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Non-homogeneous Characterization of Chang3 Sandstones in the Baipao Area of the Ordos Basin

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Abstract: The Chang3 formation group in the Baibao area has a large variation of distribution both vertically and horizontally, resulting in a high degree of reservoir non-homogeneity and increasing the difficulty of reservoir exploration and development. This leads to strong reservoir in homogeneity, which increases the difficulty of reservoir exploration and development. In this paper, the non-homogeneity characteristics of the Chang3 oil formation group are studied in depth from both macroscopic and microscopic aspects by means of core observation, cast thin section identification, scanning electron microscope analysis and well logging data statistics. The results show that: The Chang3 oil formation group is mainly deposited at the front edge of the delta, and spreads in the under water diversion channel; the sandstone clasts in the reservoir of Chang 3 Reservoir mainly consist offeldspar and quartz, and the particles mainly consist of fine grains, with good particle sorting; thereservoir variability coeficient, extreme deviation, stratification coefficient and sandstone density areall very high, and the development of parallel lami nations, horizontal lami nations, plate inter layers and groove interlayers, with strong, inter layer and intra layer non-homogeneity;, the variation range of theme dian radius of the pore is not wide, and the physical characteristics are relatively poor. Theme dian radius of pore space varies little, the physical characteristics are poor, and it belongs to low porosity, extra low porosity-low permeability reservoir, with relatively strong microscopic non-homogeneity;, the planar non-homogeneity is strengthened with the change of the width of the river channel, and the sand body spreads continuously in sheets, and the section is in the shape of a plate or asymmetric lenticular, and the sand body has the flow ability, with strong planar non-homogeneity.

Keywords: Ordos Basin; Reservoir; Inhomogeneity; Sandstone.

1. Introduction

In the exploration and development of oil reservoirs in the Ordos Basin, low-permeability oil and gas play an important role (Qiu Yinan, 1997; Jiang Lingzhi et al., 2004). The Chang 3 oil reservoir group of the Upper Triassic Yanchang Formation is one of the main oil-bearing strata (Li Ping et al., 2023; Li Yuhong, 2016; Zeng Lianbo et al., 2007). Scholars have gradually conducted a series of studies (Wang Zhao, 2024), and the rock porosity of this formation is generally about 10%, with permeability typically not exceeding 10×10^{-3} μm², classifying it as a low-permeability sandstone reservoir (Yuan Guangjin et al., 2017; Li Fengjie et al., 2005). The sedimentary, diagenetic, and tectonic processes in low-permeability reservoir areas are typically characterized by severe heterogeneity, which can even affect the deployment and effectiveness of reservoir exploration and development (Yang Zhengming, 2006; John C L et al., 2002; Finkbeiner T et al., 1997; Wu H et al., 1995). Therefore, the heterogeneity characteristics of the reservoir have a very significant impact on the development of low-permeability oil fields (He Ziqiong et al., 2021), and research on reservoir heterogeneity has gradually developed from the microscopic to the macroscopic level (Yu Cuiling et al., 2007). Luo Xiaorong et al. analyzed the heterogeneity characteristics of river-lake facies in the western Ordos Basin from a microscopic perspective (Luo Xiaorong et al., 2016); Zhang Xiaoyin et al. used UAV technology to investigate oil sand outcrops and retrogradation, and explored the impact of sandstone heterogeneity on the structure and diagenetic characteristics of individual sand layers, concluding that the distribution of oil in the reservoir is significantly influenced by sedimentary environment and diagenesis (Zhang Xiaoyin et al., 2024); He Tuoping et al. elaborated on the large-scale heterogeneity of deep-sea gravity flow reservoirs based on deep-sea flow sedimentology theory (He Tuoping et al., 2020).

The Bai Bao area is located in the southwest of the Ordos Basin, and its oil reservoir group has become one of the potential layers for exploration and development in recent years. As one of the main oil-bearing strata, the Chang 3 oil reservoir group consists of underwater distributary channel sandbars formed by deltaic deposits. The Chang 3 oil reservoir group is controlled by nose-like uplifts and lithology, resulting in strong heterogeneity both vertically and laterally (Guo Yanqin et al., 2013), which leads to low reservoir productivity and difficulties in maintaining stable production (He Hui et al., 2021; Li Yuanliu, 2020). Therefore, this paper mainly conducts an in-depth study on the heterogeneity characteristics of the Chang 3 oil reservoir group in the Bai Bao area, from both macroscopic and microscopic perspectives, through core observation, cast thin section identification, scanning electron microscopy analysis, and well logging data. The study focuses on heterogeneity across three aspects: interlayer, intralayer, and planar heterogeneity. These studies provide geological evidence for the future effective development of the reservoir.

2. Regional Background

During the Late Triassic period, the lake basin deposition and evolution in the Ordos Basin went through a process that began with initial subsidence, gradually expanded and reached its peak, followed by a slowdown until it eventually

disappeared, completing the entire process of lake basin formation, growth, and extinction (Fu Jinhua et al., 2005). The study area is located in the southwest part of the northern slope of the Ordos Basin, influenced by the Indosinian orogeny, where large-scale lakes were formed (Li Wenhou et al., 2009). During that time, basin subsidence and sedimentary activity were concentrated in the southern and southwestern directions. This region contains sedimentary systems from multiple geological periods, which are rich in petroleum and natural gas resources. Particularly, the Upper Triassic Changyan Formation, formed in an inland lake delta environment, is an important oil and gas reservoir (Wu Fuli et al., 2004), and is also the main oil-bearing stratum in the study area of this paper.

3. Reservoir Characteristics

3.1. Petrographic Types and Colors

The sandstone of the Chang 3 oil reservoir group in the Bai Bao area is mainly feldspathic litharenite, followed by feldspar sandstone, with the primary particles being feldspar, quartz, and rock fragments (Fig. 1). The quartz content ranges from 35% to 55%, with an average of 46.47%; feldspar content ranges from 25% to 50%, with an average of 38.29%; and rock fragment content ranges from 5% to 15%, with an average of 15.24%. Among the rock fragments, the volcanic rock fragment content is 0% to 4%, the sedimentary rock fragment content is 0% to 4%, the metamorphic rock fragment content is 2% to 8%, and the mica rock fragment content is 4% to 10%. The pore-filling material is mainly cement, with carbonate minerals such as ferroan calcite and ferroan dolomite, which average 3.12% and 0.02%, respectively. The clay minerals are predominantly chlorite, illite, and kaolinite, with average contents of 2.00%, 0.61%, and 0.12%, respectively. The study area is mainly composed of gray, gray-green, and gray-brown fine sandstones, and interbedded gray-brown fine sandstones with gray siltstones. The lithological characteristics indicate that the study area is a delta front sedimentary environment.

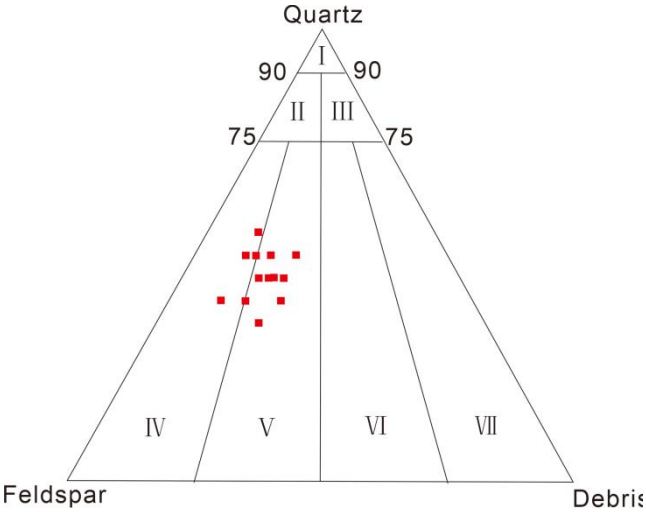


Fig 1. Triangle diagram of rock types in the Chang-3 oil reservoir group in the Baibao area
(I: Quartz sandstone; II: Quartz-feldspar sandstone; III: Quartz-litharenite; IV: Feldspar sandstone; V: Feldspathic litharenite; VI: Lithic-feldspar sandstone; VII: Litharenite)

3.2. Reservoir Petrophysical Characteristics

Reservoir properties are important parameters for characterizing and describing reservoir heterogeneity. The petrophysical analysis of the Chang 3 oil reservoir group in the study area indicates that the porosity generally ranges from 7% to 17%, with a distribution range of 7% to 17% and an average value of 11.62%. The permeability is typically low, ranging from 0.1×10^{-3} to 3×10^{-3} μm², with an average value of 1.42×10^{-3} μm², indicating that the reservoir is classified as low-porosity, ultra-low porosity to ultra-low permeability (Fig. 2 andFig. 3).

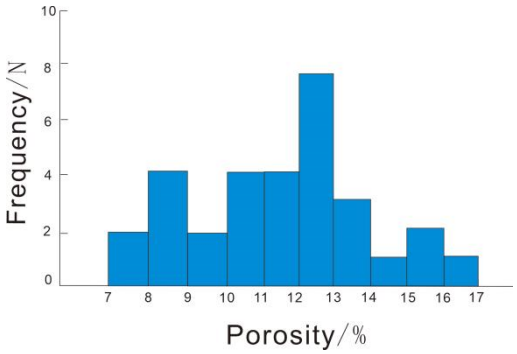


Fig 2. Histogram of Reservoir Porosity Distribution

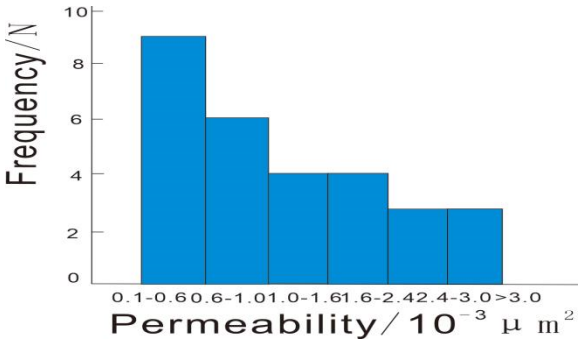


Fig 3. Histogram of Reservoir Permeability Distribution

4. Reservoir Heterogeneity Characteristics

4.1. Microscopic Heterogeneity

(1) Particle Heterogeneity

The study indicates that the particles in the Chang 3 fine sandstone of the study area have good roundness, mostly ranging from sub-rounded to sub-angular, with pore-type contacts being dominant. The sorting is moderate to good. The particle size frequency curve shows a peak around 20%, with the main peak located on the fine-grained side, indicating that the fine-grained components are predominant (Figure 4). This reflects the underwater depositional characteristics.

(2) Pore Heterogeneity

The pores in the Chang 3 oil reservoir group are classified into primary pores and secondary pores. Data analysis shows that the average pore surface porosity of Chang 3 is 4.22%, with the primary intergranular pores being the dominant type (Fig. 5-a), accounting for 2.89%. Secondary pores follow, with feldspar dissolution pores (Fig. 5-b) and rock fragment dissolution pores (Fig. 5-c) having surface porosities of 0.86% and 0.47%, respectively. The minimum value of the average pore diameter is 28 μm, and the maximum value is 35μm. The maximum value of the median pore radius is 0.43μm, and the minimum value is 0.24μm. The pores are mainly

characterized by small pores with fine throats.

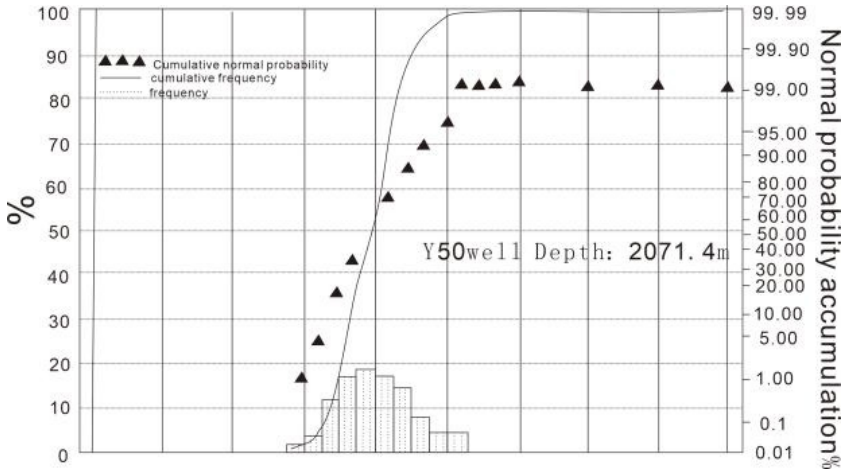
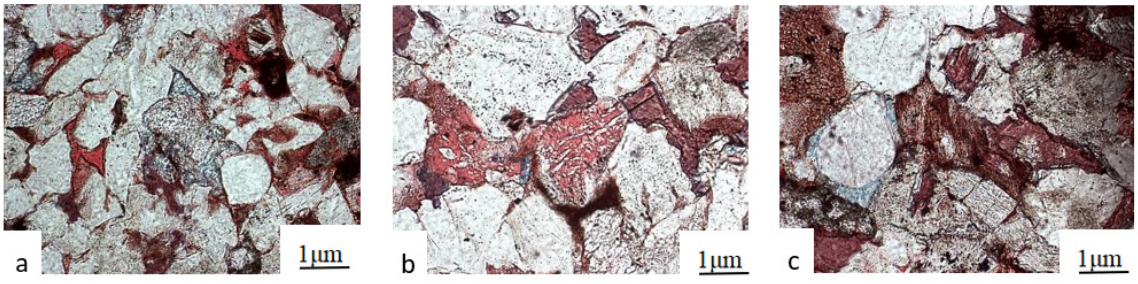


Fig 4. Statistical Chart of Grain Size Distribution of Chang-3 Oil Formation in Baibao Area



a-H609,1721.85m,primary intergranular pore

b-Li31,1920.1m,feldspar intragranular dissolution pore

c-Be206, 1776.22m, ferroan calcite replacing feldspar

Fig 5. Common pore types in Chang 3 reservoir in Baibao area

4.2. Macroscopic Heterogeneity

4.2.1. Intralayer Heterogeneity

(1) Grain Size Distribution Characteristics

The grain size cumulative probability curve in the study area shows a distinct bimodal characteristic, which corresponds to the sedimentary process of distributary channels. One side of the curve has a relatively gentle slope, indicating lower sorting efficiency, which represents the overall suspended particles. On the other side, the steep slope suggests higher sorting efficiency and a large amount of leap components, typically accounting for 80-90% of the total, with a higher proportion of these leap components. In contrast, the proportion of suspended particles is much lower, around 10-20% (Fig. 6). This also indicates that the Chang 3 oil reservoir group in this region has a strong and stable depositional hydrodynamic environment, showing good sorting ability of sedimentary particles, which is consistent with the characteristics of underwater distributary channels.

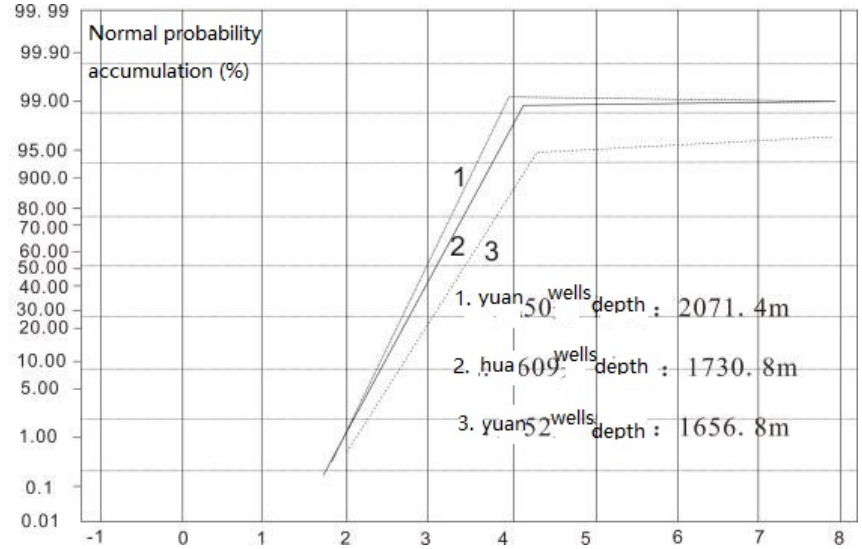


Fig 6. Cumulative probability curve of grain size for Chang 3 sandstone in the Baibao area

(2) Grain Size Profile

The study area is primarily characterized by the development of delta front subfacies. The sandy structures of the underwater distributary channels at the front of this type of delta are similar to those of typical river channel facies, presenting a conical shape with a flat top and prominent base. From a planar perspective, they expand towards the lake interior in a petal-like or footprint pattern. As the channel continues to extend into the lake basin, its depth and width gradually decrease until it eventually disappears. The main sedimentary feature of underwater distributary channels is the alternation of thick sandy layers with delta mud at the base or mudstones between distributary channels, forming a unique sedimentary series (Fig. 7). Vertical analysis of the profiles shows that the sandy layers become progressively sparser from the bottom upwards, indicating that as sediment accumulation continues, the water depth will decrease, and the water's kinetic energy will also reduce. Consequently, the thinner sandy sections' natural potential curvature and natural gamma curves will show as finger-like or sharp peaks (Fig.8).

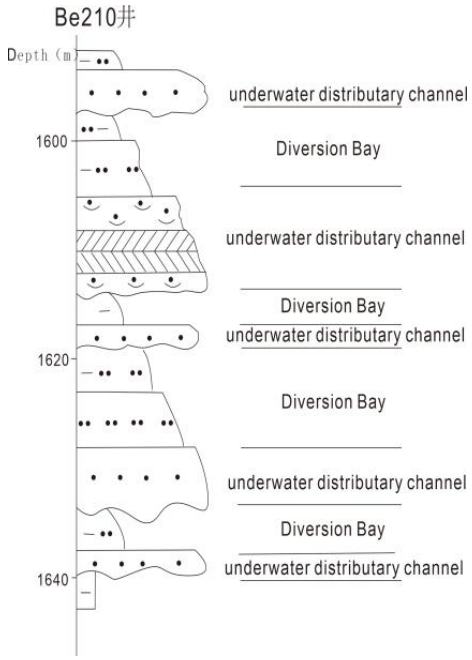


Fig 7. Sedimentary sequence diagram of underwater distributary channel in the delta front

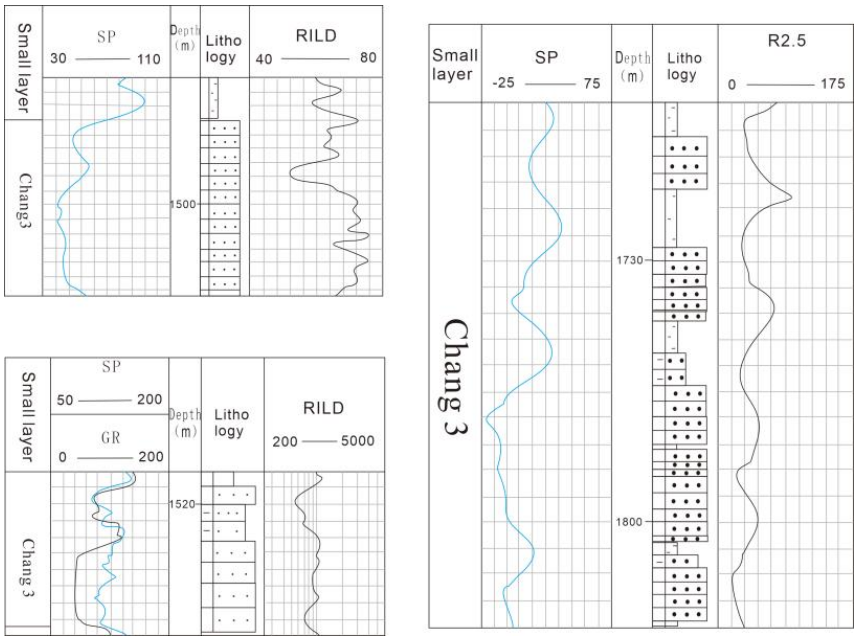


Fig 8. Sedimentary rock electrical characteristics of underwater distributary channels in the delta front

(3) Stratification Structures



a-Horizontal bedding (Bai 210, 1728.39m)

b-Horizontal bedding, ripple bedding (Bai 210, 1726.24m)

c- Parallel bedding (Bai 210, 1725.05m)

d-Ripple cross-bedding (Xin 38, 1501.10m)

e-Planar cross-bedding (Hua 609, 1735.50m)

f-Trough cross-bedding (Hua 209, 1903.50m)

Fig 9. Layered structural characteristics of Chang 3 sandstone in the Baibao area

Stratification structures are structural phenomena formed during the sedimentary process or before consolidation and lithification. Primary sedimentary structures are referred to as primary sedimentary fabrics, while quasi-synchronous deformations are defined as quasi-synchronous deformation structures. These structures reflect the hydrodynamic conditions of the sediments and can reveal the properties and strength of the medium. Through core studies, it has been found that in the Chang 3 reservoir area of the Bai Bao region, the predominant stratification structures are horizontal stratification (Fig.9-a, b), parallel stratification (Fig.9-c), and cross-bedding. Notably, the commonly observed cross-bedding includes ripple cross-bedding (Fig. 9-b, d), planar cross-bedding (Fig. 9-e), and trough cross-bedding (Fig.9-f). These three types of cross-bedding are typically found in underwater distributary channels, delta front, and tidal bars, and are also present in the bay areas between distributaries.

4.2.2. Interlayer Heterogeneity

Interlayer heterogeneity primarily reveals the distribution of isolation layers between the small layers in the vertical direction, the variation characteristics of permeability, and the cyclical development of sand bodies. Therefore, the heterogeneity between layers is the core reason for the uneven vertical distribution of oil and gas, water flooding conditions, and the differences in the distribution of residual oil.

(1) Layering Coefficient and Sandstone Density

The indicators used to measure interlayer imbalance include the layering coefficient and sandstone density, which can reveal the development status and characteristics of the sand. We calculated and statistically analyzed the number and total thickness of sandstone layers in the internal drilling wells of the region. The results show that the range of the layering coefficient is from 0 to 19, with an average layering coefficient of 5.25 for the region, indicating a considerable variation between the layers. For the Chang 3 layer segment, which has three layers, the average oil layer coefficient is approximately 2.00, suggesting a relatively balanced distribution of oil in the sand. However, the overall sandstone density of the Chang 3 segment is higher, with values ranging from 3.2% to 92.6%, primarily concentrated between 20% and 70%. The average value for the Chang 3 segment is as high as 34.68%, which is the smallest among all layers (Table 1). Additionally, many oil and oil-water mixed layers were found in the study area. Based on this initial inference, we can observe that most of the porosity values in this region are low, but the permeability values fluctuate significantly. This phenomenon creates barriers in the vertical direction while establishing favorable flow paths in the horizontal direction, effectively trapping liquids and aiding in oil and gas generation.

Table 1. Stratification coefficient and sandstone density of Chang 3 reservoir in Baibao area

Layer position	Number of single sand layers per interval	Layering coefficient		Oil layer coefficient		Sandstone density / %	
		Interval	Average	Interval	Average	Interval	Average
Chang3	0-13	0-19	5.25	0-5	2.00	3.2-92.6	34.68

(2) Interlayer Permeability

The study shows that the minimum permeability of the Chang 3 oil reservoir group in the study area is 0.01×10^{-3} μm², while the maximum permeability reaches 75.5×10^{-3} μm². The variation degree ranges from 0.42 to 2.27, and the advance degree ranges from 1.36 to 17.92, with the difference falling between 3.98 and 3775 (Table 2). Based on the permeability heterogeneity indicators, it can be concluded that there is a significant heterogeneity phenomenon in the Chang 3 layer segment of this region. Similarly, the distribution pattern of the stratification difference index and advance degree is very similar, especially showing a strong heterogeneity trend in the east-west direction. This suggests that the heterogeneity in this region not only affects the vertical sealing effect but also creates beneficial horizontal pathways, thus having a positive impact on the large-scale accumulation of oil and gas.

Table 2. Statistical Table of Permeability Parameters for Some Wells in the 333 Layer Section

Layer position	Well number	Max K ($\times10^{-3}$um^2)	Min K ($\times10^{-3}$um^2)	Avg K ($\times10^{-3}$um^2)	Coefficient of variation	Advance coefficient	Gradient coefficient
Chang3	Be202	0.79	0.01	0.25	1.02	3.21	79
Chang3	Be205	0.62	0.02	0.21	0.78	2.96	31
Chang3	H155	4.12	0.01	0.79	1.09	5.19	412
Chang3	H157	15.5	0.07	3.98	0.67	3.89	221
Chang3	H160	4.71	0.03	1.97	0.78	2.4	157
Chang3	H178	4.65	0.13	1.65	0.71	2.82	35.77
Chang3	H203	3.99	0.09	0.63	1.23	6.30	44.33
Chang3	Li42	0.16	0.04	0.12	0.57	1.36	3.98
Chang3	H154	1.79	0.21	0.67	0.95	2.66	8.52
Chang3	H155	75.5	0.02	4.21	2.27	17.92	3775
Chang3	H203	0.54	0.03	0.24	0.42	2.23	18
Chang3	H98	11.6	0.01	1.31	1.40	8.88	1160

4.3. Planar Heterogeneity

The sand bodies of the Chang 3 formation in the study area exhibit a sheet-like distribution on the plane, with a tabular or asymmetrical lens shape in the profile (Fig.10). Some single sand bodies located in the central part of the study area show a dry layer across the entire region. Their main feature is their extension to the north and south, with a well-connected, flat layout. Along the north-south axis, only some sand bodies in the Wuqi and surrounding areas exhibit slight extension, while other sand bodies are mostly asymmetrical lenticular shapes and lack good connectivity. In contrast, the sand bodies in the central part of the study area show better connectivity, especially in the east-west direction. The main oil-bearing layers exhibit extension and are connected with certain single sand bodies in the southern Nanliang area.

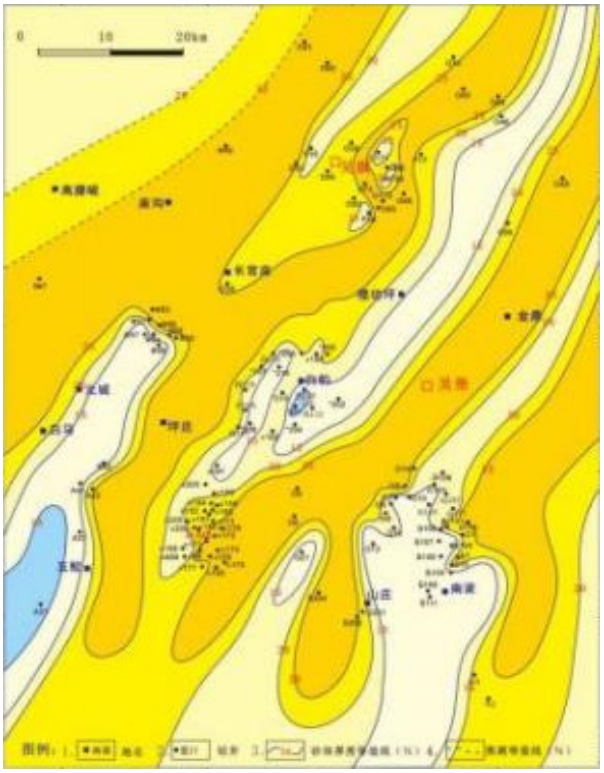


Fig 10. Plan of Thickness of Long 3 Sand Body in Baibao Area

5. Conclusion

(1) The sandstone of the Chang 3 oil reservoir group in the Bai Bao region is primarily composed of feldspar lithic sandstone. The clastic particles mainly consist of feldspar and quartz, with good roundness, predominantly sub-rounded to sub-angular, and mainly exhibiting pore-type contact. The sedimentary particles are well sorted, indicating a depositional environment typical of underwater distributary channels.

(2) The Chang 3 oil reservoir group in the Bai Bao region was deposited in the delta front rock layers, with the main reservoir formed by distributary channels. The sand bodies in each layer exhibit a vertically developed pattern, while the horizontally distributed sand bodies display horizontal bedding, parallel bedding, ripple bedding, planar bedding, and trough bedding.

(3) The macro heterogeneity of the Chang 3 reservoir in the Bai Bao region can be divided into two aspects: vertical (interlayer, intralayer) and horizontal heterogeneity. Sedimentary processes are the main controlling factors for the plane distribution of the reservoir. The vertical heterogeneity of the reservoir is strong, with micro heterogeneity being secondary. The primary cause of the micro heterogeneity of the reservoir lies in the sandstone pore structure, which is significantly influenced by the development of secondary pores.

(4) The Chang 3 reservoir in the Bai Bao region is a low-porosity, ultra-low porosity to low-permeability reservoir. The sand body layering coefficient and sandstone thickness are both relatively large. Indicators such as the coefficient of variation, advance coefficient, and range show that the reservoir exhibits strong and stable heterogeneity, which is favorable for the formation of oil and gas reservoirs.

Acknowledgments

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