventional wells, mainly due to the problems of low formation energy, the rapid decline of well production, and the rapid rise of water content. Combined with drill coring, logging, and other data, the main objectives of this study were to (1) investigate the sedimentary environment and sedimentary microfacies of the Chang 6 member; (2) study the types of depositional microfacies of the Chang 6 member; and (3) discuss the sedimentary patterns of the Chang 6 member in the Dalugou Area of the Jing'an Oilfield, Ordos Basin. The study may provide great practical significance and guidance for the efficient development of this region and improvement of oil recovery.

2. Geological Setting and Methods

The Dalugou area of the Jing'an Oilfield is located in the north-central part of the north slope of the Ordos Basin (Figure 1). The regional tectonic structure is a west-dipping monocline with east–high and west–low inclination, and the dip angle is less than 1°, the axial length is 14.43 km, and the axial width is 6.3 km. The tectonic movement in this area is fragile, and only a few rows of wide and slow nose-like uplift zones and small-amplitude trap structures with a degree of closure of less than 20 m have been developed in the west-dipping monocline. The nose-like uplift and small-amplitude tectonics on the west-dipping monocline play an important role in controlling the oil and gas enrichment.

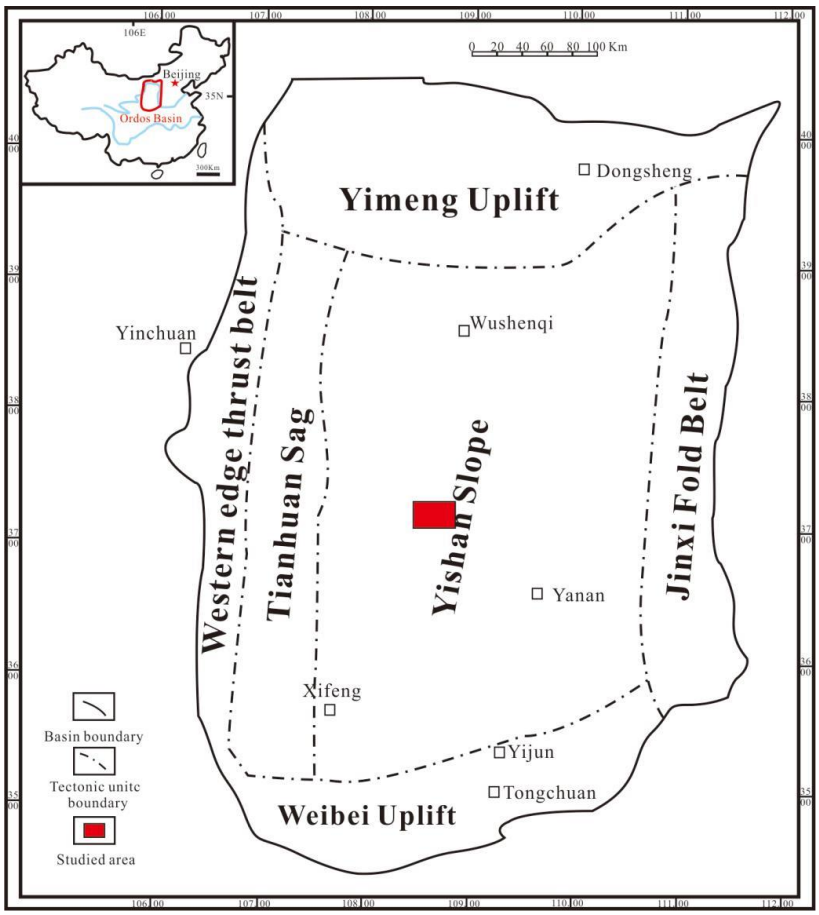

Figure 1. A map showing the studied Dalugou area and the division of tectonic units of the Ordos Basin.

The strata drilled from top to bottom in this area include Quaternary, Tertiary, Cretaceous, Jurassic, and Triassic. The primary oil-bearing formation is the Chang 6 member of the Triassic Yanchang Formation.

The Upper Triassic Yanchang Formation is a terrigenous clastic rock system characterized by river–lake facies accumulated during the continuous development and stable sedimentation of the Ordos Basin depression, and its sedimentary characteristics record the history of this large freshwater basin from its occurrence and development to its demise [15,16]. The development of the lake basin reached its peak in the early stage of the third section of the Yanchang Formation, i.e., in the Chang 7 member, and the lake flooding range could reach the northern part of the basin from Hengshan to Ushenqi. After that, with the continuous injection and filling of the river, the lake basin shrank.

The appearance of the lake basin changed significantly in the Chang 6 member: the deep lake and semi-deep lake area was greatly reduced, and the deltaic depositional system became highly developed [17]. The west coast of the lake basin in the Chang 6 member developed the Shigouyi fan delta, Huanxian fan delta, Zhenbei braided river delta, and Jingchuan braided river delta. The large-scale turbidite fan developed in the Chang 7 member in the Maling–Qingyang area was greatly reduced, mainly replaced by the delta front facies. The prominent feature of this period was that the material sources in the northeast and east were greatly strengthened. The Yulin–Hengshan area was transformed into a plain river facies by the delta frontal margin of the Chang 7 member with the strengthening of sedimentation. The deltas of Ansai, Yan'an, and Fuxian entered into the heyday development of the delta. The delta front of the northeast already intersected with the Yanci–Dingbian delta in the northern part of Wuqi to form a huge delta front and at the same time passing through Wuqi to the south until the Huachi–Yueluo area. Another feature was that the sedimentation of the Fuxian delta was obviously strengthened, and it moved westward through the Hulu River and Taibai area directly to the Guchengchuan, which was the primary source of the Heshui–Guchengchuan turbidite fan. The deep lake area moved back from north Yanchi in the Chang 6 member to the south Jiyuan area in the Chang 7 member, along with the eastern part also significantly moving to the southwest backward, and the Chang 7 member of the deep lake area in the east of the deep lake area could be up to the continental ditch–Zhidan–Xihekou–Fuxian area, which backed up to the Danbazhen, Yongning, and the Hulun River to the west of the area [5,18].

The Yanchang Formation in this area is a large inland shallow water lacustrian delta, and the stratigraphic thickness is stable, with a set of gray-black and gray-green mudstone, muddy siltstone, and gray-green and gray-white medium- and fine-grained feldspathic sandstone interbedded. The thickness is about 500–600 m. The Chang 6 member has an oil reservoir buried at a depth of 1500–1800 m. The Chang 6 reservoir is a typical low-permeability, low-pressure, and low-production oil reservoir, with no initial production from conventional drilling, and industrial oil flow can be obtained after fracturing.

The methods used in this study included the core description, mineral identification based on microscope images, wireline log curve analyses, and sedimentary facies interpretation. The wireline log curves used in this study were from the database of PetroChina Changqing Oilfield Company. Detailed descriptions of the cores in the Chang 6 member were taken for the identification and interpretation of sedimentary facies.

3. Petrological Characterization

3.1. Petrographic Analysis

The lithology of the Chang 6 member in the Dalugou area is mainly fine medium-grained feldspar sandstone, followed by lithic feldspar sandstone (Figure 2). The whole rock is divided into two major components as terrigenous debris and matrix, of which terrigenous debris accounts for 88.43%. Terrigenous debris mainly contains quartz, feldspar, and rock debris. Feldspar is the dominating component, with an average content of 51.29%. Quartz accounts for 24.46% of the terrigenous debris, with an average content of 21.63%. The cathodoluminescence shows that the quartz is mainly dark blue-purple, which is high-temperature quartz, primarily originating from volcanic rocks, plutonic intrusive rock, and contact metamorphic rocks. The feldspars are mostly bright blue and dark gray-brown under the cathodoluminescence, which are plagioclase and alkaline feldspars, with a small

amount of yellowish-green feldspar and reddish-brown feldspars. The clasts mainly consist of volcanic clasts and metamorphic clasts with a certain amount of a terrestrial source of mica. The metamorphic debris and mica, after long-term metamorphism, generally show plastic deformation and volume expansion. The volume will be expanded several times, showing destruction for the storage space. The average content of the filler material accounts for 11.15% of the whole rock. Its types mainly include clay minerals, zeolites, carbonates, siliceous, and a small amount of pyrite. Chlorite in the clay minerals and turbidite zeolite in the zeolites are the dominant minerals, with contents of 3.67% and 3.19%, respectively. The above analysis indicates that the compositional maturity of the rocks in the Dalugou area is relatively low.

Figure 2. Core photographs of the facies documented in the Chang 6 member of the Yanchang Formation in the Dalugou area. (**a**) Trough cross-bedded sandstone. (**b**) Gray black silty mudstone, with visible biological burrows. (**c**) Gray-black mudstone. Fossils of ancient plant leaves can be seen on the surface. (**d**) Cross-bedding sandstone intercalated with mudstone bands. (**e**) Evenly bedded sandstone. (**f**) Sand grained cross-bedded fine sandstone.

3.2. Sedimentary Structures

Sedimentary structures record the environment, climate, and other factors at the time of the initial deposition of the strata. The study of the sedimentary structures is significant for determining the depositional environment and delineating the depositional microfacies.

Core observations of the coring wells in the study area show a variety of sedimentary structures (Figures 2 and 3). Parallel laminae, horizontal laminae, large-scale interbedded laminae, sandy interbedded laminae, plate-like interbedded laminae, groove-like interbedded laminae, deformation laminae, wrapped laminae, disturbed structures, groove molds, sand balls, sand pillows, flame structures, scouring surfaces, and so on can be seen in the core, while there are also locally developed coal lines. The diversity of the laminae indicates that the water flow is turbulent and changeable, which is the depositional characteristic of the river–lake confluence area.

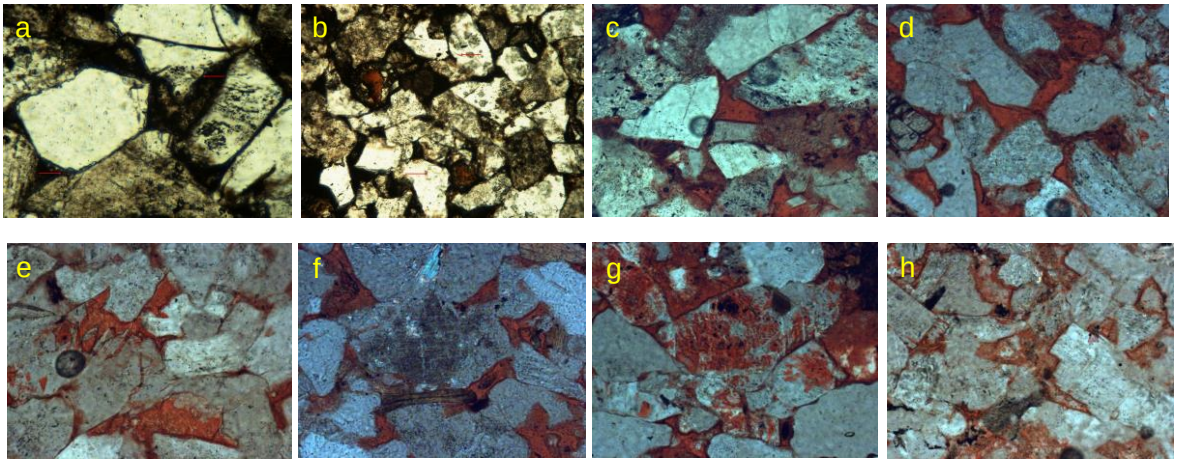

Figure 3. Representative microscope images of coarse-grained turbidites (CT) from the Chang 6 member of the Yanchang Formation. (**a**,**b**) Quartz and feldspar under single polarized light. (**c**,**d**) Primary intergranular pores and authigenic quartz. (**e**,**f**) The feldspar is moderately weathered and the surface is clayed. (**g**,**h**) Point and line contact between particles.

3.3. Particle Size Distribution Characteristics

The rock particle size distribution characteristics reflect the depositional environment. The size of the particles directly determines the type and nature of the rock. Particle size and particle sorting are two of the metric markers of the transport capacity and efficiency. The particle size analysis of the depositional microfacies is an essential basis for research. The Chang 6 member in the Dalugou area is dominated by fine- to medium-grained feldspathic sandstone, with 0.16% of coarse sand, 10% of medium sand, 86.27% of fine sand, 2.48% of chalk, and 1.08% of mud; the primary grain size is concentrated in the range of 0.1–0.3 mm; and the average grain size is 2.71, with a standard deviation of 0.56, a skewness of 0.19 (positively skewed), and a kurtosis of 1.08 (sharp), which indicates that the sediment is dominated by relatively coarse fractions. The sediments are well sorted. In addition, the thin-section analysis shows that the study area has a medium degree of rounding, dominated by a sub-angular shape, and partly reaches a sub-rounded shape. Therefore, the rock has a medium degree of structural maturity.

The particle size probability curve is mainly characterized as a three-segmented curve (Figure 4), followed by a two-segmented curve. The two-segmented curve lacks rolling components. This indicates poor sorting, strong hydrodynamic force, and complex and diverse current depositional environments.

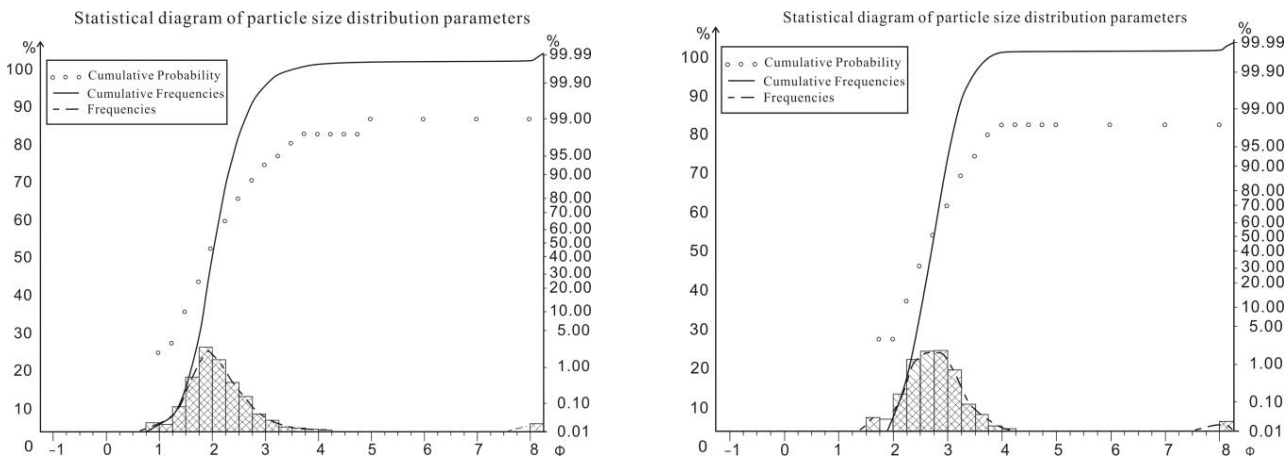

Figure 4. Statistical diagram of the particle size distribution parameters for the Chang 6 member in the Dalugou area.

3.4. Biological Features

Using core observations and descriptions, the paleontological features were divided into two main categories: biotite structures (i.e., fossilized biotites) and biological remains. Biological relic structures refer to traces of biological activities preserved in the sediment layer and within the layers, such as crawling and resting traces preserved on the sediment layer and habitation traces and borehole traces preserved within the layers. The most common are wormholes, including vertical and horizontal wormholes, which generally occur in lacustrine depositional environments. There are also bioturbation structures, which are typically found in shallow water environments. Benthic organisms disturb and damage unconsolidated sediments in various ways, deforming the sedimentary body and causing irregularities in the stratigraphy, which is generally in the form of upright or inclined burrows and funnels. Biological remains refer to plant leaves, stems, roots, and various animal fossils. Fossilized animal remains and plant leaves generally occur in deeper water, plant stems occur in relatively shallow water, and plant roots generally occur in embankment environments.

Plant fossils are abundant in the study layer system, and plant fragments and plant stems can be seen in the sandstones of the Chang 6 member. Plant fragments and plant leaves are often seen in the mudstone, and thin coal lines can be seen in some of the wells, which suggests that plant growth flourished in the local area, forming a localized swamp.

4. Sedimentary Microfacies Analysis

Previous studies have shown that during the Chang 6 period, braided river sedimentation was mainly developed, with river sand bars as the main reservoir [19]. The oil source mainly comes from the high-quality source rock of the Chang 7 member in the central area of the Yanchang Formation lake basin [20–22]. Due to its relatively far distance from the oil source and limited hydrocarbon supply capacity, the Chang 6 member has the characteristic of low oil saturation [23]. The distribution and enrichment of the Chang 6 oil reservoir are mainly controlled by the comprehensive influence and control of sedimentary facies zones, nose-shaped uplift structures, cap rock distribution, migration channels, and lateral blocking conditions. In the early stage of the Prolonged Epoch of the Jing'an Oilfield, the periphery of the basin was significantly uplifted, forming a large brackish water lake with a large area, a wide watershed, a shallow depth, and a flat substrate. The lake basin formed and developed in the Chang 10–Chang 7 member, reaching full bloom in the Chang 7 member with a vast range of water flooded and organic-matter-rich shale deposits. The Chang 6–Chang 4 + 5 period was the continuous and stable sinking stage of the lake basin, and the Chang 3–Chang 1 period was the contraction to extinction stage of the lake basin. The Chang 6 member formed a series of large constructive river-controlled lake delta deposits at the lake basin margin. On the basis of this regional sedimentary background, a dragnet sedimentary microfacies analysis of the study area was carried out from point (single-well facies analysis) to line (sectional facies analysis) to surface (sedimentary microfacies distribution).

4.1. Single-Well Facies Analysis

The single-well facies analysis describes and analyzes the cores of coring wells in detail, providing various kinds of finger facies information, such as lithology combination characteristics, primary sedimentary structures, fossil characteristics, grain size analysis results, and facies sequence characteristics. A single-well facies analysis histogram was built after a comprehensive analysis. The single-well facies analysis histogram mainly reflects the orientation markers of the sand layer, determines the facies type and facies sequence in the longitudinal direction, and selects the finger facies logging curve. The reliability of the single-well facies analysis directly affects the final results of the facies analysis. The cores were observed and described from 15 coring wells in the study area, with a total core length of approximately 500 m, and corresponding single-well facies analysis histograms were created (Figure 5).

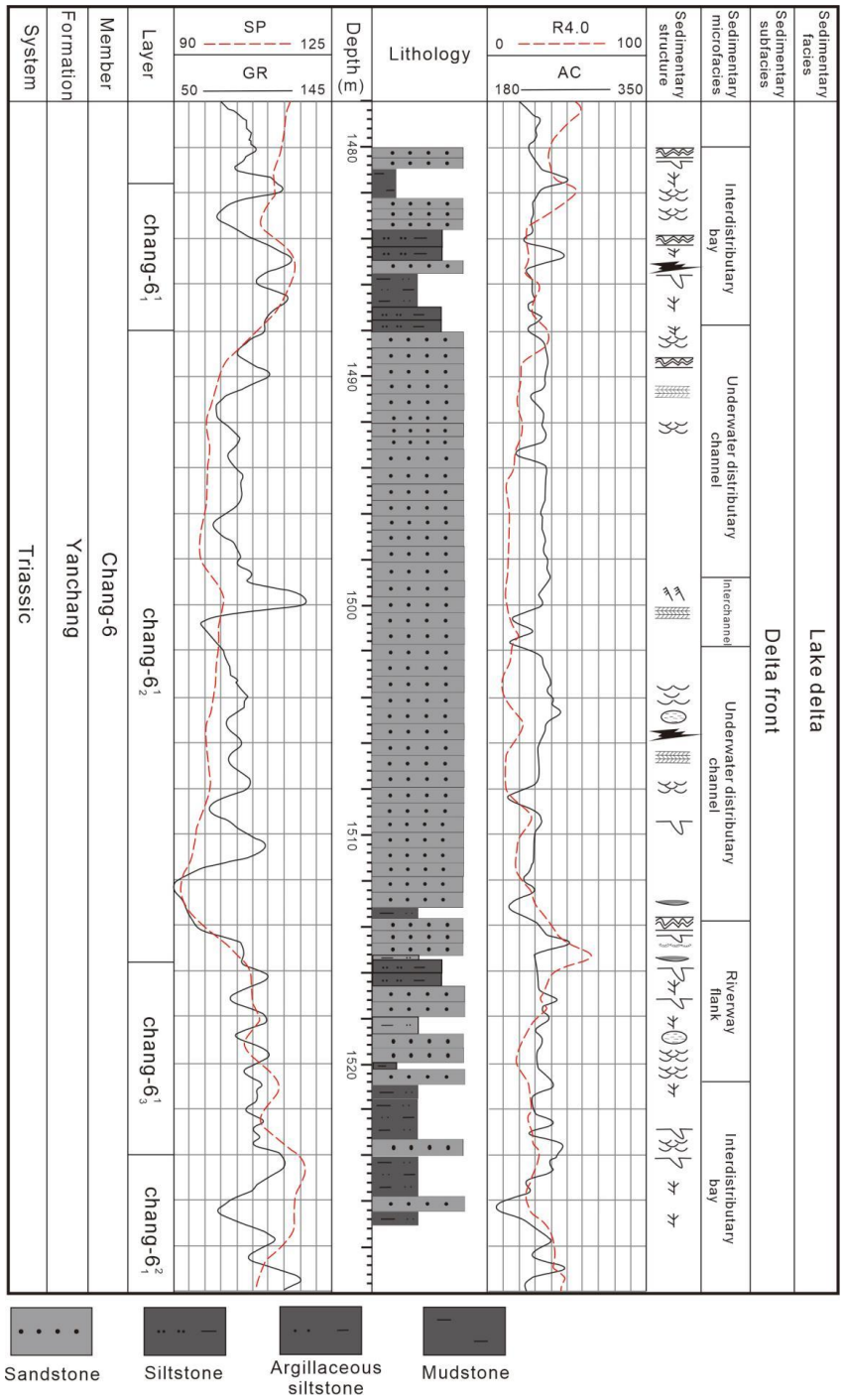

Figure 5. Lithology and lithofacies histogram of the Chang 6 member in the Dalugou area.

4.2. Types of Depositional Microfacies

The comprehensive petrological analysis and logging facies analysis identified the Chang 6 member in the Dalugou area as the delta front subfacies. On this basis, six depositional microfacies, an underwater distributary channel, underwater distributary channel flanks, mouth bars, sheet sands, inter-diversion channel, and inter-diversion bays, were further identified. Facies were referred to as the main body of the underwater distributary channel when the distinction between the flanks of the diversion channel in the non-dominant layer was not apparent.

4.2.1. Underwater Distributary Channel

The underwater distributary channel is an essential part of the deltaic system, and these low-bend channel deposits have some inheritance from the river system in the upstream direction. The bottoms of the diversion channels in this area are mostly in contact with the underlying strata at the scour surface, with muddy gravel segments and muddy gravel interaction segments at the bottom. Muddy gravels are direct evidence of river channelized water erosion. Muddy gravels are of in situ or ex situ origin, with most being flattened ex situ origin. Some poorly rounded muddy gravels are mud clasts, with other muddy gravels torn by the current as lacerated clasts. Most of these lacerated clasts are oriented, with some aligned subparallel to each other and others trending in a staggered pattern. Sandy sediments fill between the muddy gravels.

The microfacies of the underwater distributary channel are dominated by medium- and thick-bedded medium- to fine-grained feldspathic sandstone and rocky feldspathic sandstone, with the top siltstone constituting a positive rhythm of coarse and fine on the lower part. The morphology of the sandstone is lenticular or wedge-shaped in the cross section and tends to be extinguished in the direction of the riverbank. The morphology of the sandstone is tongue-shaped in the plane, with the development of parallel laminations, plate-like interbedded laminations, massive laminations, and groove interbedded laminations, which can be seen in local areas. The top of the siltstone has undulating laminations or parallel laminations (Figure 2d,f).

There are two kinds of underwater distributary channels in the study area: the underwater distributary channel of the primary layer Chang $6_1{}^2$ sub-member can be divided into the main body of the underwater distributary channel and the flanks of the underwater distributary channel. The main body of the underwater distributary channel is distributed in the form of branches and is mostly in abrupt contact with the underlying mudstone layer, forming a substantial thick massive sandstone upward. The logging curves are mostly in the form of boxes, and the curves are relatively smooth. The flanks of the underwater distributary channel show more mudstone interlayers or calcium interlayers in the middle of the thick sandstone. Hence, the log curve is either a box shape with upward convergence or a stepped bell shape (Figure 5).

The main body of the underwater distributary channel is in direct contact with the sheet sand or interbay mud. The microfacies of the underwater distributary channel is also mostly in contact with the underlying mudstone scouring. However, only the size of the channel is smaller, the thickness of the sandstone is thinned, the grain size is also relatively smaller, and the color is deepened; there is the development of more plate-like interbedded laminations, groove interbedded laminations, or blocky laminations. The SP and GR curves are mostly bell-shaped, and there is also a small amount of upward convergent box shapes.

4.2.2. Mouth Bars

Mouth bars are formed by the accumulation of river-borne detrital material at the mouth of the river as a result of reduced flow velocities. As the delta continues to advance toward the center of the lake, the main part of the mouth bars gradually pushes forward and covers the tail of the mouth bars and the former deltaic mud in turn, so that an upwardly coarsening and thickening anticyclonic sequence of layers appears on the profile and constitutes an important symbol for identifying the delta.

Mouth bars are the product of the joint action of the river and the lake, with lithology dominated by fine siltstone or siltstone. The development of low-angle (wedge-shaped) interbedded laminations or S-shaped texture advances, forming an anticyclonic sequence in the longitudinal direction that changes from fine to coarse (Figure 2a). The morphology of the mouth bars is mostly elliptical in plan with the direction of the long axis parallel to the direction of the river.

The mouth bars are mainly located below the maximum magnitude of the negative deviation of the spontaneous potential curve, with the magnitude of the curve lower than the above underwater distributary channel and higher than the below-sheet sand or far sand dams. They are predominantly funnel shaped or stepped funnel-shaped.

The development of the mouth bars in the study area is less obvious in the main depositional period of the Chang $6_1{}^2$. During Chang $6_1{}^2$ period, the underwater distributary channel is wider, and the hydrodynamic force is stronger, showing stronger scouring effect. In the process of the deltaic sandstone advancing forward, it is difficult for the mouth bar sandstone deposited in the early period to be preserved in its entirety. Therefore, it is often formed in the main body zone of the underwater distributary channel facies in contact with the former deltaic mud syncline, and the scouring effect on the underlayer by the flanks of the underwater distributary channel is also more pronounced, making it possible to form a reservoir sandstone of larger thickness superimposed with the pre-deposited river sandstone. It rarely forms a separate river dam deposit.

4.2.3. Sheet Sand

In this study, sheet sand is a collective term for channel flank sheet sand and leading-edge sheet sand. Channel flank sheet sands are located on both sides of the underwater distributary channel, and frontal sheet sands are located in front of the mouth bars. The sedimentary characteristics of the channel flank sheet sand are similar to those of the channel flank. Still, its grain size is finer, the thickness of the single sandstone is thinner, and the ratio of the layer to the sandy land is smaller (<30%); it mainly develops sandy interbedded laminations, lenticular laminations, and deformation laminations; the sedimentary sequence is mostly symmetrical and rotational, mainly upward half-rotation; and the bottom of the sandstone is also visible as the scouring surface. The spontaneous potential curve is generally a low-amplitude toothed bell shape. The depositional characteristics of the frontal sheet sands have some similarities to the mouth dam, but the difference is also more obvious. In comparison, the frontal sheet sands show finer particles, a thinner sand layer, and rare large-scale interbedded laminations, with parallel laminations and low-angle oblique mainly developed (Figure 2e), and the undulating laminations and undulating interbedded laminations can be seen occasionally. The depositional sequences are mostly manifested in the top–bottom syncline, and the spontaneous potential curves are finger-shaped and toothed. The sheet sand is coeval with the diversion channel and mouth bars.

4.2.4. Underwater Distributary Inter-Channel

The microfacies between the diversion channel are located on both sides of the underwater distributary channel, and the location is closer to the lake shore than the inter-diversion bay. The underwater distributary channel has fewer branches, with a large size of the single branch diversion channel; the location of the channel is more fixed; and the distance between the two branches is also larger. There exists a certain range of muddy sedimentation area in the middle of the two branches of the channel. Muddy siltstone, silty mudstone, and siltstone deposits are dominant between the underwater distributary channels, and fine sandstone deposits can also be seen. The morphology of the logging curve is similar to that of the inter-branch bay, but the grain size is significantly coarser (Figure 5).

4.2.5. Distributary Interbay

The distributary interbay is developed in the low-lying area between the flow channels or in the subsidence area of the abandoned delta dolomite, which is mostly connected with the lake facies mud in the plane, and the water body is generally deeper. Often formed by an organic-matter-rich stagnant reduction environment, the lithology is mainly dark organic-matter-rich mud, peat or lignite deposits, rare thin siltstone interbedded, with blocky laminations, lenticular laminations, waves that can be seen in the wave marks,

bioturbation structures, wormholes, worm track structures, etc., the development of a large number of aquatic Lumulus and other plant debris, roots, rhodochrosite nodules, and so on (Figure 2b,c). Mudstone deposition is dominant, and sandstone lenses are visible. The spontaneous potential and natural gamma ray curve morphologies are low-amplitude microdentate or linear (Figure 5).

4.3. Sedimentary Microfacies Distribution

The distribution of sedimentary microfacies is an important geological basis for development analysis, a key step to study the non-homogeneity of the reservoir and the distribution of residual oil. The distribution of sedimentary microfacies is governed by a series of factors, including paleoclimatic conditions, the mode and intensity of fracture block activity, the bathymetric change of the lake basin, the direction of the source area, and the paleo-topography of the lakeshore, as well as the developmental status and energy of the river system and other factors [24–27]. Based on determining the sedimentary facies and sedimentary subfacies, the present study took the single-well columnar section of the coring well as the starting point, combined it with the microfacies characteristics of the logging wells, and carried out the sedimentary microfacies analysis of the connecting-well section and the planar distribution analysis of the sedimentary microfacies in the study area. The target stratum of this study was the Chang 6 member; since Chang $6_2{}^2$ and Chang 6_3 were not drilled in the area, the sedimentary microfacies map was limited to Chang 6_1 and Chang $6_2{}^1$, and the analysis of the results is as follows.

4.3.1. Chang $6_2{}^1$ Sub-Member

The Chang $6_2{}^1$ period is the earliest period of the Dalugou area that turned to deltaic deposition. After the growth of the previous period to the Chang $6_2{}^1$ period, the delta began to decline, but the area was still mainly characterized by the development of a underwater distributary channel. However, the channel was not very large.

Several underwater distributary channels developed during the Chang $6_2{}^1$ period, and these underwater distributary channels can be roughly divided into two water systems, east and west. The west water system is smaller, and the channel can be divided into two branches. One branch divides east to south and then into three smaller units. The east water system is more extensive, with more channel branches, and the underwater distributary channel generally spreads in a northeast–southwest direction. The extension direction of the underwater distributary channel is shown in Figure 6. The Chang $6_2{}^1$ stage mouth bars are more developed. The mouth bars are mainly distributed at the end of the river's sandstone, which is generally in plan as an elliptical, and the direction of the long axis of the ellipse is the same as the direction of the underwater distributary channel sandstone. The frontal sheet sand, like the mouth bars, is mainly distributed at the front end of the channel, but some is also distributed at the outside. Submerged diverging channels end in sheet sand deposition within the study area, and diverging interbay deposits are widely developed between channels.

4.3.2. Chang $6_1{}^3$ Sub-Member

Compared with the small sedimentary facies of the Chang $6_2{}^1$ sub-member, the underwater distributary channels are less developed at this time, and the number of underwater distributary channels in this period is large. Still, the scale is very small, and many channels are distributed in the interbay mud in the form of branches. The mouth bars in the study area are more developed in the period of the Chang $6_1{}^3$ sub-member; as in the period of the Chang $6_2{}^1$ sub-member, the mouth bars are mainly distributed at the end of the underwater distributary channel. However, the mouth bars of this period do not all show oval shapes in the plane, and part of the mouth bar sandstones are branching out along the forward extension of underwater distributary channels, which are more like the front end of the underwater distributary channel from the viewpoint of the location of the development and the shape of the development and filling (Figure 7).

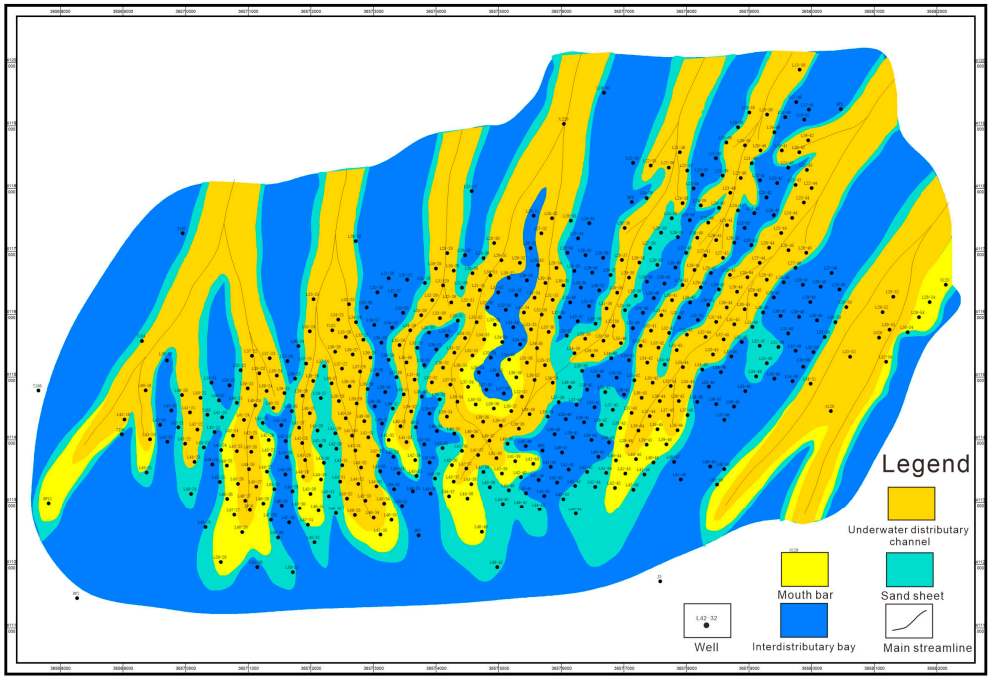

Figure 6. Sedimentary microfacies distribution of the Chang 6_2^1 sub-member in the Dalugou area.

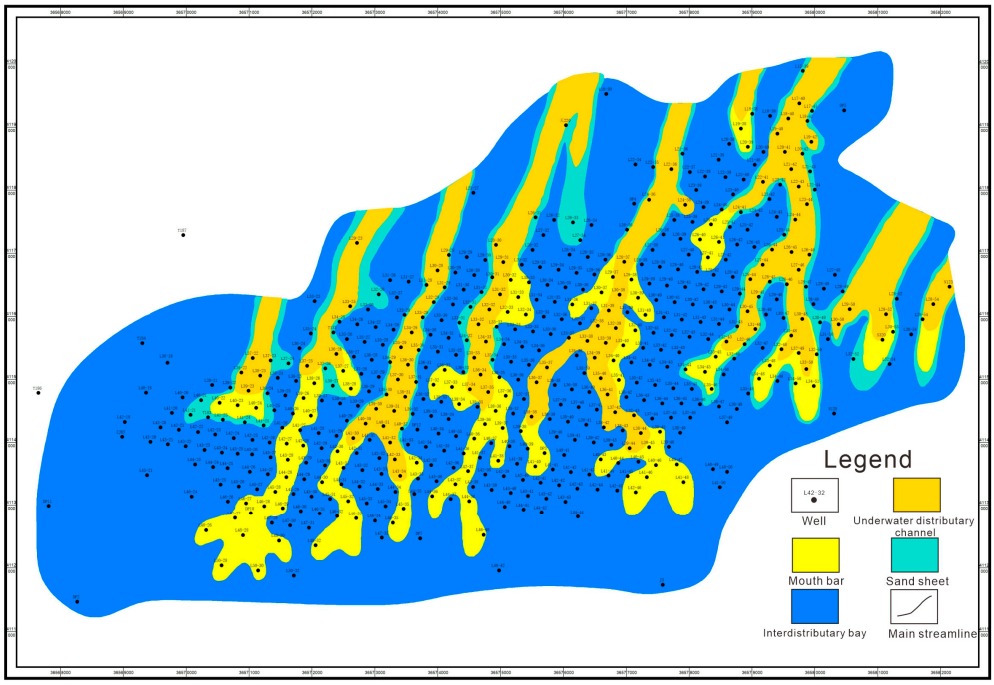

Figure 7. Sedimentary microfacies distribution of the Chang 6_1^3 sub-member in the Dalugou area.

4.3.3. Chang 6_1^2 Sub-Member

This period is the most dominant depositional period of the Chang 6 member because the previous sediments have filled the topography of the lake bottom. The slope of the front edge is very gentle, the delta depositional range is further expanded, the stability is strengthened, and the propulsion of the underwater distributary channel is very significant. Compared with the underwater distributary channel deposition in the Chang $6_1^{1\text{-}3}$ sub-member, the extent of the underwater distributary channel increased significantly, and almost all of the study area was filled by the river channel. To have a clear understanding of the channel trend, the main body of the underwater distributary channel and the flanks

of the underwater distributary channel were subdivided in this period. Figure 8 shows that the main body of the underwater distributary channel was distributed in a branch-like manner. The flanks of the underwater distributary channel were distributed on both sides of the main body of the river and filled the zone between the two main bodies of the river, thus forming the wide seat of a huge body of river sands. It can also be seen from the figure that the underwater distributary channels in the central part of the Dalugou area in the Chang $6_1{}^2$ sub-member are more developed than those on the east and west sides. The underwater distributary channels in the central part of the area extend out of the study area along the northeast–southwest direction. In contrast, the underwater distributary channels on both the east and west sides terminate within the study area and form the mouth bar deposition at the end of the river channel, and the mouth bar sandstone develops in patches and extends out of the study area. The inter-channel deposit is developed in the north of the boundary, and the river is distributed in a strip-like manner. In the south of the boundary, the inter-channel deposition is no longer developed, and the river is distributed in a piece-like manner. The main band of the river starts to show the characteristics of diverging and converging (Figure 8).

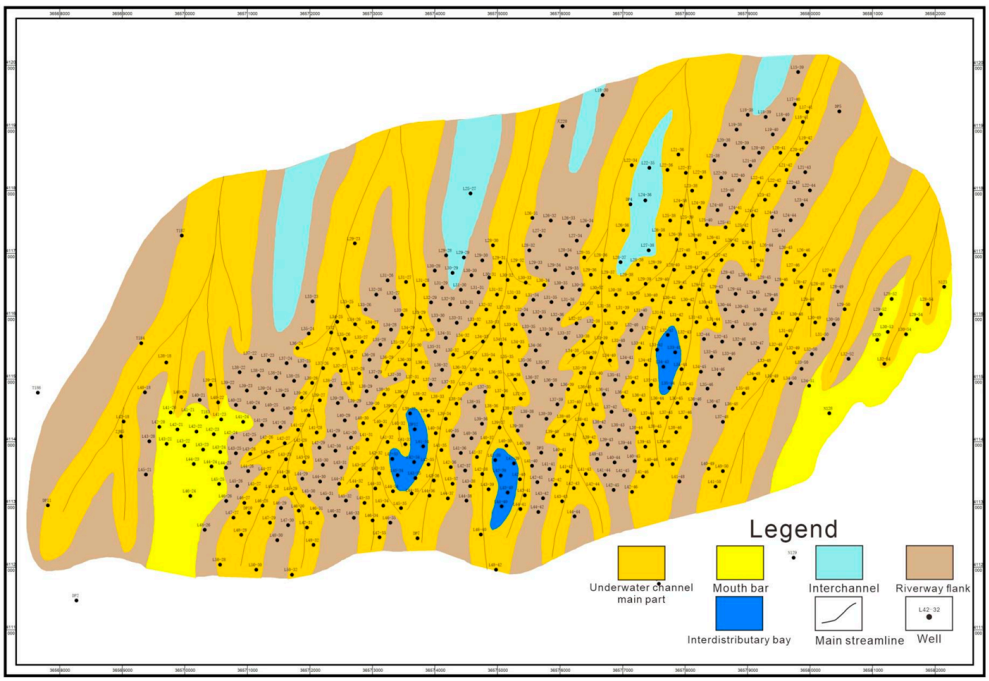

Figure 8. Sedimentary microfacies distribution of Chang $6_1{}^3$ sub-member in the Dalugou area.

4.3.4. Chang $6_1{}^1$ Sub-Member

After the rapid growth of the delta in the Chang $6_1{}^2$ sub-member, the delta started to shrink in the Chang $6_1{}^1$ sub-member, and large areas of interbay deposits began to appear in the study area. However, the overall view of the underwater distributary channels in the Chang $6_1{}^1$ stage is still relatively developed. It can be divided into two water systems, east and west. The channels of the two systems are distribution in a northeast–southwest direction. In the west water system, the energy of the river channel is weaker, and the end of the river channel forms a large area of mouth bar deposition. The mouth bars and the periphery of the river channel are also common sheet sand deposition. The east water system has more substantial river energy, and the river channel extends farther (Figure 9).

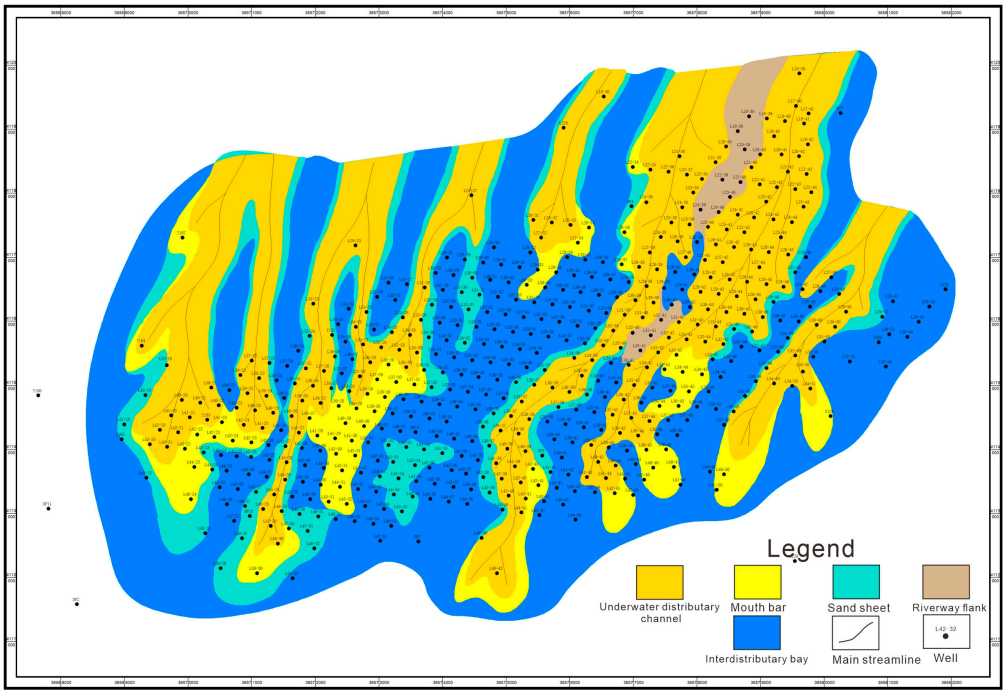

Figure 9. Sedimentary microfacies distribution of the Chang $6_1{}^1$ sub-member in the Dalugou area.

5. Depositional Patterns and Implications

5.1. Dendritic Sandstone Depositional Pattern

The delta front consists of a dendritic distribution of underwater distributary channel sandstone and extensive diversion interbay mudstone (about 50%). The channel sandstone is distributed in strips or intermittent strips, and the thin layer of sheet sand is distributed in surrounding areas. Previous studies suggested that among the deltaic and fluvial facies, sandstones in subaqueous distributary and distributary channels in the deltaic and subaqueous channels in the deltaic environment compose the hydrocarbon reservoir [28–30]. The morphology of the whole sandstone seems to be a dry branch of a tree. The dendritic sandstone depositional pattern originates from the delta's absence of an extensive plain facies zone. In addition, the slope angle of the delta front was large, the depth of the lake varied greatly, and the strength of the river action differed markedly. Thus, the distribution of the sediments varied greatly. This pattern is mainly distributed in the Chang $6_2{}^1$ and $6_1{}^3$ sub-members, and the Chang $6_1{}^1$ sub-member is locally distributed (Figure 10).

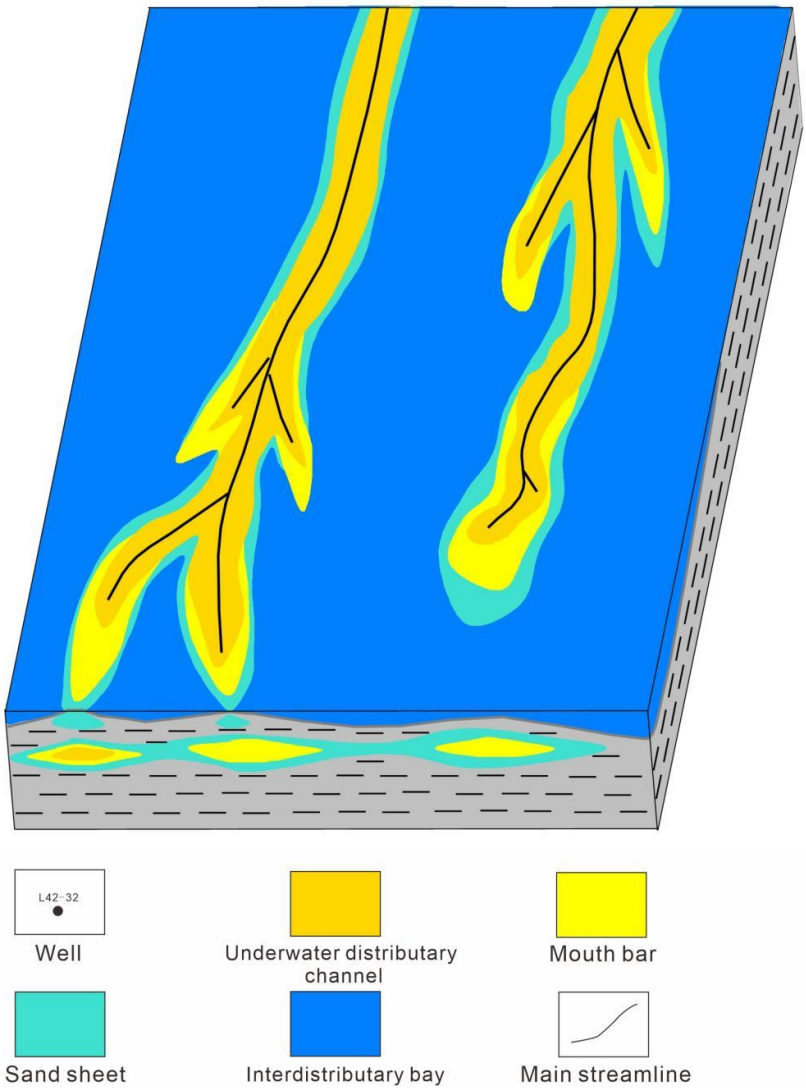

Figure 10. Dendritic sandstone sedimentary pattern patterns of the Dalugou area.

5.2. Lobate Sandstone Depositional Pattern

The forming reason for this type of sandstone is the delta plain was well developed, occupying more than 3/4 of the delta area, while the delta front facies belt is not well developed. Meanwhile, the lake waters are vast, and the slope of the delta front is relatively gentle, causing a small energy difference between the river and the lake. In addition, the material source is abundant, and the substrate is stable. The delta is in a continuous advance to the center of the lake, causing the lake basin to be gradually filled. The lake water becomes shallow, and the sorting and transformation of debris particles gradually increases. Even though the river action is weakening, it can still supply abundant debris materials. With the delta range constantly expanding, the slope of the delta front gradually slows down, and the underwater distributary of the river branching gradually increases. The sandstones show small thickness differences and good contiguity, and it is distributed in foliation. There is a gradual trend between the facies zones and no obvious sign of mutation. In the study area, this pattern is mainly developed locally in the Chang $6_1{}^2$ sub-member and Chang $6_1{}^1$ sub-member (Figure 11).

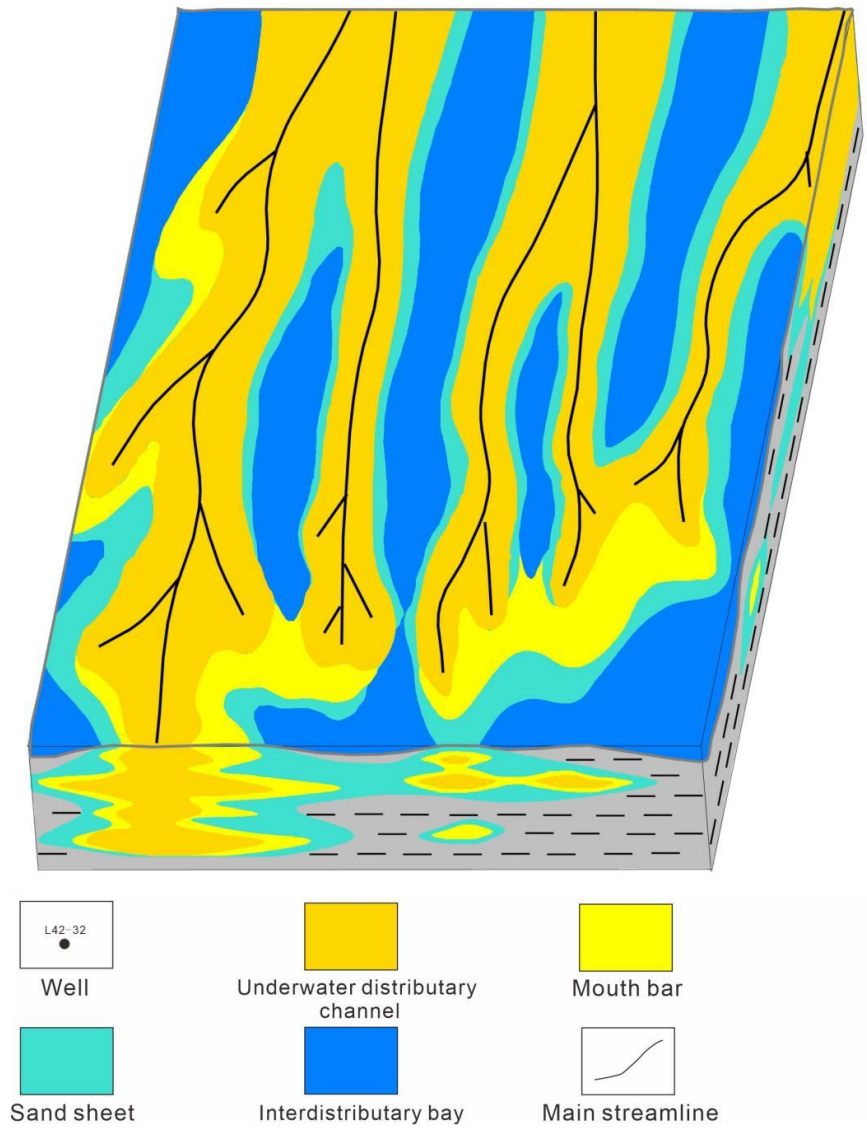

Figure 11. Lobate sandstone depositional pattern of the Dalugou area.

5.3. Insights to Reservoir Characterization and Oil Development

Affected by sedimentation and diagenesis, the sandstone undergoes lateral phase change pinching out or recombination, and the vertical mudstone interlayer and carbonate cemented tight interlayer develop, resulting in strong vertical and horizontal heterogeneity of the reservoir. By observing the field outcrops and core data and conducting a series of single well facies, logging facies, rock facies, profile facies, and planar facies, we summarized a depositional pattern that is instructive or useful for this area and similar areas. The study on sedimentary types and patterns of the Chang 6 member of the Triassic Yanchang Formation in the Dalugou Area of the Jing'an Oilfield can provide significant information for the evaluation of reservoir characterization. Furthermore, the heterogeneity of the Chang 6 reservoir under various depositional patterns has an important influence on oil enrichment.

6. Conclusions

(1) The Chang 6 member in the Dalugou area of the Jing'an Oilfield belongs to the subfacies of the delta front, and six microfacies such as the underwater distributary channel (main belt of underwater distributary channel and the flanks of underwater distributary channel), mouth bars, sheet sand, underwater distributary inter-channel,

and distributary interbay are subdivided based on combining various geological and geophysical logging data. Because the hydrodynamic conditions in the study area are relatively weak and the lake bottom is flat, the river enters the flat and quiet shallow lake. The sediment carried by the rapid advancement of the scouring effect is apparent, and it is difficult to form a complete mouth bar deposition. The mouth bar deposition in this area is not very well developed, and the reservoir in the study area is mainly the underwater distributary channel deposition.

(2) On the whole, the river channel in the study area can be divided into east and west branches. The west branch is distributed in the direction of north–south, and the east branch is distributed in the direction of northeast–southwest. The sediments along the river channel are converging into the lake basin from two directions. From the history of the channel development and change, within the same sand layer, the succession of the channel is better, and the migration swing is not significant. Usually within the sand layer channel, it is largely developed in the same or an adjacent position, and the location of the main channel is also largely the same. The river channels show the characteristic of changing from small to large and then from large to small, and the underwater distributary channels become the largest and deposit the thickest sandstone during the Chang $6_1{}^2$ period.

(3) There are two main sedimentary facies patterns in the study area: the dendritic sandstone depositional pattern and the lobate sandstone depositional pattern. The study on sedimentary types and patterns of the Chang 6 member of the Triassic Yanchang Formation in the Dalugou Area of the Jing'an Oilfield can provide significant information for the evaluation of reservoir characterization. Furthermore, the heterogeneity of the Chang 6 reservoir under various depositional patterns has an important influence on oil enrichment.

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