Evaluation of Sedimentary Characteristics of the Chang 9 Oil Layer Formation in the Yanchang Formation, Ordos Basin

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Abstract: Shallow-water deltas are a subject of sedimentary research and represent a significant target for oil and gas exploration. The Yanchang Formation of the Triassic in the Ordos Basin comprises numerous shallow-water delta blocks. This paper addresses the core issues pertaining to the sedimentary facies, sedimentary characteristics and sand body distribution of the Chang 9 oil layer formation of the Upper Triassic in the Ordos Basin. Guided by the relevant theories and methods of contemporary sedimentology and sedimentary geology, the reservoir characteristics are described and studied in detail through ordinary thin sections, cast thin sections, graphical representations of particle size and scanning electron microscopy experiments. The experimental results indicate that the porosity in the study area ranges from 3% to 12% and that the permeability is between $0$ and $1.5 \times 10^{-3} \mu m^2$, which is consistent with classification as an ultra-low-porosity and ultra-low-permeability reservoir. The Chang 9 sandstone is composed of feldspar sandstone and lithic feldspar sandstone. The average content of quartz is low, at less than 31%, while the average content of feldspar is high, at more than 34%. The average content of rock debris is between 10% and 20%. Therefore, the compositional maturity of the Chang 9 sand body is generally low. The particle size distribution exhibits a positive deviation, indicating that the sediments in the sand body are primarily coarse-grained components. The kurtosis of the particle size–frequency curve is observed to vary from flat to very sharp. The Chang 91 lake is classified as a shore shallow lake with basin subsidence and lake transgression. The Chang 9 period saw the development of the Chang 91 sedimentary facies into a semi-deep lake–deep lake environment. The vertical structural style of the Chang 9 oil layer formation in the basin can be roughly summarized into three basic structural types: the sedimentary structures observed in the area include box-shaped upward thinning, bell-shaped upward thinning and funnel-shaped upward thickening. The delta front area in Chang 9 is notable for its size and the prevalence of underwater distributary channel microfacies. The sand body distribution is stable, with sand layer thicknesses ranging from 15 to 30 m. The evaluation and summary of the sedimentary characteristics of the Chang 9 oil layer formation provide a geological basis for future exploration and development in the study area.

Keywords: Ordos Basin; Chang 9 oil layer formation; sedimentary facies; sand body characteristics

1. Introduction

In recent years, tight oil has emerged as a significant area of focus in the realm of unconventional oil exploration and development globally. In 2013, the EIA predicted that the recoverable tight oil resources globally amounted to $473 \times 10^8$ t [1], with the geological tight oil resources in China estimated at approximately $120 \times 10^8$ t. These resources are primarily distributed in the Yanchang Formation of the Ordos Basin, the Cretaceous of the Songliao Basin and the Shahejie Formation of the Bohai Bay Basin [2–5]. Among these, the tight oil resource Chang 9 of the Yanchang Formation in the Ordos Basin has developed three types of reservoir combination: the self-generation and self-storage type, the lower generation and upper storage type and the upper generation and lower storage type. Among these, the self-generation and self-storage accumulation...
combination utilizes Chang 9 dark mudstone or oil shale as the source rock and Chang 9's own sandstone as the reservoir, exhibiting the greatest exploration potential. The reservoir space is primarily composed of residual primary intergranular pores, exhibiting excellent reservoir performance. Currently, there is a paucity of comprehensive research on the sedimentary facies, sedimentary characteristics and sand body distribution of Chang 9 from the perspective of the entire basin. This is likely to impede subsequent exploration and development of Chang 9 in the Ordos Basin. Consequently, a comprehensive analysis of the sedimentary facies and characteristics of Chang 9 from the perspective of the entire basin was undertaken to reveal the plane distribution characteristics of sedimentary facies, study the distribution law of sand bodies within the sedimentary framework of the basin, predict favorable reservoir facies belts and provide a geological basis for improving the success rate of exploration and development of Chang 9 in the Ordos Basin.

Since the 1950s, significant advances have been made in the study of geology and sedimentary geology. Potter and Pettijohn [6] proposed in their book, “Paleocurrent and Basin Analysis”, that the process of sediment accumulation from top to bottom in the medium occurs in the form of sediment “rain”, with the sedimentary layer accumulating vertically. Strata without inversion are always new above and old below. A rock interface with continuous extension of the same property must be isochronous, and the rock phase transition does not conform to Walter’s law of phase transition. Hein [7] highlighted that in geological history, the different characteristics of regional geotectonics and regional paleogeomorphology units are among the main factors controlling the distribution and development of sedimentary facies belts. In areas of high paleogeomorphology, the deposition of beach sediments conducive to the formation of reservoirs is influenced by the presence of an open water body and relatively strong hydrodynamic conditions. Neal [8] posited that the diagenesis process exerts a significant influence on the properties of sedimentary organic matter. The diagenetic stages of organic matter in sediments are distinct, and the products converted to hydrocarbons are also different. From the 1980s to the end of the 20th century, the development and application of high technology and the mutual penetration of various disciplines led sedimentology workers to gradually realize that there are various scales in geological records. Pemberton and Tao Youbing et al. [9,10], found that the geological records are vertically distributed with regularly and laterally distributed sedimentary cycles or rhythmic events that can be correlated intracontinentally, intercontinentally or globally. In the early stages of sedimentary geology, Parrish [11] highlighted the significance of paleoclimate in sedimentary records and emphasized the global synchrony of sedimentary records. Ojala [12] underscored the significance of various sedimentary events and the influence of global sea-level fluctuations on sedimentary records. Delgado-Fernandez [13] posited that the investigation of sedimentary characteristics should prioritize the examination of the sedimentary environment, sedimentation and spatiotemporal alterations of matter within a specific region of the crust, encompassing changes in nature, scale and rate. This should be followed by an investigation into the causes and driving forces behind such changes.

Yang Yongqiang, Liu Jiangbin and others [14–18] have demonstrated that tight sandstone reservoirs in China are primarily developed in three sedimentary environments: continental facies, marine continental transitional facies and marine facies. The continental tight sandstone reservoir is currently the most prevalent unconventional reservoir type, including the Yanchang Formation of the Mesozoic in the Ordos Basin, the Jurassic in the Sichuan Basin and the Shahejie Formation in the Bohai Bay Basin. The sedimentary types include alluvial fans, rivers, deltas, beach bars and deep lakes, among others. The research of Shen Yulin and Xiao Xiaoguang [19,20] indicates that the tight sandstone reservoir of marine continental transitional facies is represented by the Sulige Shihezi Formation in the Ordos Basin. The sand body is primarily a shallow-water delta sedimentary system. Marine tight sandstone reservoirs are distributed in the Silurian in the eastern Tarim Basin, the Silurian in the Sichuan Basin and the Carboniferous–Permian in the Ordos Basin. They are mainly developed in braided river deltas, sand bars, tidal flats and other environments.
Gaswirth and Smith et al. [21–23] found that foreign tight sandstone reservoirs are mainly marine facies and marine continental transitional facies. For instance, the Bakken Formation of the Williston Basin is a set of marine clastic deposits.

Herein, theories and methods of contemporary sedimentology and sedimentary geology are employed to analyze the sedimentary environment of the basin. This is achieved through a comprehensive analysis of field geological sections, drilling cores, logging and analysis test data. The analysis begins with an examination of the basin’s sedimentary background and progresses to the sedimentary characteristics of Chang 9 and the plane distribution characteristics of sedimentary facies. The genetic types and structural characteristics of sand bodies in different sedimentary facies belts of Chang 9 in the basin are studied, and the distribution characteristics of sand bodies in Chang 9 in the basin are analyzed. The reservoir characteristics of the Chang 9 oil layer formation in the Yanchang Formation are studied, with a focus on the main controlling factors of the reservoir. This provides a deeper understanding of the geological context, leading to the discovery of a previously unidentified “desert” reservoir development area. These data can inform future exploration and subsequent development of the Yanchang Formation area.

2. Research Materials and Methods

2.1. Research Materials

Rock samples were uniformly collected from various wells (W9, D38, H4, C88, C19, Q41, X208, etc.) across the study area to ensure a comprehensive representation of its rock characteristics. Thirty typical samples were then chosen for analysis. Thin section experiments were conducted using rocks from depths of 51.55 m (well W9) and 761.25 m (well H4). Additionally, SEM experiments utilized samples from depths of 840.47 m (well C19) and 864.77 m (well C88). Cores for X-ray diffraction experiments were obtained from depths of 875.47 m (well Q41), 793.69 m (well X208) and 809.43 m (well D38). (All experimental instruments in this article come from Wuhan, China) as shown in Table 1.

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2.2. Research Methods

In this paper, scanning electron microscopy, X-ray diffraction and core casting thin section experiments were used to analyze the core of tight sandstone:

(1) Scanning electron microscope experimental analysis: It was performed mainly to obtain the micromorphology of core samples by electron signal imaging. SEM experimental analysis involves using a scanning electron microscope (SEM) to examine core samples. The process includes several key steps: preparing samples to ensure they have smooth and conductive surfaces; loading them onto the SEM stage; directing an electron beam onto the sample surface; collecting signals using detectors; processing the signals to enhance image clarity; and analyzing the images to identify microstructural features such as particle size, shape and arrangement. This method facilitates the acquisition of crucial information regarding sample composition, structure and porosity properties through quantitative or qualitative evaluations.
(2) X-ray diffraction experimental analysis: This experiment aimed to utilize X-ray diffraction to analyze the mineral content of rock samples. Initially, the samples undergo meticulous preparation before being loaded into the instrument. Subsequently, X-rays are used to irradiate the samples, and the resulting diffraction patterns are recorded and analyzed for peak positions and intensities. Analysis of peak positions allows inference of each sample’s crystal structure. Moreover, peak intensity correlates positively with mineral content, enabling quantitative analysis of different minerals’ content in the sample. Ultimately, thorough analysis of the diffraction patterns and interpretation of quantitative data yield precise estimations of mineral content in the samples, facilitating in-depth discussions regarding their geological significance.

(3) Rock casting thin section analysis: Rock thin section casting analysis involves several key steps. Firstly, thin sections are meticulously prepared from rock samples and then meticulously imaged under an electron microscope. The electron signals emitted from each sample’s surface are meticulously recorded and thoroughly processed to extract detailed information regarding its microstructure and chemical composition. Subsequently, these thoroughly processed signals undergo meticulous morphological and compositional analysis to accurately identify the rock type. This is followed by a careful comparative analysis with other samples to precisely delineate their differences and characteristics. Through meticulous signal processing via electron beam spots, the rock type of the Yanchang Formation reservoir in Ordos could be precisely determined, facilitating in-depth comparison and analysis of the characteristics of tight oil reservoirs.

3. Results and Discussion

3.1. Regional Geological Background

The Ordos Basin is situated between the northern Yinshan Mountains, the southern Qinling Mountains, the eastern Lianshan Mountains and the western Tengger Desert. It is the second largest sedimentary basin in China, with an area of approximately $37 \times 10^4 \text{ km}^2$. Surrounded by Meso-Cenozoic fault basins such as the Hetao, Yinchuan, Bayanhaote, Liupanshan and Weihe, this part is approximately 700 km long from north to south and about 400 km wide from east to west, and the total area is approximately 25,104 square kilometers. The basin is surrounded by mountains, and the basin is bounded by the Great Wall, arid desert grassland area in the north and the semi-arid Loess Plateau area in the south. There are vertical and horizontal valleys and complex terrain. The study area is located south of Wushenqi, east of the western margin of the subduction zone, west of the Mizhi-Qingrun-Yanchang-Yichuan line and north of Binxian. It is characterized by vertical and horizontal valleys and complex terrain. The location of the study area is shown in Figure 1.

A 5 m thick black shale outcrop is visible in the eastern region of the study area, where the source rock has been successfully drilled. The organic matter content is high, and the maturity level is moderate. The reservoir condition in the Chang 9 formation is favorable. The delta front is characterized by sheet sand deposits, which are primarily dominated by underwater distributary channels and mouth dam sand bodies. The reservoir space is primarily composed of residual primary intergranular pores, exhibiting excellent reservoir performance. The Chang 9 oil layer formation comprises three distinct reservoir combinations: self-generation and self-storage, lower generation and upper storage and upper generation and lower storage. Of these, the self-generation and self-storage combination is particularly noteworthy, as it utilizes the dark mudstone or oil shale of the Chang 9 source rock in conjunction with the oil layer sandstone as the reservoir. This combination is regarded as exhibiting the greatest exploration potential. In light of the aforementioned circumstances, the lithology and physical properties of the Yanchang Formation in the Ordos Basin are being subjected to investigation with a view to providing technical support for oil and gas development in this area.
Rock structure and pore characteristics of Chang 9 reservoir in Ordos Basin.

3.2. Evaluation of Basic Characteristics of Tight Reservoir

3.2.1. Reservoir Space Characteristics

The observation of drilling cores and thin sections shows that the lithology of Chang 9 oil layer formation consists mainly of sandy dolomite, oolitic dolomite, algal debris dolomite and powder fine-grained dolomite. The types of reservoir space mainly include intergranular pores, intercrystalline pores and dissolution pores. Intergranular pores are mainly developed in sand debris dolomite and oolitic dolomite, which are formed by the diffusion of intergranular pores through atmospheric freshwater dissolution (Figure 2a,b). Intercrystalline pores are mainly distributed between relatively coarse powder and fine-grained dolomite crystals, and the pore size is generally 100 µm. It is formed by further dissolution and expansion on the basis of crystals (Figure 2c,d). Dissolution pores are the most developed pore types in the gypsum-salt carbonate symbiotic system on the eastern side of the paleo-uplift in the Ordos Basin. They are common in fine-grained dolomite, dolomite and microbialite. Secondary filling minerals such as quartz, medium and coarse-grained dolomite and calcite are common inside (Figure 2e,f).

Figure 1. Geological overview (a) and representative stratigraphic histogram (b) of the study area.

Figure 2. Rock structure and pore characteristics of Chang 9 reservoir in Ordos Basin. (a,b) are Intergranular pores; (c,d) are Intercrystalline pores; (e,f) are Dissolution pores.
3.2.2. Reservoir Porosity and Permeability Characteristics

The current study employed the volume measurement method to assess the porosity of rock samples. Initially, measurements were taken for both the total volume of the rock sample and the volume occupied by the solid phase (rock minerals). The disparity between these two measurements yielded the volume of the pores. Subsequently, the pore volume was divided by the total volume to ascertain the porosity percentage. The physical property analysis of 40 sandstones in different regions of the profile indicates that the porosity in the study area is between 3% and 12% (with an average value of 7%). The permeability is between 0 and $1.5 \times 10^{-3}$ μm² (with an average value of $0.19 \times 10^{-3}$ μm²), indicating that the overall reservoir quality is poor and that the reservoir belongs to the ultra-low permeability category.

Figure 3 illustrates that 60% of the permeability is distributed at $0.01 \times 10^{-3}$ μm², with the porosity of 60% of the samples between 7% and 9%. Samples with permeability greater than $1 \times 10^{-3}$ μm² account for a small proportion of the total, indicating that the overall reservoir quality is poor. Conversely, the better reservoir is only developed in local areas.

Furthermore, it was observed that the physical properties of sandstone reservoirs in the channel were generally favorable, followed by those in the upper part of the configuration interface. In contrast, the sandstone reservoir in the lower part of the configuration interface exhibited the poorest quality. The physical properties of sand bodies at different positions in the profile were found to be significantly disparate, with notable heterogeneity.

![Figure 3. Histogram of physical properties of sandstone in a section of the Chang 9 oil layer formation.](image)

Figure 4 illustrates the pronounced heterogeneity of the Chang 9 oil layer formation, with a notable distinction between the porosity and permeability of the lipophilic sandstone and hydrophilic sandstone. The average porosity of the lipophilic sandstone is 8%, while the average permeability is 0.33 mD. In contrast, the average porosity of the hydrophilic sandstone is 6.4%, with an average permeability of only 0.03 mD. The permeability of lipophilic sandstone and hydrophilic sandstone is markedly disparate.

![Figure 4. (a) Physical properties of oil–hydrophilic sandstone in Chang 9 oil layer formation; (b) Extension of centralized data of (a).](image)
3.2.3. Maturity Characteristics of Reservoir Sand Body

The results of the identification of core thin sections from different regions and types within the basin indicate that feldspar sandstone and lithic feldspar sandstone are the primary components of Chang 9 sandstone. These results are presented in Figure 5. The average content of quartz is low, at less than 31%, while the average content of feldspar is high, at more than 34%. The average content of rock debris is between 10% and 20%. Therefore, the compositional maturity (quartz/feldspar + rock debris) of the Chang 9 sand body is generally low.

![Composition triangle of Chang 9 sandstone](image)

**Figure 5.** Composition triangle of Chang 9 sandstone.

The structural maturity of a sand body is primarily determined by particle roundness, sorting, impurity content, cementation type and other parameters. Observation of thin core sections reveals that the particle support structure of the Chang 9 sand body is pronounced, with the majority of debris particles exhibiting sub-angular or sub-circular shapes and predominantly linear contacts. These observations are presented in Figure 6.

![Optical microscope images of sand bodies from the Chang 9 oil layer formation](image)

**Figure 6.** Optical microscope images of sand bodies from the Chang 9 oil layer formation. (a) Coarse-to medium-grained debris feldspar sandstone with grain support (C19, 840.47 m); (b) Fine-grained feldspar sandstone with grain support (C88, 864.77 m).

3.2.4. Grain Size Characteristics of Reservoir Sand Bodies

The grain size parameters and their spatial distribution are useful indicators for distinguishing the paleogeographic environment and sedimentary hydrodynamic conditions during the process of sand body deposition. Additionally, they are crucial for determining the physical properties of sand body reservoirs, which are of great significance for reservoir evaluation.

As illustrated in Figure 7, the underwater distributary channel sand body of fan-delta facies is characterized by a well-sorted particle size distribution, exhibiting a positive skewness. This indicates that the sediments in the sand body are predominantly coarse-grained components. Additionally, the kurtosis of the particle size–frequency curve is
flat and very sharp, suggesting a uniform distribution of particle sizes. The particle size probability curve is primarily shaped by channelized traction flow, which is exemplified by the classical two-stage formula comprising a jump component and a suspension component. Additionally, the three-stage formula of a double jump component reconstructed by lake waves also plays a role.

Figure 7. Grain size probability diagram of channel sandstone in fan delta.

The braided river delta sedimentary system is characterized by the development of onshore and underwater braided distributary channel sand bodies. According to Figure 8a, the sand particle size distribution in the braided distributary channel of the mainland is positively skewed, indicating that the sediments in the sand body are mainly coarse-grained components. The kurtosis of the particle size–frequency curve is from flat to very sharp. The particle size probability curve is primarily shaped by channelized traction flow, which is encapsulated in the classical two-stage formula comprising a jump component and a suspension component. As illustrated in Figure 8b, the particle size distribution of the underwater distributary channel sand body exhibits a positive skewness, indicating that the sediments in the sand body are predominantly coarse-grained components, and the kurtosis of the particle size–frequency curve is medium to very sharp. The particle size probability curve is primarily shaped by channelized traction flow, which is represented by the classical two-stage formula comprising a jump component and a suspension component. Additionally, the three-stage formula of a double jump component reconstructed by lake waves also plays a role.

Figure 8. Grain size probability diagram of braided river delta sandstone. (a) for the sand particle size distribution in the braided distributary channel; (b) for the particle size distribution of the underwater distributary channel.
The meandering river delta sedimentary system comprises two main types of sand bodies: onshore sand bodies and underwater distributary channel sand bodies. The constituent particles of the former are obviously finer than those of the latter. Figure 9 illustrates that the grain size distribution of the sand body in the land distributary channel is positively skewed, indicating that the sediments in the sand body are mainly coarse-grained components. The kurtosis of the grain size–frequency curve is from flat to sharp. The particle size probability curve is mainly formed by the channelized traction flow, which is represented by the classical two-stage formula composed of the jump component and the suspension component. Figure 9 illustrates that the particle size distribution of the underwater distributary channel sand body is positively skewed, indicating that the sediments in the sand body are mainly coarse-grained components. The kurtosis of the particle size–frequency curve is medium to very sharp. The particle size of the probability cumulative curve is primarily comprised of three sections of double jump components and suspended components, which reflect the reconstruction of sediment by lake waves. Additionally, some components are composed of four sections of small rolling components.

In conclusion, the grain size parameters and grain size distribution of the Chang 9 sand body demonstrate a complex and changeable nature, which can be attributed to the diverse types and variable sedimentary hydrodynamic conditions present in the sedimentary microfacies delta system.

3.3. Plane Distribution Characteristics of Sedimentary Facies in the Study Area

According to the comparison profile of eight Chang 9 sedimentary facies connected wells, the dominant facies division principle was adopted [24–27]. Then, under the guidance of delta sedimentary facies model lake, the boundary between sedimentary microfacies was finally determined according to the sandstone thickness trend of the distribution and contour map and the sandstone/stratum thickness ratio of contour map. The plane distribution map of sedimentary facies of Chang 9 sub-layer of Chang 9 oil layer formation in the whole basin was drawn up, as shown in Figure 10.

It can be seen from the plane layout of Chang 9 sub-layer sedimentary facies shown in Figure 10 that the sedimentary pattern of this period basically inherited the sedimentary facies distribution characteristics of Chang 9 period. However, due to basin subsidence and large-scale lake transgression, lake shoreline moved to land, the lake area expanded and lake water deepened, a new semi-deep lake–deep lake landscape appeared in the southeastern basin. On the delta plain, sandy distributary channels and argillaceous distributary plains are distributed in the growth zone. In the delta front facies belt, affected by multi-source injection and the development of underwater distributary channel network, the stable lake
area is mainly distributed in the Zhengning-Fuxian area of Tiebian City and expands to the southeast. The northwest is dominated by a shallow lake environment, and the southeast develops a semi-deep lake–subfacies deep lake environment.

![Figure 10. Sedimentary facies distribution of Chang 9_1 in Yanchang Formation, Ordos Basin.](image)

3.4. Vertical Structural Characteristics of Sand Body in the Study Area

The vertical structure of a sand body refers to the vertical change mode of the sand body’s debris composition, sedimentary structure and logging response, that is, the sedimentary sequence or sedimentary rhythm. This is the sedimentary response to the variation of sedimentary environment factors such as provenance supply and sedimentary water capacity with time. Therefore, the vertical structural style of a sand body is obviously controlled by the sedimentary environment and sedimentary facies and is also related to the relative rise and fall of the sedimentary base level or lake level. Different sedimentary environments or facies often form sedimentary sequences with different characteristics. The vertical structural style of sand body is not only an effective way to explain the sedimentary environment but also helpful to judge the development position of high-quality reservoirs in a sand body. Based on the vertical structural style of sand bodies, this paper discusses the structural characteristics of the Chang 9 sand body.

According to the core profile description and sedimentary microfacies analysis, combined with the shape of the logging curve and sedimentary microfacies interpretation, the longitudinal structural style of the sand body of the Chang 9 oil layer formation in the basin is roughly summarized into three basic structural types: box-shaped upward thinning, bell-shaped upward thinning and funnel-shaped upward thickening. The results are shown in Figure 11.

Figure 11 shows that the A-type vertical structure in the sand body has a typical box logging curve and slightly upward thinning sedimentary sequence characteristics, the bottom has an obvious erosion mutation surface and the top has gradual mutation. The sand body is mainly composed of coarse-grained components, and the sedimentary structure is mainly composed of massive bedding, large-scale cross bedding and parallel bedding, which is obviously the sedimentary response to a high-energy environment and has a strong sedimentary hydrodynamic force. Among them, the continental and underwater main distributary channel sand bodies of the Chang 9 braided river delta and meandering river delta usually have this A-type vertical structure. Due to the coarse lithology and low
shale content, it is the most favorable sand body type for reservoir development. The B-type vertical structure is characterized by the upward fine sedimentary sequence developed by the sand body. The bottom is an obvious mutation surface. The coarse-grained debris deposits accumulate on the scouring surface. The upward particles gradually become thinner, the mud content increases and the top gradually changes. The corresponding GR logging curve is usually bell-shaped. The typical feature of the C-type vertical structure is the upward coarsening sedimentary sequence developed by sand body, with a gradient at the bottom and a mutation at the top. The sediment particles coarsen gradually from bottom to top, and the mud content decreases continuously. The corresponding GR logging curve is usually funnel-shaped.

![Sample diagram of vertical structure style of single sand body with Chang 9](image)

**Figure 11.** Sample diagram of vertical structure style of single sand body with Chang 9.

### 3.5. Sedimentary Model

The Chang 9 reservoir of the Yanchang Formation in the Ordos Basin can be considered to be part of the slow rising period of the lake basin as a whole. The sedimentary evolution of Chang 92 and Chang 91 is highly consistent with the overall sedimentary evolution law of the Chang 9 period in the Ordos Basin. The provenance supply system of the Chang 9 sedimentary period is mainly Qinling ancient land in the south and Longxi ancient land in the southwest. From a regional perspective, the Chang 9 period in the study area was a significant period of delta formation. The water body in the Chang 9 sedimentary period is relatively shallow, and a shallow sedimentary environment was developed. The central area of the lake basin is located in the Huachi area. The sedimentary microfacies map and sedimentary model map indicate that during the early Chang 9 period, the lake transgression expanded, the shallow lake area continued to expand, the area of the delta front continued to decrease, the thickness of the sand body decreased and the thickness of the sand layer was between 5 and 15 m. During the middle and late stages of the Chang 9 period, the lake basin continued to expand at a slow rate. The provenance of the lake basin was primarily sourced from the southwest, and the provenance supply was sufficient. The delta front area was relatively large, and numerous underwater distributary channel microfacies were developed in the area. The sand body distribution was stable, and the sand layer thickness was between 15 and 30 m. A schematic diagram of the sedimentary environment is presented in Figure 12.

The sedimentary environment of the Chang 9 oil layer formation in the Ordos Basin exhibits similarities to and differences from sedimentary environments in other regions, both within and outside of China. Domestically, similar environments may be present in areas such as the Tarim Basin, Badain Jaran Desert and Ebo Liang, influenced by geological structures and continental lakes. Internationally, analogous environments can be observed in regions such as the Altai Mountains of Central Asia and the Baikal Basin in Siberia, char-
characterized by comparable geological backgrounds and climate conditions [28–31]. Despite these parallels, variations exist in sediment sources, deposition processes and paleoclimatic conditions among different regions. By comparing with these areas, a better understanding of the sedimentary environment characteristics of the Yanchang Formation in the Ordos Basin can be obtained, contributing to a more insightful exploration of oil and gas resources.

Figure 12. Sedimentary model of Chang 9 oil layer formation in Yanchang Formation.

4. Conclusions

1. In the study area, the reservoir porosity of the Chang 9 oil layer formation is between 3 and 12%, and the permeability is between 0 and \(1.5 \times 10^{-3}\) \(\mu\)m\(^2\), classifying it as an ultra-low-porosity and ultra-low-permeability reservoir; Chang 9 sandstone is composed of feldspar sandstone and lithic feldspar sandstone. Among them, the average content of quartz is low, at less than 31%; the average content of feldspar is high, amounting to more than 34%; and the average content of rock debris is distributed between 10% and 20%. Therefore, the compositional maturity of the Chang 9 sand body is generally low. The particle size parameters and particle size distribution are complex and changeable, and the particle size distribution shows positive skewness, indicating that the sediments in the sand body are mainly coarse components; the kurtosis of the particle size frequency curve is flat to very sharp.

2. By analyzing the plane distribution characteristics of sedimentary facies in the Chang 9 period of the Chang 9 oil layer formation in the Ordos Basin, it has been determined that the sedimentary pattern of the Chang 9 period basically inherited the distribution characteristics of sedimentary facies of the Chang 9 period. However, due to the basin subsidence and large lake transgression, the lake shoreline moved landward, the lake area expanded, the lake water deepened and a semi deep lake–deep lake facies belt appeared in the southeast part of the basin.

3. The vertical structure of the sand body of Chang 9 oil layer formation in the Ordos Basin can be roughly summarized as a box-shaped structure with upward thinning, a bell-shaped structure with upward thinning and a funnel-shaped structure with upward thickening. The sedimentary microfacies evolution of the Chang 9 oil layer formation has certain continuity, and the reservoir of the Chang 9 oil layer formation in the Chang 9 period belongs to the slow rising period of the lake basin. In the early stage of Chang 9, the lake basin rose, the shallow lake area became larger and the delta area gradually decreased. In the middle to late stage of Chang 9, the delta front area expanded, the source supply was sufficient and the sand body developed well.
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